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FACTORS DETERMINING POLLUTION FROM LOCAL SOURCES IN INDUSTRIAL AND URBAN AREAS*

By F. PASQUILL

General role and action of the atmosphere. The discharge into the atmosphere of gases and small particles from combustion and chemical processes is the beginning of a complex series of actions. These may be considered in three main stages :

(a) general drift in the prevailing airstream with progressive spreading sideways and vertically,
(b) chemical and physical transformation in the airborne stage, and
(c) removal from the atmosphere by various natural processes.

All these stages are important to some degree in controlling the resultant level of pollutant concentration. For the local effects, i.e. those within a distance of say 10 kilometres from the source, the determining factor is more often (a), though (b) and (c) cannot be generally ignored and may sometimes be decisive.

The general drift in the airstream introduces a particularly effective and direct dilution of the pollutant when, as is usual, this is emitted gradually. Then the pollutant emitted over a given time will tend to be distributed through a volume of air directly proportional to the wind speed. In this respect wind speed is one of the most important meteorological factors.

Apart from the general transporting action and initial dilution the lower atmosphere also exerts a progressive diluting action, through the vertical and sideways spreading by the turbulent and convective motions which disturb an otherwise steady flow. In the same way material released in concentrated batches is spread alongwind as well as vertically and sideways.

The intensity of the turbulent variations in the wind is greater the rougher the underlying surface, and is markedly affected by the day-time heating or nocturnal cooling of the surface, vertical mixing being respectively enhanced or suppressed. The depth of the atmosphere over which rapid vertical mixing extends (the mixing depth or layer) depends on the temperature profile and is frequently limited decisively by an overhead stable layer in which there is an inversion.

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The velocity fluctuations which produce vertical spread are so rapid that in most cases their full action is achieved in 10 minutes or so, i.e. in so far as the concentration downwind of a continuous emission is dependent on vertical spread, the concentration will have reached a fairly steady value when exposure to the effluent has continued for such a period. However, those fluctuations (in wind direction) which affect sideways spread include very much slower variations in addition, extending over hours and days. Accordingly the reduction of average concentration by crosswind spreading continues progressively as the exposure time of interest (or sampling time) is extended into tens of minutes, hours, days and so on.

Theoretical treatments of dispersion. The literature available on the theoretical treatment of the effects of atmospheric turbulence in diluting windborne material is now very extensive.[1,2] All treatments demand idealization of the flow situation as a prerequisite for representing the dispersive action in a way that can be handled mathematically. Different degrees of sophistication are attempted in the various mathematical analyses but all the resulting dispersion formulae are necessarily of common form to the extent that the concentration downwind of a continuous emission is

(a) directly proportional to the rate of emission, and

(b) inversely proportional to the product of the wind speed, the crosswind spread and the vertical spread.

The product in (b) represents the effective volume of air over which a given amount of material has been spread and neglects effects of wind speed other than that of direct dilution. In this respect the theoretical treatments do no more than formalize relations expected on simple physical grounds, and their most important potential is in correctly representing the magnitudes of the spreads in relation to measurable meteorological properties.

The fact that the theoretical treatments refer to idealized conditions of flow and terrain, which are rarely realized in situations for which air pollution is a problem, is often quoted as a criticism of their inherent value. Moreover, such are the virtually random variations in the apparent dispersive behaviour of the natural atmosphere that at best the theoretical treatments offer estimates of *average* behaviour, from which the behaviour on individual occasions may be expected to depart to some extent. It is important to keep these reservations in mind, but there are many situations of weather and terrain and many types of practical questions for which it will be technically useful and economically worth while to be able to make estimates of likely pollutant concentration without embarking on difficult and prolonged measurements of actual pollutants or of tracers simulating them. In all cases it is preferable that the application of the theoretical treatments should be made by scientists with meteorological experience, who can also through that experience make as much allowance as possible for the particular nature of the site and terrain and for the non-ideal nature of the airflow.

Practical systems for estimating dispersion. In any practical system for estimating the dispersion of pollutants the aim must be to combine to the best advantage three components :

(a) the idealized theoretical treatments, reduced to a simple but flexible type of formula,

(b) the practical experience gained from tracer studies and previous air pollution surveys, and

(c) the specialized knowledge available or obtainable on the particular configuration of the emission site and the area downwind.

In addition to the information on wind velocity — and here of course the general direction is important in defining the zone affected — the main meteorological problem is that of appropriately representing the crosswind and vertical spreads. Full use of the available theoretical treatments requires meteorological measurements which except in special and limited projects are too detailed and specialized to be envisaged. Examples are the fine detail of the temperature profile near the ground and the magnitude and scale of the turbulent fluctuations. For general and extensive practical use the estimation has to proceed in terms of routine meteorological data.

Of the available routine data the factor most directly reflecting the amount of day-time surface heating or night-time cooling (hence the 'stability' in the lower atmosphere) is the amount of cloud. It is possible to define combinations of state of sky and wind speed to represent categories of stability and to assign to them 'normal' values of the spreads. A system on such lines[3] was designed in the Meteorological Office over 10 years ago and continues to be used widely. Rough but useful estimates of the effects of a given source on the level of pollution may thus be made given only the wind speed and direction and state of sky (with the locality, date and time otherwise determining the amount of sunshine). Such a system can be used in planning studies and also in operational studies in the absence of special meteorological data. Improvements in various aspects of the system may be expected as basic knowledge is increased and experience gained.[4] The accuracy achievable depends on how well the terrain and flow conditions conform to the ideal state and on the correctness of the meteorological data. On individual occasions the actual short-term concentration may differ one way or the other from that estimated, by a factor of several-fold.

Effect of elevation of sources. The significance of the usually gradual nature of pollutant emission as regards dilution has already been noted. The other very important characteristic of the source is its elevation above the general ground level. Elevation is advantageous as long as the plume of pollution is not deflected downwards as a whole. Then a definite amount of vertical spread (and a corresponding amount of crosswind spread) must occur before the edge of the plume reaches ground level. The more intense concentration of pollution close in to the source is thereby avoided at ground level, and the maximum concentration now occurs some distance away depending on the height of the source. Thereafter the concentration at ground level decreases, always being lower than that which would have occurred had the same source been at ground level, but tending closer and closer to this value as distance increases.

For a given elevation of source the distance at which the pollution appears at ground level with maximum effect depends on the rate of vertical spreading and hence on the stability of the atmosphere. Thus the effects of an elevated source may be apparent at very short range in unstable conditions. On the other hand in stable conditions it has been known for an elevated plume to travel tens of kilometres without the ground being affected.

Wind speed has an important effect on the behaviour of an elevated plume, in addition to the diluting effect, in that it controls the amount by which a hot plume may rise above the chimney exit and so determines the effective total height of the plume. A strong wind keeps the plume low, so that a relatively small amount of vertical spread is required for the ground to be affected, and so this effect of wind speed is in opposition to its direct diluting action. It is also likely that at the greater heights reached by modern power station plumes the relative magnitudes of the vertical and crosswind spreads are also affected by wind speed, but to an extent which is not yet clear. The overall influence of wind speed may thus be rather more complex then is assumed in the usual simple model treatment of an elevated source. However, recent surveys[5] suggest that except in a combination of light wind and unstable conditions the concentrations are on average somewhat less than those estimated from the simple model, in which the ratio of the spreads is taken to be a constant independent of wind speed and distance.

Multiple sources. Although there may be considerable interest in the effects of a single large source of pollution there is also an obvious and perhaps overriding interest in the combined effect of an array of various sources in an urban-residential area or an urban-industrial complex. There has accordingly been a focusing of interest recently on the methods of making estimates of concentration in such cases, from source inventories and meteorological or climatological data. This so-called 'mathematical modelling' of the effects of multiple sources is essentially a matter of summing individual contributions which in the simplest context are independent and directly additive.

The summation may be carried out in two ways :

(a) by a mathematical integration — which is possible for certain simplified forms of the dispersion formulae — leading to a convenient formula representing the overall effect in terms of the total output over a specified area, and

(b) by a numerical summation on a computer — the effects at any point being first evaluated separately for all sources or convenient combinations of small sources.

It should be emphasized however that both methods depend ultimately on the validity of the dispersion formulae, and on the quality of the data on source inventory, wind speed and direction, and spread.

Both methods have been tried, though recently the emphasis has been on the second.[6] Very extensive arithmetic is required but this can be carried out very quickly on modern high-speed computers. It is debatable however whether the realism of the final answers is always likely to be enough to justify the great elaboration advocated in the numerical models. There is some indication[7] that a combination of both methods may be advantageous in eliminating much of the numerical labour without seriously reducing the validity of the results. The advantage may be particularly significant when use is made of the principle that other things being equal the concentration at a given position will be dominated by the sources in a relatively small area immediately upwind.

It is to be expected on theoretical grounds, and is evident from practical surveys, that in a multiple-source situation concentrations vary widely from position to position in the area, and from time to time. Nevertheless, the concentration averaged over a long time and over the whole of the multiple-source area may be predictable with some accuracy (within a factor of two, say). On the other hand, the concentration estimated for a particular position, even when averaged over some hours, may be very much more in error.[8] Thus although much of the point of method (b) lies in the prospect of correctly representing variability of the concentration in space and time this seems unlikely in respect of individual positions and periods. It is possible however that the application of the method to a large number of periods may provide a realistic estimate of the *range* of variation at a given position.[9]

Complexities of weather and terrain. It has already been emphasized that ideal conditions of flat uniform terrain and straightforward airflow are necessarily assumed in any simple generalizations about the local distribution of air pollution. In practice there are many departures from this ideal, the more important being as follows :

(a) *The effect of buildings.* In a collective sense these affect the general level of turbulence in the airflow, and some useful allowance for this may be estimated when the dispersion has proceeded sideways and vertically well beyond the sizes of individual buildings. The principal difficulty arises from the immediate local effect on a nearby source of the aerodynamic disturbance by an individual building. Only very crude generalizations can at present be offered, and the best hope for accumulation of necessary experience seems to lie in wind-tunnel work.[10]

(b) *Topographical effects.* Irregular terrain introduces important modification of the general drift of pollutants. Apart from the physical deflexion and channelling of the airflow there occur downslope (drainage) winds from cooling at night and upslope winds from heating during the day. Dispersion tends to be affected adversely mainly by the vertical confinement of the air in valleys in stable conditions and the direct prevention of cross-stream spreading by valley sides. Useful attempts have been made to allow for such effects in the adaptation of the methods applicable to flat terrain.

(c) *Light winds and calms.* These are the conditions which, especially in association with slow or restricted vertical mixing or with topographical confinement of the airflow, lead to the disastrous air pollution incidents. The slow drifting and dispersive action of the atmosphere is then not readily and reliably estimated by the usual procedures. Such extensions as are made of these procedures must be regarded with caution and even more reliance than usual placed on actual experience at particular sites in stagnant air situations.

Warning, forecasting, climatology. The ultimate basis for the preparation of warnings or forecasts of the incidence of important levels of air pollution is in the known relations between the concentration field, the source distribution and the meteorological conditions. In principle therefore a warning procedure may be designed in terms of continuous measurements of a significant meteorological parameter — such as the level of turbulence or the detailed form of the vertical profile of temperature — from which these relations may be evaluated. In the practice of warnings and forecasting, as in that of planning and operational studies of air pollution, the meteorological requirements must generally be reduced to those normally satisfied in the regular programme of a national weather service. This means also that the parameters of the source/dispersion relation must be in terms of wind speed, broad vertical profile of temperature as available from routine upper air data, and state of sky.

The only general system[11] known to be in current and continuous operation is based on forecasting the expected occurrence and continuation of large areas of stagnant air, within which a build-up of pollution would be possible. Extension of this purely qualitative 'air pollution potential' forecasting is in hand in terms of a simple 'box' model in which the pollutant is assumed uniformly distributed over the 'mixing depth'. The product of this 'mixing depth' and the wind speed constitutes an effective dilution factor to be applied to the amount of pollutant released upwind of any position. An approximation to the 'mixing depth' is available from the routine upper air data by applying the same procedure as the weather forecaster uses for estimating the likely vertical extent of convection.

A further possible step in the development of pollution forecasting would be to use forecasts of wind speed and cloud cover, to derive a forecast 'stability category' which could be used in more detailed calculations of concentration. It would be important in any such further elaboration to keep in mind the very rough quality of the final answers. However, in practice the important requirement will often be the provision of warnings of the likely incidence of relatively intense pollution. In respect of sulphur dioxide pollution in urban areas it seems likely that useful rules may be formulated from an examination of available data on day-to-day variations in relation to wind speed, temperature and stability.[12]

The climatological statistics on wind speed, wind direction and cloud amount prepared from routine observations are immediately usable in any requirement for the estimation of long-term average concentration or of the frequency of incidence of specified levels of pollutant concentration. The procedure does of course need to be used with caution, not only because of the inevitably crude representation of the dispersive action of the atmosphere, but also because there may be correlations in the occurrence of the basic meteorological elements, e.g. cloud cover and wind direction, which are not evident from separate statistics of these properties.

There is now the possibility of deriving a more specialized climatology for such features as the mixing depth and stability categories, but so far such analyses have been on a very limited scale.

Transformation and natural removal of pollutants. The pollutants of major interest are neither chemically inert nor permanently retainable in the atmosphere and their dispersion after release is accompanied by a complex chain of chemical reactions[13] and physical removal processes.

One of the most important transformations is the solution and oxidation of sulphur dioxide to give sulphuric acid and sulphates. The solution may occur at free water surfaces, on wet ground and other solid surfaces, on vegetation, and in drops of fog, clouds and rain. The process is of immediate practical importance as regards corrosion of materials. If the oxidation is in the presence of ammonia, hygroscopic ammonium sulphate results and in aerosol form this has an important effect on visibility. Transport to ground in rain or direct uptake at wet surfaces (including vegetation even in a nominally dry state) progressively depletes the atmosphere of the sulphur dioxide or secondary products. The relative amounts of sulphur dioxide deposited and remaining airborne depend on many factors: the initial elevation of the source, the dispersive conditions, the intensity of rain and the nature and wetness of the underlying surfaces. The complexity of the processes is reflected in the variability of the effective life-time of sulphur dioxide in the atmosphere — estimates range from an hour to several days[13-15] — and the significance of this to the concentration and effect of sulphur dioxide locally requires continuing study.

The other chain of processes which attracts great interest is that which leads to the 'photochemical smog' so well known in Los Angeles. Photochemical dissociation of nitrogen peroxide, which appears to be enhanced in the presence of certain hydrocarbons (including those in car exhausts), produces ozone, which in turn reacts with the hydrocarbons to form compounds with irritant properties. For these processes the favourable meteorological conditions are those of limited transport and dispersion in the presence of abundant sunshine, a combination occurring most effectively in anticyclonic conditions in relatively low latitudes, especially when there is topographical impedance to the large-scale airflow, as in the Los Angeles basin.

Future needs. Features which are considered to be in special need of further consideration are :

(a) The provision of improved low-level temperature soundings or of other measurements capable of prescribing the general 'mixing depth', and the extension of the climatology of 'mixing depth' and 'stability categories'.

(b) Standardization of the practical systems for estimating and forecasting the levels of air pollution from emission data and meteorological data, embodying improvements provided by recent researches but avoiding complexities which are not warranted by the expected quality of the final answers.

(c) Improvement of the understanding and representation of the chemical transformation and natural removal of air pollutants.

REFERENCES

1. PASQUILL, F.; Atmospheric diffusion. D. van Nostrand, London, 1962.
2. SLADE, D. H. (editor); Meteorology and atomic energy. Oak Ridge, Tennessee, United States Atomic Energy Commission, 1968.
3. PASQUILL, F.; The estimation of the dispersion of windborne information. *Met Mag, London*, **90**, 1961, pp. 33–49.
4. PASQUILL, F. and SMITH, F. B.; The physical and meteorological basis for the estimation of the dispersion of windborne material. Proceedings of the 2nd International Clean Air Congress, Washington, D.C., 1970, (in press).
5. London, Meteorological Office. A discussion on recent research in air pollution. *Phil Trans R Soc, London*, **265**, 1969, pp. 139–318.
6. North Carolina, Research Triangle Park, U.S. Environmental Protection Agency. Proceedings of symposium on multiple-source urban diffusion models, 1970.
7. GIFFORD, F. A. and HANNA, S. R.; Urban air pollution modelling. Proceedings of the 2nd International Clean Air Congress, Washington, D.C., 1970 (in press).
8. MARSH, K. J. and WITHERS, V. R.; An experimental study of the dispersion of the emissions from chimneys in Reading — III: the investigation of dispersion calculations. *Atmos Environ, Oxford*, **3**, 1969, pp. 281–302.
9. PASQUILL, F.; The prediction of diffusion over an urban area — current practice and future prospects.[6] 3-1–3-26.
10. HALITSKY, J.; Gas diffusion near buildings.[2] pp. 221–255.

11. MCCORMICK, R. A.; Meteorological aspects of air pollution in urban and industrial districts. *Tech Notes, Wld Met Org, Geneva*, No. 106, 1970.
12. SMITH, F. B. and JEFFREY, G. H.; The prediction of high concentrations of sulphur dioxide in London air. London, Meteorological Office, 1971 (in press, copy to be available in the Meteorological Office Library, Bracknell).
13. JUNGE, C. E.; Air chemistry and radioactivity. New York, Academic Press, 1963.
14. ROBINSON, G. D.; Long-term effects of air pollution — a survey. Hartford, Connecticut, The Center for the Environment and Man, Inc., 1970.
15. MEETHAM, A. R.; Atmospheric pollution, 3rd Edn. Pergamon Press, Oxford, 1964.

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PROBABILITIES OF AIRCRAFT ENCOUNTERS WITH HEAVY RAIN

By J. BRIGGS

Summary. Estimates of probabilities of aircraft encounters with heavy rain have been obtained for three localities. The estimates are necessarily based on somewhat arbitrary assumptions, especially as regards the variation in rainfall probabilities with variation of height. However, the assumptions are reasonably supported by observational evidence and the method used has the merit that estimates can be made fairly readily for any area where the available rainfall data are adequate.

Introduction. The possibility of erosion of aircraft structures by rain becomes increasingly important as the operating speed of aircraft increases. Designers and airworthiness authorities require estimates of the chances that an aeroplane will meet rain that might cause structural damage or might lead to the wearing-away of materials.

This note presents some estimates of the probability that an aircraft will meet heavy rain. The estimates are based on available rainfall data and are limited to flight in the vicinity of a few stations but the method can be used for any place or route for which data are to hand. Since the problem of rain erosion is of great importance to supersonic aircraft the estimates have been based on the probable operating conditions for Concorde.

Method. Suppose that the probability of a particular rate of rainfall at a point on the ground is P_p whilst the corresponding probability of the same rainfall rate somewhere inside an area of unit radius is P_a. If the typical radius of a rain cell of the intensity being considered is R [where R is considerably less than unit radius] then

$$P_a \approx P_p/R^2.$$

Now assume that the rainfall probability is the same aloft as at the ground and that no avoiding action is taken, then the chance of an aircraft encounter with a rain cell during the crossing of an area of unit radius is

$$\frac{4P_aR}{\pi} \text{ or } \frac{4P_p}{\pi R}.$$

If the aircraft speed is V then the time taken to cross the area is $2/V$ and so the probability of an encounter with rain of the specified intensity in unit time is

$$\frac{4P_p}{\pi R}\,\frac{V}{2} = \frac{2P_pV}{\pi R}. \qquad \ldots (1)$$

Estimates of P_p. Much rainfall information is available for many stations though the data are often limited to daily or monthly rainfall totals whereas the problem here relates to instantaneous rainfall rates. However, for an increasing number of places the use of recording rain-gauges has permitted hourly rainfall totals to be obtained and these totals can be used to determine the required probabilities of instantaneous rainfall intensities.

Briggs and Harker[1] have obtained typical distributions of two-minute rainfall rates about the clock-hour totals and have hence derived conversion factors which enable occurrence of instantaneous rates of rainfall to be assessed on the basis of available clock-hour data. Estimates of P_p thus obtained are presented in Table I for a limited number of stations and rainfall rates.

TABLE I—PROBABILITY OF OCCURRENCE OF INSTANTANEOUS RAINFALL AT OR EXCEEDING SPECIFIED INTENSITIES

	Rainfall intensity (mm/h)		
	25	50	100
		probability	
Heathrow	$1\cdot26\times10^{-4}$	$1\cdot94\times10^{-5}$	$1\cdot14\times10^{-6}$
Singapore	$1\cdot83\times10^{-3}$	$6\cdot85\times10^{-4}$	$1\cdot48\times10^{-4}$
Freetown	$3\cdot31\times10^{-3}$	$1\cdot26\times10^{-3}$	$3\cdot19\times10^{-4}$

Rain-cell diameters. The pattern of rainfall during the passage of a heavy shower can vary widely but in general each period of light or moderate rain will include a shorter period of heavier rain. On the average the shower profile will have a reasonably smooth intensity/time distribution and the higher the intensity considered the shorter will be the typical duration.

Durations of rainfall can be determined by inspection of the charts of recording rain-gauges and may then be combined with estimated speeds of movement of the rain-bearing clouds to give values for the rain-cell diameters. Table II presents estimates of typical rain-cell diameters obtained for the places listed in Table I.

TABLE II—AVERAGE CELL DIAMETER (km) FOR RAINFALL AT OR EXCEEDING SPECIFIED INTENSITIES

	Rainfall intensity (mm/h)		
	25	50	100
		kilometres	
Heathrow	3	2	1·5
Singapore	3·5	2·5	2
Freetown	4	3	2

As must be expected the typical diameter decreases as the intensity of the rainfall increases. The table also reflects the influence of the average temperatures of the places concerned — the amount of water vapour which is ultimately available for release as rain is temperature-dependent and so the average cell diameter increases as the temperature rises. The figures of Table II are also in good accord with the diameters suggested by radar studies of the cores of heavy showers.

Rain-cell diameters will vary with altitude but it will be assumed here that the diameter remains reasonably constant throughout the depth of a heavy shower.

Variation of the probability of rainfall occurrence with height. The rainfall rates of interest in the rain erosion problem are mainly those exceeding, say, 10 mm/h and such rates are normally limited to showery conditions, though orographic intensification can cause such intensities inside widespread frontal-type rain. Radar studies, see, for example, Hamilton,[2] give some indication of the distribution of precipitation in the vertical. Although widespread rain usually shows a steady decrease of precipitation content with height increase it seems that the large precipitation densities occurring in the core of severe showers have a fairly uniform distribution throughout the bulk of the shower cloud.

The problem here is to determine how the probability of rainfall occurrence varies with height on the average, not just for one particular shower cloud. The probability at a given height will be compounded of the probability of a shower cloud top reaching to that height together with the probability of a given rainfall rate inside a shower cloud which extends to a given height.

Some indication of the probability of a given precipitation rate inside a shower cloud has been obtained by Donaldson[3] who measured radar reflectivities inside some 233 thunderstorms over New England. Radar reflectivity is essentially a measure of the water-substance contained in the larger raindrops, snow and hail but in interpreting the radar observations it is necessary to consider how the normal fall-off of temperature with height affects the rain/snow ratio. In many rainfall situations most of the large raindrops can be expected to have become frozen at heights above that corresponding to temperature of −20°C, i.e. above about 7 km for temperate climates and about 8 km for tropical climates. However, the heavy rain of main interest occurs in heavy showers or thunderstorms where strong updraughts rapidly distribute the water drops and so give good reason to ignore the freezing of the drops in the time available before cloud top is approached. Thus it is thought that Donaldson's profiles of radar reflectivity in thunderstorms give a good picture of the height distribution of the large rainfall rates now being considered.

Figure 1 presents the median profiles obtained by Donaldson. The figure suggests that the median rainfall rate is nearly constant to about 6 km and then decreases rapidly. Variation of median rainfall rate with height is not quite what is needed — the assessment of the variation in frequency of occurrence of a specific rainfall rate as height varies — though of course Figure 1 does suggest that there is little variation up to about 6 km. Again Donaldson gives us some guidance by presenting frequency distributions for specified reflectivity values at levels of 5000, 20 000, 30 000, and 40 000 ft.* These frequency distributions yield, approximately, the rainfall rate distributions summarized by Table III.

TABLE III—PERCENTAGE OF NEW ENGLAND THUNDERSTORMS WHICH HAVE PRECIPITATION RATES EQUAL TO OR EXCEEDING SPECIFIED VALUES

	Precipitation rate (mm/h)		
Height	25	50	100
km		*per cent*	
1·5	55	30	20
6	40	20	10
9	10	3	1
12	5	1	<1

* 1000 ft ≈ 305 m.

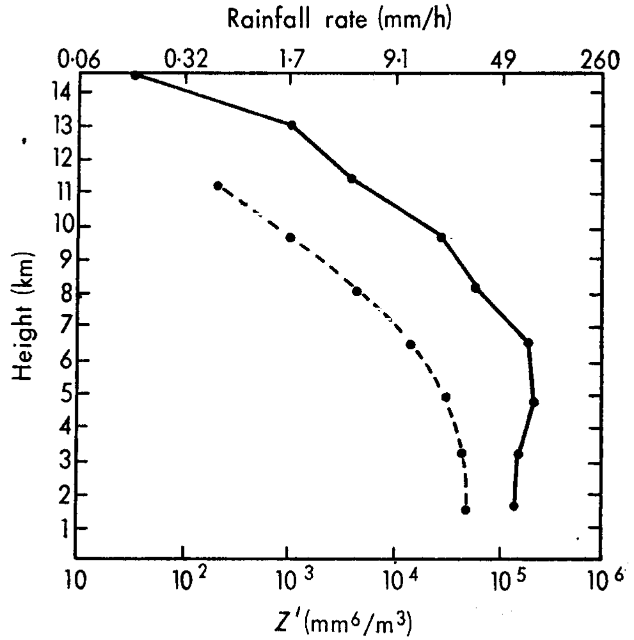

FIGURE 1—MEDIAN VALUES OF RADAR REFLECTIVITY AND OF EQUIVALENT RAINFALL RATE FOR NEW ENGLAND THUNDERSTORMS

(After Donaldson[3])

·– – – –· Rain, 182 cases. ·————· Hail, 51 cases.

$Z' \doteq$ radar reflectivity of small spherical water drops which would have the same total back-scattering cross-section as the measured echo

Table III refers to total precipitation whereas it is intended to determine variations in rainfall only. It is seen that the fall-off with height in the frequency of occurrence of a given total precipitation rate is most marked for high values of that rate. Now, the largest precipitation rates are associated with the largest updraughts and so with the lowest likelihood of drops becoming frozen by a given height. Hence freezing will affect relatively more raindrops at precipitation rates of 25 mm/h than of 50 mm/h, or again of 100 mm/h, and so will tend to even out the differences between the columns of Table III when the probability of rainfall only is being considered. Again this implies that column 4 of the table is the most likely to indicate how the frequency of occurrence of a given rate of rainfall falls off with height. Thus, at least for New England storms which extend to over 12 km, it seems that the probability of occurrence of a given rate of rainfall is nearly constant to about 6 km and then becomes 10 times less for each 3-km increase in height.

As indicated above, the overall probability of occurrence of a given rainfall rate depends also on the height distribution of shower cloud tops. Radar studies indicate these distributions and, for example, Moore (unpublished) has obtained the following percentage frequencies for radar echoes around Singapore.

TABLE IV—PERCENTAGE FREQUENCY DISTRIBUTION OF THE HEIGHTS OF THE HIGHEST RADAR ECHOES NEAR SINGAPORE

Height *km*	Frequency *per cent*	Height *km*	Frequency *per cent*
≥ 9	85·1	≥16	16·6
≥10	83·0	≥17	9·7
≥11	77·7	≥18	4·0
≥12	68·2	≥19	1·4
≥13	53·2	≥20	0·5
≥14	40·2	≥21	0·2
≥15	27·6		

Table IV suggests that the frequency of cloud tops at a given height begins to decrease at some height near mid-troposphere and that near the tropopause (around 16 km at Singapore) the frequency of occurrence of cloud tops becomes ten times less for each 3-km increase in height.

Combining the indications of the two preceding paragraphs it seems that the probability of occurrence of a given rainfall intensity is near constant to about mid-troposphere then becomes ten times less for each 3-km increase in height though around the tropopause the probability becomes ten times less in 1·5 km. So the probability of occurrence of a given rainfall intensity, P_H, at a given height can be expressed as

$$P_H = P_p \text{ for } H \leqslant T/2$$
$$P_H = P_p 10^{-k(H-T/2)} \text{ for } H > T/2 \qquad \ldots (2)$$

where T = tropopause average height and k has a value somewhere between $\frac{1}{2}$ and $\frac{2}{3}$.

In using the relation (2) above it must be noted that since water drops tend to freeze spontaneously even without nuclei when the temperature approaches −40°C then it is likely that all raindrops will be frozen at heights somewhere about 13 km so rainfall probabilities above 13 km should approximate to zero. However, at heights above 13 km or so mushy hail may produce effects equivalent to those of rain and so the use of relation (2) may still be informative.

Estimates of rainfall encounters for Concorde. Relations (1) and (2) can be used together with the appropriate values of P_p, R and T to determine probabilities of aircraft encounters with rainfall of a specified intensity. It is necessary to know the height–speed profile of the aircraft, and for Concorde the following values are indicated by probable operational routines :

Height *km*	Speed *m/s*	Height *km*	Speed *m/s*
3	200	12	375
6	250	15	500
9	300	18	600

Using these values and relevant rainfall data for Heathrow, Singapore and Freetown, the intensity of rain likely to be met once in 10^5 flight hours has been determined. Figure 2 presents the results using two values, i.e. $\frac{1}{2}$ and $\frac{2}{3}$, for the factor k in relation (2). It is thought that the pecked lines corresponding to $k = \frac{2}{3}$ are more likely to correspond to actual experience especially at the highest levels, though the solid lines corresponding to $k = \frac{1}{2}$ may provide safer planning guidance.

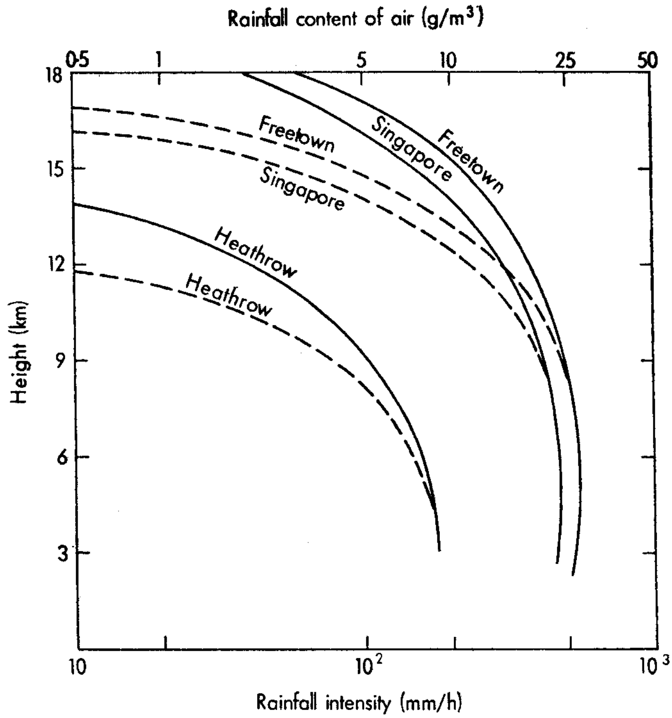

FIGURE 2—INTENSITY OF RAIN MET ONCE IN 10^5 FLIGHT HOURS (ALL AT CONSTANT HEIGHT)

——— Assumes $P_H = P_p \times 10^{-\frac{1}{2}(H-T/2)}$
– – – Assumes $P_H = P_p \times 10^{-(2/3)(H-T/2)}$

REFERENCES

1. BRIGGS, J. and HARKER, J. A.; Estimates of the duration of short-period rainfall rates based on clock-hour values. *Met Mag, London*, **98**, 1969, pp. 246–252.
2. HAMILTON, P. M.; Vertical profiles of total precipitation in shower situations. *Q J R Met Soc, London*, **92**, 1966, pp. 346–362.
3. DONALDSON, R. J. D.; Radar reflectivity profiles in thunderstorms. *J Met, Lancaster, Pa*, **18**, 1961, p. 292.

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AN OBJECTIVE AID FOR ESTIMATING THE NIGHT MINIMUM TEMPERATURE OF A CONCRETE ROAD SURFACE

By JOHN E. THORNES*

Summary. Many factors influence nocturnal cooling of a concrete surface. This investigation has confirmed that the minimum temperature can be estimated by a simplified mathematical approach which is described. The important variables are the sunset surface temperature, length of night, overnight wind speed, cloud type and amount, and dew-point. When estimations were below 0·0°C the theoretical formula gave minima which were too low, and on the basis of actual data a correction was applied to allow for the release of latent heat.

* Geography Department, University of Manchester.

A chart suitable for use on the forecast bench was produced. The method can also be used to estimate the time of occurrence of surface temperatures of 0·0°C. Data on road surface temperatures from sites at Tuxford, Nottinghamshire, for a period in 1968 and 1969 were provided by the Road Research Laboratory. For independent data good agreement was found between the estimated and observed minimum surface temperatures with a r.m.s. error of 0·76 degC but none of the variables were forecast. Also an accuracy of almost 100 per cent was obtained for the estimation of frost or no frost.

Introduction. With the advent of high-speed transport, associated both with motorways and with runways, the importance of accurately forecasting the night minimum surface temperature is obvious. Although the motorway motorist should adapt his speed to prevailing conditions, frost and ice are not always as obvious as a phenomenon such as fog. Many empirical formulae have been devised to forecast minimum air, grass and soil temperatures, but no direct formula has been presented for concrete surfaces. Many correlations, for example between air minimum and concrete minimum temperatures, have been attempted. Unfortunately correlation and regression methods often fail at the crucial times, when frosts form under conditions special to an occasion; averaging methods do not pick these out. The provision of a useful and economical forecast service requires that frosts occur only when predicted. The problem is made complex by the many factors which influence nocturnal cooling, and all should be taken into account for accurate forecasts. A mathematical approach is required that can be justifiably simplified when used in practice.

The theory of nocturnal cooling. Reuter[1] produced a practical solution to a rather complex mathematical treatment of the problem to forecast minimum soil temperatures. He modified an earlier approach by Brunt,[2] to take into account the effect of wind speed. Reuter noted that the conditions which favour nocturnal cooling of the ground surface are :

(a) Absence of wind.
(b) Clear skies.
(c) Low vapour pressure in the atmosphere above the surface.
(d) Low coefficient of thermal conductivity and low specific heat of the surface.

Reuter's basic formula is

$$\Delta T = F(E + Bk_g + (\gamma - \gamma_d)\, c_p A)\, t^{\frac{1}{2}},$$

where ΔT = fall in temperature at the ground surface from sunset to sunrise during a night of length t

$$F = \frac{2}{\pi^{\frac{1}{2}}} \; \frac{1}{(\rho_g c_g k_g)^{\frac{1}{2}} + c_p(\rho A)^{\frac{1}{2}}}$$

ρ_g = density of soil
c_g = specific heat of soil
k_g = coefficient of heat conductivity of soil
c_p = specific heat of air
ρ = density of air
A = coefficient of eddy conductivity in air
E = net outgoing long-wave radiation from surface under cloudless conditions
B = lapse rate in soil at sunset
γ = lapse rate in air at sunset
γ_d = dry adiabatic lapse rate.

The following assumptions should be noted :

(a) Nocturnal radiation is constant during the night. (In fact it falls by about seven or eight per cent between sunset and sunrise.[3])

(b) Specific heat, density and coefficient of heat conductivity of ground surface are constant with respect to depths and time during the night.

(c) Initially there is linear variation of temperature in the vertical in the ground surface and in the air.

(d) The coefficient of eddy conductivity in the air is constant during the night.

Reuter also made allowance for cloudiness when testing his formula. He replaced the term E by

$$E_w = E(1 - w\,k),$$

where E_w is the observed net loss of radiation from the ground when w tenths of the sky are covered with clouds, and the factor k depends on the height and type of cloud.

The expression for E_w was the one used by Dorno, but a better estimate has been given by Mizon:[4]

$$E_n = E(1 - \sum_{i=1}^{r} n_i k_i) = KE,$$

which allows for an estimate E_n when there are r layers of cloud with amount n_i and factor k_i for layer i.

Reuter had difficulty in finding accurate soil constants $k_g c_g \rho_g$ as these vary with moisture content as well as with constituents. Also he used screen air temperatures T instead of ground surface temperatures in estimating E when using Ångström's formula

$$E = \sigma\,T^4(0{\cdot}194 + 0{\cdot}236 \times 10^{-0.069e}),$$

where σ is Stefan's constant $8{\cdot}132 \times 10^{-11}$ cal/(cm^2 (degC)^4 min) and e is vapour pressure at sunset in millimetres of mercury (1 cal = 4·1868 J; 1 mm Hg $\approx$ 1·33 mb).

For a concrete surface it seems reasonable to use a modified version of Reuter's formula

$$\Delta T = F(E + B\,k_c + (\gamma - \gamma_d)\,c_p\,A)t^{\frac{1}{2}},$$

where $F = \dfrac{2}{\pi^{\frac{1}{2}}} \quad \dfrac{1}{(\rho_c c_c k_c)^{\frac{1}{2}} + c_p(\rho A)^{\frac{1}{2}}}$,

$$E = \sigma\,T_c^4\,(0{\cdot}194 + 0{\cdot}236 \times 10^{-0.069e}),$$

T_c = surface temperature of concrete at sunset,

and ρ_c, c_c, k_c are values of density, specific heat and coefficient of heat conductivity of concrete.

Reuter also showed that the terms $Bk_g + (\gamma - \gamma_d)c_pA$ are about 10 times smaller than E and can be neglected. Likewise $Bk_c + (\gamma - \gamma_d)c_pA$ may be neglected and the equation may be simplified to

$$\Delta T = Ft^{\frac{1}{2}}\,E.$$

Finally an allowance for cloud can be introduced by multiplying E by a factor K allowing for cloudiness; thus

$$\Delta T = Ft^{\frac{1}{2}}KE.$$

Data used. Data on road surface temperatures were provided by the Road Research Laboratory. Two sites near Tuxford, Nottinghamshire, on the A1, were used. At 'Tuxford North' a concrete slab nine inches deep, of the same structure as the road to which it is adjacent, has thermocouples embedded in it. The thermocouple at half-inch depth was taken to represent the surface temperature. The slab is sheltered somewhat from the north and west by observers' huts. On the whole, the continuous recordings made by the copper–constantan thermocouples were good, but because of breakdowns only the winter 1968/69 was completely recorded.

The site at 'Tuxford South' has thermocouples embedded in the road and the road is on an embankment. However, records for this site are of poorer quality than those from Tuxford North; because of this, and the fact that Tuxford South is affected by other variables such as passage of transport and the accumulation of salt and grit in winter, results from Tuxford North were examined in most detail.

For each night considered the sunset temperature at a depth of half an inch was recorded, and the minimum, thus giving the fall in temperature overnight (ΔT). Strictly one should record the fall from sunset to sunrise, but little difference was observed between the minimum and the sunrise temperature.

The nearest meteorological station with a similar terrain is at Finningley, about 20 miles ($\approx$ 32 km) to the north. In order to obtain the average dew-point temperature, wind speed and cloud cover for each night, the three-hourly records at Finningley were examined. Data from Watnall, some 20 miles west and in the Pennine foothills were also examined, and an average taken. However, the Finningley data alone proved more representative because of its similar environment.

Data for the winter 1968/69 were analysed, and also for July 1969. The months October, November, December, January and March were used as development data, and February, April and July as test data. (The February surface data were from Tuxford South during a period when the slab at Tuxford North was covered with snow.)

For January the Finningley data for 15 , 18 , 21 , 00 , 03 , 06 and 09 GMT each night were averaged, whereas in July only the 21 , 00 and 03 data each night were required.

The fact that a meteorological station 20 miles away had to be used, shows how little research has gone into this problem. It is only recently that stations began recording a concrete minimum temperature, but the value of these measurements has yet to be proved.

Practical application of the formula.

(a) *The estimation of F.* The function F is a characteristic function of the concrete and varies with A the coefficient of eddy conductivity. No accurate data relating wind speed and coefficient of eddy conductivity could be found for the conditions considered and a relationship had to be worked out. Observed values of ΔT, t and KE for the site at Tuxford, Nottinghamshire, were used to determine F from the equation

$$\Delta T = Ft^{\frac{1}{2}} KE,$$

and F was plotted against wind speed (Figure 1) using the development data, and a curve of best fit was drawn. The test data were then examined and values of F obtained for various wind speeds. These values were incorporated

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PLATE I—HOT-AIR BALLOON 'CHRISTABELLE'

This balloon is owned and piloted by Wing Commander G. F. Turnbull, O.B.E., A.F.C., who supplied the photograph (see page 25).

Photographs by No. 42 Squadron, RAF

PLATE II—WATERSPOUT JUST NORTH-EAST OF BISHOP ROCK LIGHTHOUSE PHOTOGRAPHED FROM A SHACKLETON AIRCRAFT AT ABOUT 06 GMT ON 23 MAY 1971

Some of the Isles of Scilly can be seen in the background. The north-westerly airstream was unstable and main cloud base was estimated to be about 1500 feet. The crew of the aircraft thought that the diameter of the spout at the surface was about 20 feet.

PLATE II—*continued*

To face page 17

PLATE III—AWARDS TO CIVIL AIRLINE PILOTS

From left to right: Mrs J. B. Linton, Captain J. B. Linton, Director-General of the Meteorological Office, Captain and Mrs W. C. Parke (see page 29).

into Figure 1 and a curve drawn which represents the whole data. The two curves differ little and only at high wind speed. At low wind speeds an anemometer reads too low because of friction and inertia effects and the curve derived from the data was adjusted accordingly (curve C).

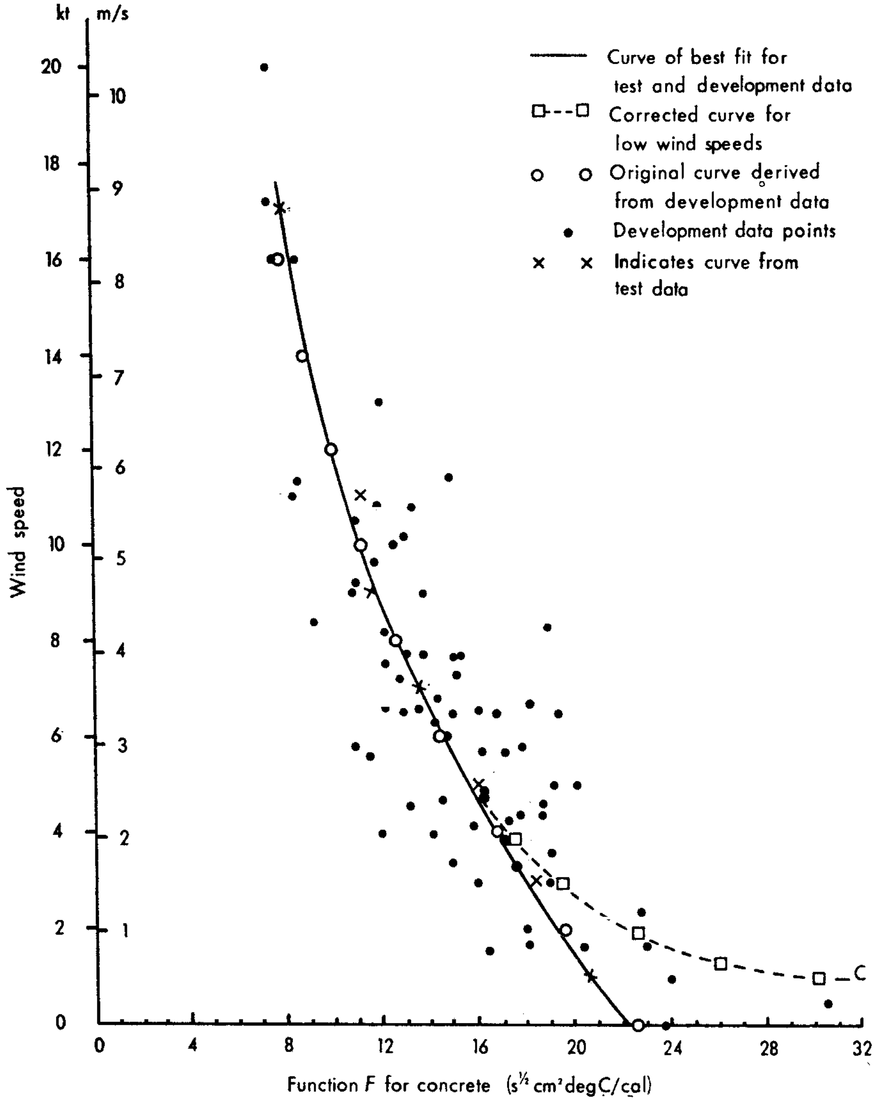

FIGURE 1—GRAPH RELATING WIND SPEED TO FUNCTION F FOR CONCRETE

Note that F is given in c.g.s. units, $s^{\frac{1}{2}}cm^2degC/cal$, if E is given in units of cal/(cm² min) and t is given in hours.

(b) *The estimation of* $Ft^{\frac{1}{2}}$. From the curve relating F to wind speed a series of curves can be drawn (Figure 2) giving $Ft^{\frac{1}{2}}$ for given wind speeds and given duration of night. The scale for $t^{\frac{1}{2}}$ is linear and a scale for the time of year has been added for convenience.

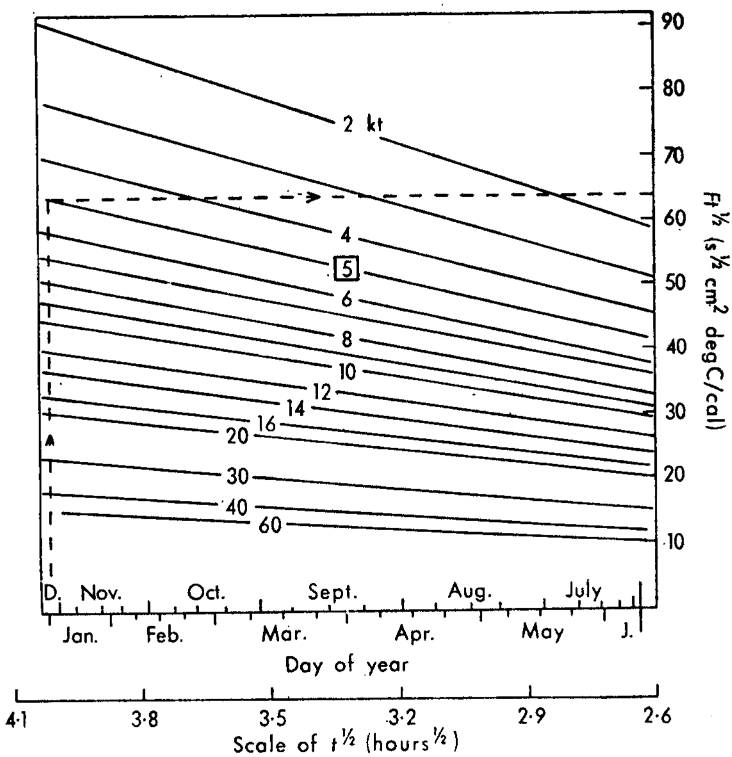

FIGURE 2—ESTIMATION OF $Ft^{\frac{1}{2}}$

The arrowed pecked lines on Figures 2–5 show points of entry to the diagrams.

It is unlikely that the overnight wind speed can be estimated to better than one or two knots (1 kt ≈ 0·5 m/s), thus a range of values should be considered rather than a single value to give an idea of the range involved in the final answer. This applies to all the estimations. The graphs are to be used as an objective guide, not as a mathematical instrument!

(c) *The estimation of E.* Graphs of E were drawn in Figure 3 related to the surface temperature of concrete at sunset and an average dew-point for the night instead of vapour pressure. The dew-point temperature does not usually vary much during the night. Moreover, a formula by Swinbank[5] estimates the outgoing radiation E to be a function of temperature only, i.e.

$$E = 5{\cdot}31 \times 10^{-14}\, T^6 \text{ mW/cm}^2.$$

Thus a variable may be removed from the argument, but this possibility has not been pursued.

(d) *The estimation of K.* Reuter gives Dorno's factors for 1/10 cloud of various types as: Cs 0·031; As 0·063; St 0·085; Ns 0·099. These factors were taken as factors for $\frac{1}{8}$ cloud and the resulting values of K were similar to the values of K used by Mizon. Graphs were drawn in Figure 4 to obtain K for various types and amounts.

$$\text{As } K = 1 - \sum_{i=1}^{r} n_i k_i\,, \quad K = \left[\sum_{i=1}^{r} K_i\right] - (r-1).$$

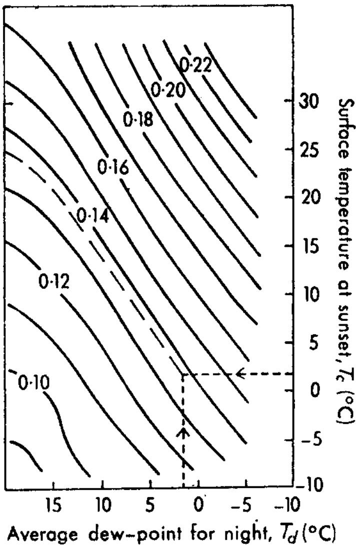

FIGURE 3—ESTIMATION OF E

Isopleths of E are drawn at intervals of 0·01 cal/(cm^2 min).

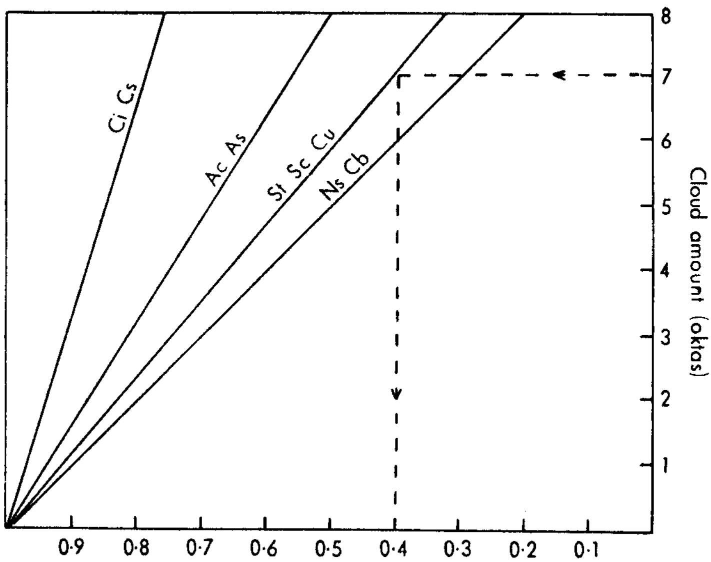

FIGURE 4—ESTIMATION OF K

Problems occur when more than one layer of cloud is expected, e.g. the total cloud cover may be 6/8 made up of 3/8 Cu, 4/8 Sc, 3/8 Ac. It would be wrong just to add up the components as 2/8 of the sky is clear. Obviously as the Cu is the lowest layer, it is all visible. The remaining 3/8 is either made up of 1/8 Sc and 2/8 Ac, or 2/8 Sc and 1/8 Ac, or 3/8 Sc.

These give :

(1) 3/8 Cu, 1/8 Sc, 2/8 Ac $K = (0{\cdot}75+0{\cdot}92+0{\cdot}87)-2 = 0{\cdot}54$
(2) 3/8 Cu, 2/8 Sc, 1/8 Ac $K = (0{\cdot}75+0{\cdot}83+0{\cdot}94)-2 = 0{\cdot}52$
(3) 3/8 Cu, 3/8 Sc $K = (0{\cdot}75+0{\cdot}75)-1 = 0{\cdot}5$

These values are a little high as no account of obscured cloud is taken. The value obtained by adding up all the layers is too low, as the obscured cloud does not have as great an effect as visible cloud.

(4) 3/8 Cu, 4/8 Sc, 3/8 Ac $K = (0{\cdot}75+0{\cdot}66+0{\cdot}81)-2 = 0{\cdot}22$

A guide is to look at the value for the thickest type of cloud, i.e. Ns and Cb for 6/8 = 0·4.

(e) *The estimation of KE.* The part of Figure 5 above the thick diagonal is a nomogram for reducing the quantity *E* by the factor *K* to give *KE.*

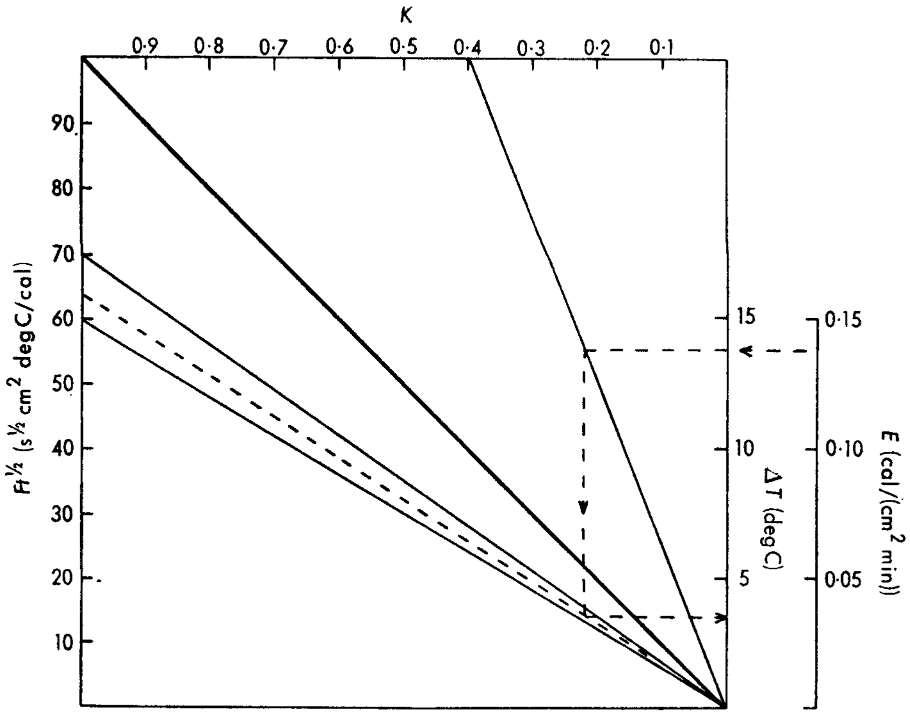

FIGURE 5—ESTIMATION OF *KE* AND $Ft^{\frac{1}{2}} \times KE$

(f) *The estimation of* $Ft^{\frac{1}{2}} \times KE$. The part of Figure 5 below the thick diagonal is a nomogram for obtaining $Ft^{\frac{1}{2}} \times KE$. The scale of *KE* when multiplied by $Ft^{\frac{1}{2}}$ gives the scale for ΔT in degrees Celsius.

Comparison of estimations of ΔT and measurements of ΔT. The diagrams (Figures 2–5) were used to estimate ΔT from estimates of wind speed, cloud amount and type, and dew-point, along with known sunset temperature and length of night. Nights were not included if snow lay on the ground, if a front passed over the sites, or if marked wind changes occurred suggesting large-scale advection. In Figure 6 the estimated ΔT has been plotted against actual measurement of ΔT and the full line is the line giving estimations equal to actual measurements. For nights with frost at the concrete surface it was found that the forecast temperature drop was nearly always too great and a correction was applied, based on the small-pecked line in Figure 6 indicating the best estimate of the actual for various forecasts below zero.

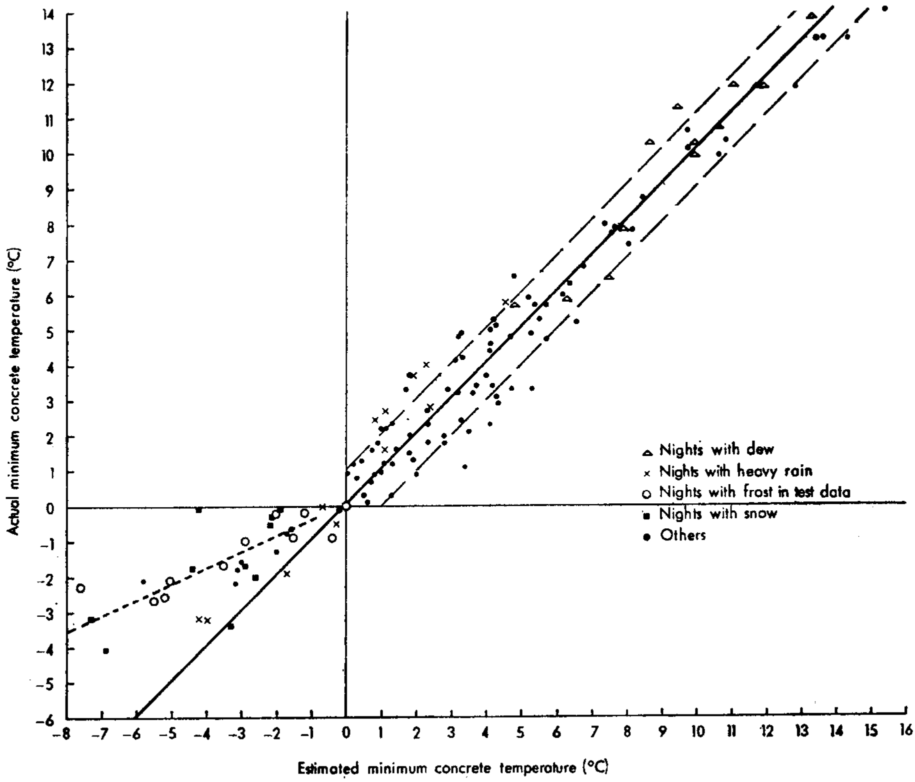

FIGURE 6—ESTIMATED MINIMUM CONCRETE TEMPERATURE AGAINST ACTUAL MINIMUM CONCRETE TEMPERATURE

———— Estimation equals actual
—— —— Lines enclose estimates differing from actual by up to 1 degC
– – – – – Line of best estimate of actual when estimates fall below zero

The difference is due to latent heat release when water in and on the concrete freezes (see Appendix). The accuracy of the estimations of frost or no frost occasions is almost 100 per cent (see also Appendix). Table I summarizes the results for the development data, the test data and the combined data and gives the number of estimates of ΔT which were within various ranges of error.

Corrected results for nights when the actual minimum fell below 0°C, for the development months gave root-mean-square error = 0·38 degC, and for the test data r.m.s. error = 0·66 degC. The accuracy for the test data is notable because frost only occurred on the days considered in February when Tuxford South data were used. Thus the amount of traffic and the presence of salt and grit, etc. (not taken into account) would appear to have little effect.

TABLE I—FREQUENCY OF ESTIMATES OF ΔT WITHIN DEFINED RANGES

Period	No. of estimates	Range of ΔT (degC) ±0·5	±1·0	±1·5	±2·0	±2·5	Root-mean-square error
				frequency			
(a) Development data							
October 1968	19	10	14	17	18	19	0·83
November 1968	25(2)	7(2)	16(2)	19(2)	25(2)	25(2)	1·14
December 1968	20(8)	16(7)	19(8)	20(8)	20(8)	20(8)	0·24
January 1969	17(2)	8(1)	10(1)	15(2)	16(2)	17(2)	1·03
March 1969	22(7)	13(4)	18(6)	21(6)	22(7)	22(7)	0·52
Total	103(19)	54(14)	77(17)	92(18)	101(19)	103(19)	0·75 0·38*
(b) Test data							
February 1969	12(10)	5(5)	9(8)	11(9)	12(10)	12(10)	0·73
April 1969	15	7	13	13	15	15	0·55
July 1969	22	10	14	20	22	22	0·87
Total	49(10)	22(5)	36(8)	44(9)	49(10)	49(10)	0·76 0·66*
(c) Combined data							
Total	152(29)	76(19)	113(24)	136(27)	150(29)	152(29)	0·75 0·51*
				percentages			
		50·0	74·25	89·5	98·7	100·0	

Figures in brackets show number of nights with frost, i.e. minimum of 0·0°C or below.

* Root-mean-square errors for the nights with frost.

The r.m.s. error for all the data is 0·75 degC. There is a forecast accuracy (Table I) of 50 per cent within 0·5 degC, 74·25 per cent within 1 degC, and 100 per cent within 2·5 degC.

For the development data a r.m.s. error of 0·75 degC was obtained with a standard error of 0·05. The test data gave 0·76 degC (S.E. 0·07), a remarkable but fortuitous agreement. Note that the estimations of ΔT were done on the basis of actual observations after the event and were not done under operational conditions. Thus the results should not be compared directly with the results discussed elsewhere.[6]

Application to forecasting. The method described for estimating ΔT should give the forecaster an accurate guide to the fall of temperature to be expected overnight. Even if the surface temperature at sunset has to be forecast in order to issue a frost warning early in the day the value of ΔT can be accurately obtained and with experience this should be a sufficient guide to forecast frost on the concrete surface.

For convenience Figures 2–5 can be placed together as sections of a forecasting diagram Figure 7, which, along with Table II, shows how the entries in the various sections lead to the final answer of −0·7°C for a particular night in December 1968 (the actual minimum was −0·9°C).

An estimate can be made of the time of frost formation if the formula is considered in the form $\Delta T_t = Ft^{\frac{1}{2}}KE$ where ΔT_t is the fall in temperature after time *t*, where *t* varies from 0 to the length of night. If ΔT_t equals the surface temperature at sunset then *t* can be obtained from Figure 7 by the method given in Table II(b).

Discussion. From the results it appears that all the suggested factors that effect nocturnal cooling (T_d, T_c, *t*, wind speed, *K*) play important roles, and should be taken into account. Mizon[4] in an investigation into soil

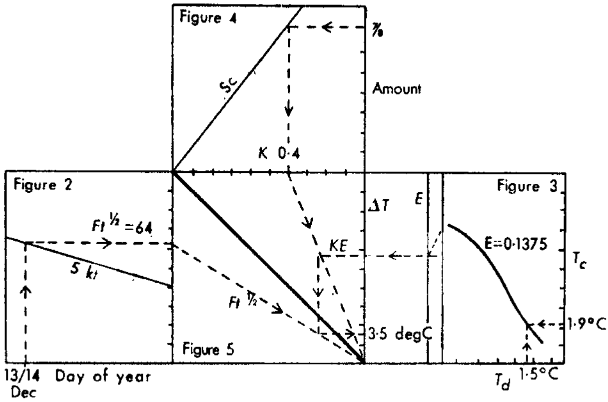

FIGURE 7—ESTIMATION OF ΔT

The arrowed pecked lines show points of entry to the diagrams.

TABLE II—APPLICATION OF METHOD ON 13/14 DECEMBER 1968

(a) To forecast minimum surface temperature

	Method	Result
From Figure 2 :	obtain value of $Ft^{1/2}$ according to day of year and forecast overnight wind speed	Wind 5 knots gives $Ft^{1/2}=64$ $s^{1/2}cm^2$degC/cal
From Figure 4 :	obtain value of K according to forecast cloud cover and type overnight	8/8 Sc all night clearing by morning Take 7/8 Sc as average 7/8 Sc gives $K=0{\cdot}4$
From Figure 3 :	obtain value of E according to forecast average dew-point and surface temperature at sunset	Dew-point overnight 1·5°C Surface temperature 1·9°C at sunset Hence $E=0{\cdot}1375$ cal/(cm^2min)
From Figure 5 above diagonal :	obtain KE	Intersection of $K=0{\cdot}4$ and $E=0{\cdot}1375$
From Figure below diagonal:	obtain $KE \times Ft^{1/2}$ and read off value of ΔT	Intersection of KE with $Ft^{1/2}=64$ gives $\Delta T=$ 3·5 degC This gives a temperature below zero (−1·6°C)
From Figure 6 :	obtain correction on basis of small-pecked line	Corrected minimum temperature= −0·7°C.

(b) To forecast time of onset of frost

From Figure 4 : 8/8 Sc probably persisted until frost
For 8/8 Sc, $K = 0{\cdot}32$

From Figure 3 : Dew-point overnight = 1·5°C
Sunset surface temperature = 1·9°C
Hence $E = 0{\cdot}1375$

From Figure 5 above diagonal : Intersection of $K = 0{\cdot}32$ and $E = 0{\cdot}1375$ gives KE

From Figure 5 below diagonal : Intersection of KE and $\Delta T = 1{\cdot}9$ degC gives $Ft^{1/2} = 46{\cdot}5$

From Figure 2 : Intersection of $Ft^{1/2} = 46{\cdot}5$ and wind 5 knots gives $t^{1/2} \approx 2{\cdot}95$ and $t = 8{\cdot}7$ hours (With sunset at 1550 GMT frost can be expected soon after midnight) minimum temperatures in Australia found no significant relationship between *F* and wind speed; he used a constant value of $Ft^{\frac{1}{2}}$. Reuter[1] working in Austria and Canada did little work into the effect of cloud. However, in the British Isles, which are blessed with ever-changing weather, one can afford to make no such approximations.

It is significant and useful that no monthly trends appeared in Figure 1; however, wind direction plays a role in forming the distribution. Northerly winds gave bigger falls of temperature (i.e. larger value of *F* for a given wind speed). This problem has not been examined in any detail however.

The effect of dew formation was considered as was the effect of heavy overnight rain. No detailed examination was made, but data are shown in Figure 6.

The accuracy of the results indicates the validity of the formula used. However, only actual recorded data have been used, and because of a lack of readily available data no forecasting has been attempted. In order to facilitate further research the following recommendations are made :

(a) This investigation has shown that the sunset surface temperature is a vital parameter in determining whether or not frost will occur. Concrete temperatures should be taken at hourly intervals as well as at sunset. The minimum on its own is of little use as it gives no indication of the fall in temperature from sunset. Of course a continuous recording thermometer would be best, and for experimental purposes one ought to be installed at some meteorological stations.

(b) Research should be undertaken to derive values of *F* for tarmac, and other surfaces. This could easily be done.

(c) For use as a forecasting tool the method must be extended to include a forecast of the sunset temperature so that a forecast of the minimum temperature can be issued by 15 GMT at the latest. It seems that in winter the surface sunset temperature bears a strong correlation to the afternoon maximum surface temperature. This has yet to be verified however.

REFERENCES

1. REUTER, H.; Forecasting minimum temperatures. *Tellus, Stockholm*, **3**, 1951, pp. 141–147.
2. BRUNT, D.; Physical and dynamical meteorology. Cambridge, Cambridge University Press, 1939.
3. HASCHE, E.; Zur Messung der langwelligen Himmels und Erdstrahlung. *Gerlands Beitr Geophys, Leipzig*, **42**, 1934, pp. 228–231.
4. MIZON, E. A.; An objective aid for minimum temperature forecasts — Alice Springs, N. Territory. *Aust Met Mag, Melbourne*, **38**, 1962, pp. 20–31.
5. SWINBANK, W. C.; Long wave radiation from clear skies. *Q J R Met Soc, London*, **89**, 1963, pp. 339–348.
6. PARREY, G. E., RITCHIE, W. G. and VIRGO, S. E.; Minimum temperatures at the surfaces of concrete roads and concrete slabs. *Met Mag, London*, **100**, 1971, pp. 27–31.

APPENDIX

Correction to estimated minimum concrete temperature for values below 0·0°C

One of the unexpected results of estimating the minimum concrete temperature by this method, is shown clearly in Figure 6. The accuracy for the estimation frost/no frost is almost 100 per cent. Also as noted in the text, there is a mechanism acting which makes estimates too low when the estimated minimum temperature is below 0·0°C. Estimates are low because there is release of latent heat when frost occurs. The correction line in Figure 6 is the line of best fit for the data used, but more research will be required before an accurate fix is possible. The correction line takes into account this release of latent heat.

The correction line cannot however be extended back to the origin 0; a discontinuity occurs when the actual minimum is just below 0·0°C, i.e. marked over-forecasting occurs. The explanation of this discontinuity is not fully understood, but it explains why the frost/no frost estimate is so accurate in this sample. In the table of results it was shown that the method of estimation has a root-mean-square error of less than 0·8 degC. Just above 0·0°C in Figure 6 it can be seen that on the whole the formula estimates too high a minimum; however, insufficient data around this region preclude any definite conclusions. When the surface temperature falls to 0·0°C, the moisture both in and on the concrete begins to change state to ice; this takes place with the water at constant temperature around 0·0°C (depending on impurities, etc.) and any further fall of the surface temperature is delayed because of the release of latent heat as the water freezes. The actual minimum is higher than the formula predicts, as energy has been gained from a source not included in the analysis. No attempt was made to include it. This energy is presumably of a greater dimension than that required to change the surface temperature by 0·8 degC (the r.m.s. error), and therefore the discontinuity is marked, and the correction line is offset as shown in Figure 6.

The results support the validity of the present definition of frost, i.e. when the temperature falls below 0·0°C.

Freezing must occur for this process to take place, e.g. if comparatively warm rain falls, less ice will form, and, as can be seen in Figure 6 the results in rain are nearer the line indicating estimate equal to actual minima.

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SOME METEOROLOGICAL AND OTHER ASPECTS OF HOT-AIR BALLOONING

By G. A. SAMUEL

The sport of hot-air ballooning is rapidly gaining popularity in this country and on the continent and becoming decidedly international in character. Organizers of fêtes and festivals are quick to add colour and interest to their social functions by suggesting hot-air balloon races and other displays. This is not surprising since the running cost is fractional compared with the more conventional balloon where one fill of helium, delivered to site, in sufficient quantities to give two or three persons enough lift to perform a successful flight can be as much as £1000 and if hydrogen is used, although the cost is less, the attendant risk is very much greater.

The hot-air balloon is a much cheaper method of becoming airborne. One hour of flight needs about £5 to £7 worth of propane fuel gas. The initial cost of the balloon, trailer and other equipment can be about £2000 but since most balloons are owned by a syndicate of five or more people the cost to the individual is reduced to a more reasonable figure. Indeed, such a syndicate is required since preparing a balloon for a flight is certainly not a single-handed operation. In fact the difficulties seem to mount as a power function of the surface wind speed. However, there are many adventurous souls who spend this sort of sum on their hobby, for example boat owners. The tranquillity of a balloon flight after the hurly-burly of modern life has a great appeal but the intermittent roar of the burner of a hot-air balloon does detract somewhat from the peacefulness of balloon flight.

The hot-air balloon can be obtained in a variety of sizes, some of the most popular being around 56 000 to 64 000 cubic feet ($\approx$ 1700 m^3) which will carry from two to four persons. The surface area of these balloons is around 900 to 1200 square yards ($\approx$ 800 m^2).

The balloon as a carrying vehicle is reputed to have quite a high safety factor but although the safety factor appears to be diminished somewhat by the antics of some of the daring people who fly them, the reverse is true because not only are they daring but they are also very safety-conscious and responsible people. The Pilots Examiner of the Department of Trade and Industry sees to this.

The fabric of which the balloon is made is high-tensile nylon of a special rip-stop weave, proofed with polyurethane containing, according to the manufacturers, 'maximum ultra-violet retardant'. The balloons, which in most cases are multicoloured, look very gay when fully inflated. The main loads on the envelope are carried on nylon tapes whilst the fabric of the envelope itself carries a very low stress as a result of its high curvature. The balloon is constructed in such a way that the segments have a bulbous gore, giving it a melon shape (see Plate I). This shape has the advantage of being safest for dynamic loads due to high rates of ascent or descent since it can 'give' in a way in which a flat-gored balloon cannot. Most balloons are also fitted with a lace-up or 'velcro' rip panel and a discharge valve — both of which are operated by a lanyard from the basket. The base of the envelope is open to enable the air trapped within it to be heated and there is usually a distant-reading thermometer giving internal temperatures in the crown of the balloon. The open end is connected to the burner frame by stainless steel wires and the envelope itself is protected by a flame-resistant, replaceable section of material. The flame is contained within the confines of this ring-like tube of material to reduce the likelihood of flame damage. However, surface winds in excess of 10 kt ($\approx$ 5 m/s) during filling cause deformation of a partially filled balloon such that the balloon fabric melts in places if the flame is not doused quickly enough.

The burner which hangs between the balloon and the basket with its nozzle directed into the open end of the balloon runs on liquid propane which is vaporized by pre-heating in a helical tube suspended in the flame. The flame itself is about 4 to 12 feet long and the burner output is around 4 000 000 Btu/h ($\approx$ 1200 kW) but this can vary considerably with ambient temperature. Control of the heating flame is effected by an on/off valve and the rate of burning can be adjusted by a needle valve. Maximum heating at the full available rate would supply enough energy to waft the balloon upwards at 1000 feet/min ($\approx$ 5 m/s) or more. The excess temperature of the air within the envelope is raised to over 90 degC, thus when the ambient temperature is high, as on a warm summer's day, an internal temperature of 110°C may be required to attain lift-off and a suitable rate of ascent. Most balloons are limited by the tolerance of the fabric to heat, and in fact a maximum ambient temperature of 25°C may make things difficult. A clear winter's day with light surface winds would give better conditions except that the saturation vapour pressure of propane limits the minimum temperature for safe flight (Figure 1). The cylinders of propane which weigh 35 lb ($\approx$ 16 kg) empty and 70 lb full are carried in the passenger basket and connected to the burner by high-pressure, quick-release hose couplings.

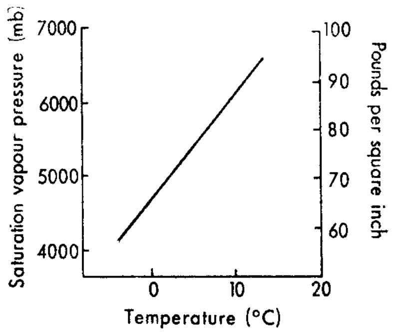

FIGURE 1—VARIATION OF SATURATION VAPOUR PRESSURE OF PROPANE WITH TEMPERATURE

By courtesy of Shell, U.K.

The basket is of traditional design being made of willow and cane with buffalo-hide protection at the edges. No doubt these conventional materials will be replaced by light-weight plastics in the not-too-distant future, but balloonists are loath to make this change since the manufacture of baskets is performed for the most part by blind workers. In any case they claim that there is a goodly amount of 'give' in a basket which cushions the landing. Support is by stainless steel wires which pass in a continuous loop under the basket, embodied in the weave. Carrying loops facilitate handling and launching especially in strong surface winds when helpers must walk with the inflated balloon during the launching process.

An interesting innovation by a Swiss group gives support to the burner by means of a rigid frame and on landing the balloon is immediately released from the basket. A restraining cord is attached to the outside of the crown of the balloon, this causes the balloon to invert with its open end upwards. Another static line rips a large panel from the balloon and thus hot air and consequent ability to lift is lost very rapidly — the envelope emptying and fluttering neatly downwind. The total weight of the rig is about 350 lb to which must be added the weight of the crew and the fuel.

The meteorologist, whether professional or amateur is most useful to the would-be balloonist and much can be learnt by close liaison and exhaustive pre-flight discussions and briefings. The meteorological problem of forecasting conditions suitable for flight of these balloons concerns both surface and upper air winds and temperatures; for example an ambient temperature in excess of 25°C — in some cases — reduces the safety factor below acceptable limits. The excess temperature needed to give adequate lift may be more than the fabric is able to tolerate.

It is thought that should the burner become accidentally extinguished, escaping propane, especially under conditions of low temperatures and high humidity, could cause the formation of ice on the nozzle and so alter its profile as to inhibit relighting, but no reports of this are known to the author. However, there would be downward heat radiation from within the envelope which would be effective even under descent conditions for some considerable time. The author has noticed frost forming on feed pipes and is of the opinion that junctions and unions with varying bore may well be the cause of some otherwise inexplicable loss of power on occasions.

Heat is lost quite quickly from the envelope and unless this heat is maintained the balloon sinks — often accelerating on its downward path. Tables are available where the ambient temperature read against altitude will give a maximum safe load but this is not the only weight-limiting consideration for at low temperatures in winter and at altitude the vapour pressure of propane falls markedly, reducing the output for a given jet size. For example a fall of temperature from 10°C to 0°C causes a loss of 22 pounds per square inch (about 1500 mb) in the saturation vapour pressure. This makes the balloon less responsive to attempts to arrest a descent.

When one considers that the all-up weight of a balloon, including the air it contains, is over two tons ($\approx$ 2032 kg) its momentum is considerably more than its lighter-than-air aspect would suggest.

Static electricity must be produced by the friction of the swirling hot gases inside the balloon and appears as an electrostatic charge outside the envelope; but it appears to be either a small effect or quickly lost through discharge — perhaps by trailing ropes, etc. Lightning risk is not so much of a hazard as with inflammable gases but even so the hot-air balloonist does not want his envelope punctured by whatever means.

Cumulonimbus is definitely unpopular as a near neighbour in the sky and all flights must be under visual meteorological conditions, so flight in any cloud is prohibited. 'Thermals', whilst being welcomed joyfully by glider pilots, are feared and certainly not appreciated by the balloon pilot. In the first place thermals lead to erratic movement and rates of ascent and secondly there is a tendency to cut-off the burner because it is judged, incorrectly, that the rate of ascent is due to the hotness of the air within the envelope. Consequently some of the less-experienced balloonists may find themselves descending rapidly away from the thermal with a cooling balloon and insufficient time to reheat. This, occurring after what has appeared to be a satisfactory rate of ascent illustrates the potential danger. Further, thermals near the ground can start a balloon on an upward rush at the very moment the ripcord has been pulled for a landing. Indeed this happened last year at Nottingham, resulting in an unexpected heavy landing, though happily only bruising was sustained by pilot and crew.

Winds of course play a very, very big part and on-the-spot measurement by hand anemometer and by pilot balloon by the meteorologist is greatly appreciated by the balloonist. Inflation becomes difficult in winds over 6 knots ($\approx$ 3 m/s) and since the envelope is very much larger than a normal sized house a partially filled balloon can quite easily and quite literally get out of hand. By using a pilot balloon and the well-tried tail method to obtain upper winds over the layer to maximum planned-altitude and knowing the estimated duration of flight one is able to dispatch the recovery vehicles to the approximate point of touch-down, thus saving considerable time, especially under conditions of only moderate visibility.

Incidentally there is a tradition amongst balloonists that a bottle of champagne is supplied by the passenger on his or her first flight for consumption either during or certainly immediately after the flight, which in itself is a heady experience. The youngest qualified balloon pilot in Britain and authoress on the subject is Miss Christine Turnbull (now Mrs Charles Bulmer) and her remark that 'One must be a little mad to take-off under a bubble of hot air sitting in a laundry basket, but the sense of freedom and feeling of exhilaration almost defy description', whilst not describing the people who fly thus, does give an insight into the 'balloonatic fraternity'.

NOTES AND NEWS

Meteorological Office awards to captains and navigators of civil airlines

A system of awards was introduced in 1954 to encourage the making of air reports by civil airline captains and navigators. The awards are in two categories. Books, suitably inscribed, are awarded to the captains and navigators who have provided the best series of reports during the year under review, while captains who have given long and meritorious service in the provision of air reports receive brief cases.

This year brief cases were awarded to Captain J. B. Linton of BOAC and Captain W. C. Parke of BEA by the Director-General at a ceremony held in the Headquarters of the Meteorological Office on Thursday, 23 September 1971 (see Plate III).

REVIEWS

Meteorology (second edition), by A. Miller. 226 mm × 150 mm, pp. iv + 154, *illus.*, Charles E. Merrill Publishing Co., Columbus, Ohio, 1971. Price: £1.

The first edition of this book was published in 1966 and was reviewed in the January 1967 issue of the *Meteorological Magazine*. The book is one of a series, the Merrill Physical Science Series, devised to provide integrated inter-disciplinary courses for the scientific education of non-science students in the U.S.A., and admirably achieves its purpose.

There is evidence throughout of minor amendments, additions and rearrangement to good advantage. One particular improvement worth mentioning is the treatment of 'Circulation patterns' as a separate chapter, thus emphasizing still further the author's concern with 'scales of motion' as a basic concept.

The satellite photograph shown in Figure 4.13, on page 108, illustrating a hurricane, is not particularly informative. It would have been very easy to choose a better one for the purpose. Additional satellite photographs could have been included with advantage, one showing the extratropical cloud systems associated with a series of depressions over an extensive area and one of the many excellent ATS photographs over a tropical area.

Undoubtedly, this edition of the book will be more attractive to the reader. The new cover design is colourful, in the modern style and, more important, illustrative of the subject. The quality of the paper is much improved and the adoption of larger print makes the reading easier. Other improvements are the use of the decimal system for numbering the contents of the chapters and the limited use of colour (one only, however) in both text and diagrams.

The book is recommended for use in schools and colleges as an elementary yet authoritative introduction to the subject.

T. H. KIRK

Radar measurement of precipitation rate, by A. M. Borovikov, V. V. Kostarev, I. P. Mazin, V. I. Smirnov and A. A. Chernikov. 245 mm × 173 mm, pp. iv + 112, *illus.*, (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), Keter Press Ltd, 15 Provost Road, London NW3 4ST, 1970. Price: £3·40.

In this book the authors first discuss the theoretical possibilities of measuring precipitation using radar, and include a summary of some of the experimental investigations made in other parts of the world. They then describe in detail the observations made by the Central Aerological Observatory of the U.S.S.R. in the Valdai region during 1964–65. In the first chapter several possible methods of using radar techniques to measure precipitation are reviewed and it is concluded, as in the western world, that the most promising practical means is to relate the echo intensity measured over an area to the rate of rainfall. The remainder of this book is concerned with this technique. A reader new to the subject may find this first chapter difficult to follow and it might be more profitable for him to commence with the second chapter, which consists of a clear, but perhaps rather laborious, account of the physical principles of the relationship between echo intensity and precipitation rate. The chapter includes an original derivation of a radar equation which turns out to be practically identical to that derived by Probert-Jones and now used by most other investigators. The remaining three chapters of the book describe the experimental investigation. This account, extending over 73 pages, will be of interest rather to the specialist in the field than to the general reader. The measurements were made using an ARS–3 radar. This radar had a wavelength of 3·2 cm so that some attenuation of the signal must have occurred in heavy rain. This does not appear to have been corrected for and so must have reduced the accuracy of the rainfall estimates at times. The radar was calibrated in terms of rainfall by matching the radar-derived total for the entire season to that recorded by gauges and by assuming that this calibration held for every rain. Echo intensities were measured from photographs of a PPI display using the stepped-gain technique. The rainfall estimates were compared with 12-hour or 24-hour totals recorded by gauge networks over areas of 100 km², 400 km² and 10 000 km². The gauge density for the smaller areas was an impressive 1 gauge per km², supplemented by 1 autographic gauge per 4 km², and for the larger area one gauge per 100 km². In all about 400 comparisons between radar-derived and gauge-derived rainfall totals were made. These are all listed in an appendix. The authors conclude from their results that they can foresee the incorporation of radar techniques in the routine observation of precipitation. It would be difficult to conclude similarly for this country from their data since the accuracy of the existing gauge network here is superior to the radar accuracy of 30–40 per cent over areas > 100 km². However, the experiment, conducted in 1964–65, does not show the present state of knowledge. During the six years since these measurements further experiments in various countries indicate that with additional precautions, recognized in this book, the accuracy can be improved significantly.

T. W. HARROLD

LETTERS TO THE EDITOR

551.509.323

A comparison of methods of forecasting night cooling at screen level

As one of the joint authors of two of the tests[1,2] referred to in the above article published in the *Meteorological Magazine* of September 1971,[3] I should like to make the following comments :

(a) McKenzie's method also had a low accuracy at Mildenhall presumably for the same reasons which lowered the accuracy of the Saunders method. In the Mildenhall test[1] it was stated that 'as far as accuracy is concerned, there is very little to choose between the methods when applied to Mildenhall. McKenzie's method is quick to handle and is recommended on that account . . .' The choice of a speedy method was the primary object of the comparison because in a busy office (as Mildenhall was at that time) the winter afternoon workload necessitated quick methods for all purposes. The graphical operations of the Saunders method as carried out at Mildenhall occupied more time and much more bench space than McKenzie's method which only required a small piece of cardboard carrying the table of constants.

(b) The conclusion that the Saunders method appears to be least accurate at stations bordering the Fens is supported by some earlier work. Mr Saunders may recall a test of his method carried out at Weston Zoyland in the early 1950s when the results were not encouraging. As the location of Weston Zoyland is in the middle of a former tidal estuary of the River Parrett, the site is akin to those adjoining the Fen country. A similar effect may therefore render the starting data for Weston Zoyland non-representative for the station.

Meteorological Office, Gibraltar J. GORDON

REFERENCES

1. GORDON, J. and VIRGO, S. E.; Comparison of methods of forecasting night-minimum temperatures. *Met Mag, London*, **97**, 1968, pp. 161–164.
2. GORDON, J., PERRY, J. D. and VIRGO, S. E.; Forecasting night minimum air temperature by a regression equation. *Met Mag, London*, **98**, 1969, pp. 290–292.
3. SAUNDERS, W. E.; A comparison of methods of forecasting night cooling at screen level. *Met Mag, London*, **100**, 1971, pp. 280–283.

551.554:551.556:551.453

Sand streets

In his interesting note on 'Sand streets',[1] Mr J. D. Hastings concludes that the absence of longitudinal dune forms over northern Cyrenaica may be attributed to an insufficiency of sand. Observations in the field confirm that this is so. The massive sand accumulations of the Libyan Desert are confined to the region south of the so-called '29th parallel oases', some 300 km away to the south. The terrain between this sand sea and the Jebel Akhdar is primarily *serir:* a uniform pebble-strewn plain devoid of any material which could easily be moved by the wind. In the north however, a series of low escarpments border upon shallow depressions in which fluviatile deposits have accumulated to produce a poor but vitally important soil. This soil is very resistant to wind action as long as it remains undisturbed, but once the surface has been broken by the impress of the feet of sheep and camels during the winter grazing season, vast quantities of dust are exposed to become ready prey to the next strong wind. It was most likely dust produced in this fashion that contributed to the streeting observed by Hastings.

It is important to make this distinction between sand and dust since they give rise to very different phenomena once lifted into the atmosphere. Because of their small terminal velocities, dust particles may be carried in suspension to great heights, producing the duststorms so familiar to meteorologists at the desert-edge airfields. Sand is too heavy to be held in suspension in this way; instead it drives over the ground in a bounding motion (saltation), rarely rising more than a metre above the surface. It seems unlikely, therefore, that secondary transverse circulations above an established dune field would be visibly revealed by streeting since the constituent sand grains are found to be comparatively large, with a minimum grain diameter of about 0·15 mm in the finest material at the dune crests. Mobile sand grains would remain close to a sand dune surface, whereas a dust surface could give rise to dust in suspension with visible streeting.

Our understanding of the complex interrelationship between wind and sand movement depends very heavily upon theory, and particularly upon R. A. Bagnold's laboratory studies and limited field observations of more than 30 years ago.[2] Bagnold has stressed the need for more meteorological observations from the desert interiors. A full knowledge of the airflow above longitudinal dune systems must await the availability of such regular observations.

Meteorological Office,
London/Heathrow Airport

W. J. T. NORRIS

REFERENCES

1. HASTINGS, J. D.; Sand streets. *Met Mag, London,* **100,** 1971, pp. 155–159.
2. BAGNOLD, R. A.; The physics of blown sand and desert dunes. London, Methuen and Co., 1941.

Meteorological Magazine: price increase

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THE METEOROLOGICAL MAGAZINE

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PROBABILITY OF AIRCRAFT ENCOUNTERS WITH HAIL

By J. BRIGGS

Summary. Estimates of the probability of aircraft encounters with hail are presented; they depend on several assumptions and cannot do more than indicate probabilities of hail within about a factor of 10. Nevertheless, comparisons made with actual aircraft experience are encouraging. The comparisons are least satisfactory for aircraft flying at the highest levels considered and so the extrapolation to the levels of most concern to supersonic transport may be less realistic, though at these levels the estimates seem more likely to be pessimistic than optimistic as regards the probabilities of large hail being met.

Introduction. Assessments of the chances that aircraft will meet hail are necessary for design purposes. It seems reasonable to base such assessments on meteorological variables for which long-term records are available and which can take account of the regional differences which undoubtedly exist. This note presents estimates of hail probabilities which are based on the incidence of thunderstorms at points on the ground, though it is necessary in obtaining these estimates to make several assumptions, notably concerning the typical hail-cell dimensions as well as variations in the probability of hail occurrence which are due to differences in height. Some comparisons with actual aircraft experience suggest that the estimates are reasonably realistic and can give a fair indication of likely experience of hail encounters supposing that avoiding action, based (say) on airborne or surface radar, is not taken.

Method. If the probability of hail at a point on the ground, or on a particular height level, is P_p and the corresponding probability of hail at any point inside an area of unit radius is P_a then, taking the average hail-cell radius as R $(R \ll 1)$,

$$P_a \approx P_p/R^2.$$

If now no avoiding action is taken, the chance of an aircraft encounter with a hail cell of radius R somewhere during the crossing of an area of unit radius is given by

$$\frac{4P_a R}{\pi} = \frac{4P_p}{\pi R}.$$

But if the aircraft speed is V then the time taken to cross the area is $2/V$ and so the chance of a hail encounter in unit time is

$$\frac{2VP_p}{\pi R}\,. \qquad \ldots (1)$$

Now, suppose the number of thunderstorms per year at a point on the ground is N and that the average duration of hail at the point is t whilst the probability of occurrence of hail of diameter x inches or more during the storm is P_x, then for stones of diameter x or more

$$P_p = \frac{NP_x t}{8760} \qquad \ldots (2)$$

(t in hours). Crossley[1] suggests t as about 1/10 hour.

So, taking V as 500 knots,* equations (1) and (2) indicate that the number of encounters with hail of diameter x or more per flight hour, assuming no avoiding action, is given by

$$3{\cdot}6\times 10^{-3}\,\frac{NP_x}{R}\,. \qquad \ldots (3)$$

In equation (3) N will vary with the locality whilst P_x will vary with the locality and height.

Variations with locality. Long-period records provide incidence of thunderstorm-days on a world-wide basis, so relative values of N are given almost directly by the number of thunderstorm-days. On the other hand there are few data on which estimates of P_x can be based.

Topographical and other factors play important parts in the production of hail and there are some regions where hail occurs fairly frequently whereas others in the same general climatic régime only rarely have hail. Reports of hail are much less reliable than those of thunder, though isopleths of hail incidence can be produced for most areas. Relative values of P_x for different places can be obtained by consideration of the relative values of the hail-day/thunderstorm-day ratio though this approach has to be used with care for there is no unique hail/thunder relation even for a given place (e.g. at London/Heathrow Airport the peak incidence of hail is in April whereas that for thunder is in June). However, if any small hail is excluded and if comparisons are restricted to places with similar temperature régimes then the hail/thunder ratio can give a good estimate of the P_x variation.

Beckwith[2] used a network of 79 stations in the vicinity of Denver, Colorado, over a period of 10 years. He had 829 reports of hail of which about 80 referred to hail of diameters one inch or larger. These figures suggest that $NP_1 = 0{\cdot}1$. Another estimate applicable to central areas of the United States is due to Souter and Emerson.[3] During flights through thunderstorms they found that 800 traverses were required for each occurrence of one-inch diameter hail or larger. So at the flight levels around 12 000 ft (1000 ft = 305 m) $P_1 = 0{\cdot}00125$. These two estimates agree if $N = 80$ and since

* 1 kt≈ 0·5 m/s

this is in close accord with the reported storm incidence for the Denver area it may be assumed that in this area $N = 80$ and $P_1 = 0{\cdot}00125$ for levels from the ground to about the middle troposphere.

In the tropics, values of N are often large but hail incidence at the ground is usually low. Frisby and Sansom[4] indicate for central Africa and Malaysia values of the hail/thunder ratio which are usually less than 1/5 of the Denver values. This suggests that even for the worst places in these areas P_1 is about 0·00025 in the lower troposphere.

For north-east India, values of thunderstorm and hail incidence are both near the values for the central plains of the U.S. Indeed, these two areas appear to have about the highest incidence of hail in the world. The Denver value of P_1, 0·00125, can be taken as typical of these two areas.

In the United Kingdom hail/thunder ratios are higher than for Denver but, as indicated above, small hail is a complicating factor. It seems unlikely that P_1 values for the United Kingdom will be higher than those for Denver, at least at usual flight levels and indeed it is considered that the Denver value of P_1 can be used for all temperate inland areas, though the values of N will generally be considerably reduced.

For high latitudes and for temperate latitudes over the sea all the evidence indicates that though small hail is relatively frequent large hail is almost unknown. No reliable values for P_1 are available but it is suggested that United Kingdom values will be reduced by a factor of 10 or more.

Variations of P_x with hailstone size. There is little reliable information on the variation of P_x with x. Estimates have been made of the probable size distribution of hail using reasonable assumptions as to equivalent rainfall rates, and of the distribution of the ice-mass amongst stones of different sizes. These estimates (R. F. Jones — unpublished) indicate broadly that the chance of a stone of given size decreases by a factor of 10 for each doubling of the stone diameter. Summers and Paul,[5] reporting on Alberta hail studies in the period 1957–66, show that for stones of diameter exceeding about ½ inch (12·7 mm) the doubling of size is equivalent to a frequency decrease of nearly 10 times. A formula which fits these data well is $P_x = P_0 10^{-x}$ (x in inches). This formula will be assumed here for each area considered. Thus in the lower troposphere and for the Denver/north-east India areas it will be assumed that

$$P_1 = 0{\cdot}00125, \qquad P_2 = 0{\cdot}000125, \qquad P_3 = 0{\cdot}0000125.$$

Variations of P_x with height. The process of hail formation is not yet understood fully but it seems certain that large updraughts are needed, and the stronger the updraughts the more probable are large stones. In a storm cloud the strong currents are likely to penetrate the bulk of the cloud, dying away only towards the cloud top. Thus, in a particular cloud which generates large hail, the chance of a stone of given size occurring at a particular level may be expected to remain fairly constant until towards the cloud top and then to diminish rapidly.

Radar studies of the precipitation content of storm clouds give support to this idea of the distribution of hail. For example, Donaldson[6] found that the median profiles of radar reflectivity for hailstorms over New England showed a concentration of precipitation at 20 000/25 000 ft with a rapid fall-off in precipitation above this region. Similarly, Marshall *et alii*,[7] averaging over summer storms around Montreal, found that the hours in excess of a given intensity of precipitation decrease by about a factor of 10 for each rise of 10 000 ft through the upper levels of a storm.

Radar reflectivity is a measure of the numbers and sizes of large raindrops and hailstones so that reflectivity profiles do not readily indicate the way in which hailstone occurrence varies with height. However, as a first estimate it is reasonable to consider that the chance of a stone of given size is closely indicated by the average reflectivity profile.

Another factor which must affect the overall probability of hail at a given height is the chance of the cloud reaching that height. All clouds which generate large hail are likely to reach near to or beyond the tropopause but even so the frequency with which these cloud tops occur is likely to decrease sharply as the height concerned approaches and exceeds the tropopause. For example, studies (Moore — unpublished) of the height of the highest radar echo in the vicinity of Singapore showed the following percentage frequencies :

TABLE I—PERCENTAGE FREQUENCY DISTRIBUTION OF THE HEIGHTS OF THE HIGHEST RADAR ECHOES NEAR SINGAPORE

Height *km*	Frequency *per cent*	Height *km*	Frequency *per cent*
>9	85·1	>16	16·6
>10	83·0	>17	9·7
>11	77·7	>18	4·0
>12	68·2	>19	1·4
>13	53·2	>20	0·5
>14	40·2	>21	0·2
>15	27·6		

These figures for cloud-top echo frequency suggest that the probability of occurrence of a hailstone of given size is likely to decrease even more rapidly with height than is indicated by the radar reflectivity profiles. However, for planning purposes the radar profiles may be taken as safely indicating the variation of the hail probability (P_x) with height. Thus, P_x may be taken as constant up to a height in the region 20 000–30 000 ft but then it decreases by a factor of 10 for each rise of 10 000 ft. The depth of the near-constant layer must be related to the average storm depth and so to the tropopause, the lower value (20 000 ft) corresponding to temperate latitudes and the higher value (30 000 ft) corresponding to tropical latitudes. On this basis the variation of the probability of one-inch hail, P_1, with height for the various areas discussed will be assumed as follows :

Denver		United Kingdom		Singapore/central Africa	
0–25 000 ft	0·00125	0–20 000 ft	0·00125	0–30 000 ft	0·00025
35 000 ft	0·000125	30 000 ft	0·000125	40 000 ft	0·000025
45 000 ft	0·0000125	40 000 ft	0·0000125	50 000 ft	0·0000025

Comparison with aircraft experience. British Aircraft Corporation (BAC) height and speed profiles for several aircraft can be combined with the assumed values for N, P_x and R to determine the probable hail experience of the aircraft and to compare with the actual hail experience. In these comparisons the radius (R) of the typical hail cell will be taken as 1 n. mile ($\approx$ 2 km) since the average hail-cell diameter is 1–3 n. miles (Crossley[1]).

(a) *Britannia aircraft.* BAC height and speed profiles indicate the following breakdown of each 30 000 flight hours :

Flight hours	Height range *feet*	Speed *kt*
2 000	0–10 000	300
14 000	10 000–20 000	300
14 000	20 000–30 000	350

With Denver/north-east India values of N and P_x, equation (3) then gives the following probabilities for one-inch hail encounters in 30 000 hours :

Height range *feet*	Probability
0–10 000	0·4
10 000–20 000	3·0
20 000–30 000	2·9
	Total 6·3

Thus, every 30 000 hours flight over Denver/north-east India areas should give 6 encounters with one-inch hail. Similarly there should be 0·6 encounters with two-inch hail or about 16 encounters with two-inch hail in 800 000 hours.

Similarly, United Kingdom values of N and P indicate 1·9 encounters with two-inch hail in 800 000 hours whilst Singapore/central Africa values indicate about 5 encounters in the same time.

Britannia experience over all routes is 2 encounters with two-inch hail in 800 000 hours.

(b) *Viscount aircraft.* BAC profiles indicate all flights between 0 and 20 000 ft at speeds averaging about 233 kt. Table II gives the number of encounters with three-inch hail in $5{\cdot}5 \times 10^6$ hours for specified areas and as actually experienced by Viscounts.

TABLE II—NUMBER OF ENCOUNTERS WITH THREE-INCH HAIL

Denver/north-east India	9
United Kingdom	1¾
Singapore/central Africa	2
Actual Viscount experience	1

(c) *Caravelle aircraft.* The distribution of each 30 000 flight hours is as follows :

Flight hours	Height range *feet*	Speed *kt*
2 000	0–10 000	about 300
2 000	10 000–20 000	about 350
2 000	20 000–30 000	about 425
24 000	30 000–40 000	about 450

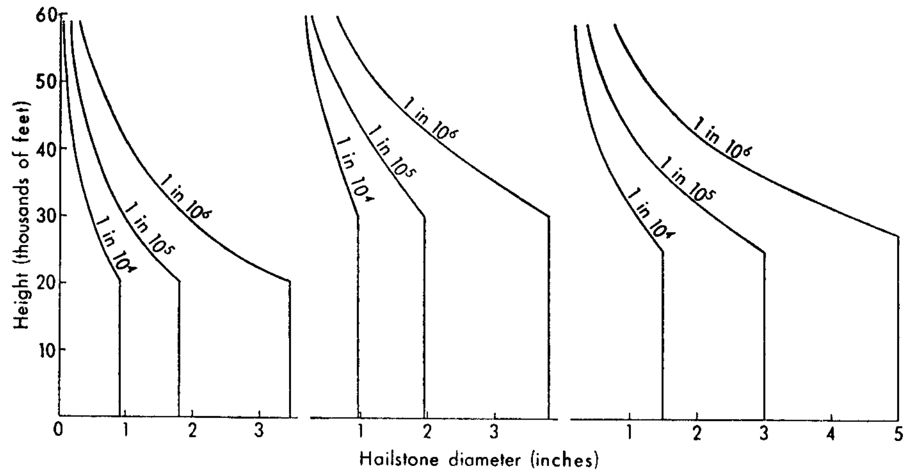
Table III gives the number of encounters with one-inch hail in $0{\cdot}9 \times 10^6$ hours for specified areas and as actually experienced by Caravelles.

TABLE III—NUMBER OF ENCOUNTERS WITH ONE-INCH HAIL

Denver/north-east India	66
United Kingdom	7
Singapore/central Africa	30
Actual Caravelle experience	2

The hail risk is extremely variable from region to region so that the above comparisons are of very limited value without more knowledge of the route histories of the aircraft concerned. For example, the hail risk must be extremely low over most sea areas and over areas such as north Africa and the Middle East. Nevertheless, the comparisons indicate that probabilities based on United Kingdom values are reasonably close to overall experience whilst probabilities for the worst hail areas are likely to be above overall experience by a factor of 10 to 10^2.

Estimates for supersonic transport. Concorde height and speed profiles have been used together with the appropriate values of N and P_x to estimate the hailstone diameter which corresponds to one encounter in 10^4, 10^5 and 10^6 hours of flight at a given level. Figure 1 presents these estimates and shows how the size of stone varies with height for the areas of the United Kingdom, Singapore/central Africa and Denver.



(a) United Kingdom (b) Singapore/central Africa (c) Denver, Colorado

FIGURE 1—ESTIMATED HAILSTONE DIAMETER FOR ONE ENCOUNTER IN 10^4, 10^5 AND 10^6 FLIGHT HOURS (ALL HOURS AT LEVEL OF INTEREST)

REFERENCES

1. CROSSLEY, A. F.; Hail in relation to the risk of encounters in flight. *Met Mag, London*, **90**, 1961, pp. 101–110.
2. BECKWITH, W. B.; Hail observations in the Denver area. Denver, Colorado, United Air Lines, Meteorology Circular No. 40, 1956.
3. SOUTER, R. K. and EMERSON, J. B.; Summary of available hail literature and the effect of hail on aircraft in flight. Washington, National Advisory Committee for Aeronautics, *Tech Note* 2734, 1952.
4. FRISBY, E. M. and SANSOM, H. W.; Hail incidence in the tropics. *J App Met, Lancaster, Pa*, **6**, 1967, pp. 339–354.
5. SUMMERS, P. W. and PAUL, A. H.; Some climatological characteristics of hail fall in central Alberta. Montreal, McGill University, Stormy Weather Group Scientific Report MW-57, 1967, pp. 17–26.
6. DONALDSON, R. J.; Radar reflectivity profiles in thunderstorms. *J Met, Lancaster, Pa*, **18**, 1961, pp. 292–305.
7. MARSHALL, J. S., HOLTZ, C. D. and WEISS, M.; Distribution of rain shower intensity as a function of height. Boston, *Proc Twelfth Conf Radar Met*, 1966, pp. 473–478.

551.501.9:551.582.1(564.3)

10 YEARS OF WEATHER OBSERVATIONS FROM MOUNT OLYMPUS, CYPRUS

By J. B. McGINNIGLE

Summary. The auxiliary meteorological station on the summit of Mount Olympus, Cyprus (1936 metres above MSL), completed 10 years of continuous observation cover in March 1971. The development of the station and its equipment are described. Some statistics are presented to assist in the description of the weather there and these are compared with the lower-level Cyprus statistics.

Introduction. Cyprus is a large island which lies at the eastern end of the Mediterranean Sea, at a latitude of around 35°N. The island and its topography can be seen in Figure 1. Cyprus enjoys a good reputation for fine, warm weather and is a popular tourist area. However, the difference between the lower-level weather of the island and the conditions experienced in the mountains is generally not appreciated, although skiing is an advertised attraction during winter. In fact, the winter conditions on the upper slopes of the Troodos Mountains are frequently severe, with high winds, sub-zero temperatures and several feet of snow and ice, often accompanied by freezing fog as cloud caps the peaks. Snowdrifts of up to 12 feet (about 4 m) have been reported.

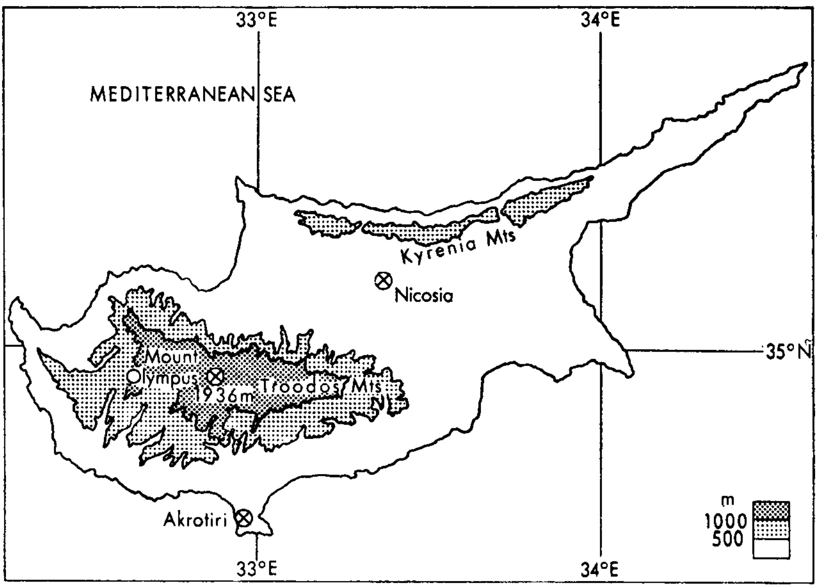


FIGURE 1—MAP OF CYPRUS

The highest summit in Cyprus is Mount Olympus, 1936 metres above MSL, and observations have now been made there for a period of 10 years. The writer has recently compiled statistics from these observations and has also photographed some of the weather conditions there.

The Mount Olympus observing station. The observing station was set up in 1958 and is located just four metres below the summit. By 1959, observations were being made three times daily on most days, at 06, 12 and

16 GMT, but there was no cover between these times or at any other time of the day or night. In March 1961, the commitment was taken over on a voluntary basis by the Royal Air Force Police, who increased observation cover to 24 hours, consisting of the normal 8 routine 3-hourly reports plus a continuous weather watch. At the same time, maximum/minimum thermometers and a rain-gauge were installed and measurements from them were included with the appropriate routine reports. Wind direction was obtained from a simple wind vane while the speed was measured by a standard Meteorological Office cup-generator anemometer mounted on the top of a 10-m pole (1942 m above MSL). The thermometers were housed in a small thermometer screen and rainfall was measured by a Meteorological Office 5-inch rain-gauge and measure.

The observations are telephoned to the Main Meteorological Office in Cyprus for use and dissemination. The form of observations is a little more simple than the standard Meteorological Office product but each observation covers dry- and wet-bulb temperatures, surface wind, cloud cover, state of ground and weather in progress (selected from 10 classifications). Additionally, maximum/minimum temperatures and rainfall are measured.

Plate IV shows the current position of the thermometer screen, which is situated across the road from the guardroom, where the anemometer dials are located. The photograph was taken on a typical summer day in 1970, while the 09 GMT observation was being made.

When the standard cup-generator anemometer was installed in 1958, it very quickly became apparent that the system was of no use for a large part of the year because the cups were frozen solid for most of the winter. A special heated anemometer was developed and this was installed on top of the 10-m pole in December 1963. However, this instrument was only partially satisfactory and icing problems persisted, amply demonstrating the severity of the winter conditions. Many wind observations were lost because of the failure of the anemometer and also because of damage to the wind vane when it was subjected to mean winds of up to 75 knots (1 kt $\approx$ 0·5 m/s).

A new heated anemometer* has since been developed and this was installed in January 1969. The operation of this new instrument has been successful. During 1970, the exposure of the anemometer equipment was improved by mounting an electric wind vane at 1959 m on top of a lattice tower and subsequently moving the heated anemometer to the same position. The latest addition to the anemometer system has been a roll-chart anemograph, suitably modified to operate from the heated anemometer head. This equipment was installed in March 1971 and is now operating satisfactorily.

It is clear from the above that records of wind are incomplete and unreliable and it should also be noted that this applies to other elements, particularly precipitation which it is not always possible to measure and wet-bulb temperature which tends to be reported as equal to dry bulb in freezing conditions. Nevertheless, the observations are of very considerable value for forecasting in Cyprus.

Weather and statistics. In comparison with the lower-lying areas of Cyprus, Mount Olympus weather is markedly colder, precipitation amounts

* HARTLEY, G. E. W.; A heated anemometer. *Met Mag, London*, **99**, 1970, pp. 270–274.

are greater, surface winds are stronger and the annual frequency of fog (often freezing fog in winter) is high because of cloud covering the peak. Winter snow depths are often several feet, with packed ice below and snowdrifts can be up to 12 feet in depth.

Plate V shows typical winter conditions at Mount Olympus; this photograph was taken on 26 March 1971 (the photographs published in the December 1962 *Meteorological Magazine* are also of winter conditions at Mount Olympus, Cyprus). Plate V shows that the snow depth was around three feet (1 m), with packed ice underneath and heavy drifting was observed in the area. At the time, the station was in freezing fog with a temperature of −1°C and a wind speed of 22 knots.

Table I (a) lists some basic climatological statistics for Mount Olympus. Column 1 shows the highest mean winds which have been recorded during the 10-year period. Gust information is not available. It can be seen that winter winds are generally stronger and this is borne out by frequency statistics which have been compiled (not reproduced here).

TABLE I—WEATHER STATISTICS FOR MOUNT OLYMPUS, CYPRUS, APRIL 1961 TO MARCH 1971

(a) Wind, temperature, rainfall and weather

	1	2	3	4	5	6	7	8	9	10	11
	Extreme wind	Mean day max.	Highest day max.	Mean night min.	Lowest night min.	Rainfall Wet days*	Ex. wet days†	Weather Fog	Snow/hail	Rain/drizzle	Columns 9+10
	kt	*degrees Celsius*						*percentage frequency*			
Jan.	SW 55	1·7	14	−2·9	−16	11	3	33·8	11·8	3·4	15·2
Feb.	S 60 SW	2·2	11	−3·0	−12	8	2	31·3	10·3	1·8	12·1
Mar.	S 72	5·2	16	−1·0	−11	7	1	18·8	7·9	1·8	9·7
Apr.	SW 52	9·7	23	2·3	−08	5	2	9·5	3·3	3·3	6·6
May	SW 47	14·1	25	6·4	−02	5	2	6·2	0·9	3·2	4·1
June	N 51	19·6	27	10·7	03	<1	<1	1·2	0·0	0·3	0·3
July	N 60	22·6	28	13·6	05	1	<1	0·3	0·0	0·3	0·3
Aug.	NE 50	22·7	29	13·9	06	<1	<1	0·2	0·0	0·3	0·3
Sept.	N 42	18·9	28	10·3	02	1	<1	3·7	0·0	0·8	0·8
Oct.	NE 52	13·1	21	6·0	−03	6	2	7·5	0·4	4·7	5·1
Nov.	SW 65	9·5	17	3·3	−10	6	2	12·7	2·3	5·1	7·4
Dec.	SW 75	3·7	16	−0·9	−10	13	5	28·2	11·0	7·0	18·0

* Wet day ⩾ 1·0 mm/24 hours
† Extremely wet day ⩾ 10·0 mm/24 hours

(b) Snowfall

	First snowfall	Last snowfall	Last snow on ground
Mean date	3 December	9 April	24 April
Extremes	21 November	23 March	2 April
	16 December	4 May	7 May

Columns 2 and 3 list maximum-temperature information. The midwinter mean maxima are shown to be not far above freezing, although the extremes indicate that mild spells have occurred, with temperatures rising to above 10°C. Summer temperatures are quite high with the extreme having risen as high as 29°C.

Night minima are shown in Columns 4 and 5 and these indicate how cold it can be on the summit of Mount Olympus. The mean values for 4 months of the year are below freezing and the extremes warn that the temperature may fall below freezing on any night during 8 months of the year.

Columns 6 and 7 show the distribution of 'wet days' and 'extremely wet days'. The definitions of these terms are given below Table I (a). Because the rain-gauge is sometimes buried under deep snow and ice, it has not been possible to calculate mean monthly rainfall figures for the winter months. Columns 6 and 7 show that precipitation is frequent in winter and is of very high intensity on several days in these months. Midsummer precipitation is infrequent but tends to be of high intensity (convective) when it occurs.

Columns 8 and 9 give the percentage frequencies of fog and freezing precipitation. These figures indicate that the peak is likely to be covered with cloud for almost one-third of the time during January, with almost as high frequencies in December and February. The frequency becomes progressively less towards summer, being quite low (0·2 per cent) in high summer, before increasing again towards winter.

A similar seasonal pattern applies to freezing precipitation, although the frequency figures are less, ranging from 12 per cent in January to no occurrence in summer. However, it is evident from Column 10 that non-freezing precipitation occurs throughout the year, though rather rarely in summer. The percentage frequency of precipitation of any type is shown in Column 11, indicating that December is the month in which there are most reports of precipitation.

Finally, mean snowfall information is reproduced in Table I(b). Snow is relatively late in coming to Mount Olympus but, once started, it persists into spring and is reported as covering the ground to some degree for almost 5 months.

Comparison with lower-level climate. Table II lists the results of a comparison of the Mount Olympus readings with those taken in the central plain just west of Nicosia (Figure 1) at an altitude of 220 metres. The Mount Olympus mean monthly maxima and minima appear to bear a conservative relationship with those of Nicosia. The mean difference in the mean maxima is 13·2 degC with a range of only 1·6 degC, while the comparable information for the minima is 8·0 degC and 1·7 degC.

The rainfall comparisons, for both amount and frequency, confirm a statement of greater rainfall at Mount Olympus. With the one exception of June, the mean monthly rainfall of the peak is greater than that of Nicosia — usually more than double. The June anomaly is also reflected in the frequencies as the only positive value, albeit only one day.

Concluding remarks and acknowledgements. While midsummer conditions at Mount Olympus can be very attractive — when, for instance, the temperature in the central plain is rising above 35°C every day — the summit experiences severe weather at times during most of the year. In particular, the midwinter conditions are very bad, and great credit is due to the many Royal Air Force policemen who have been voluntary meteorological observers during the last 10 years, working at times in the most difficult of conditions.

The writer would like to thank the Officer Commanding, Royal Air Force, Mount Olympus, for his permission to photograph the observing station, and also the Officer Commanding 230 Sqn (Det) Helicopters, Royal Air Force, Nicosia, for his valuable co-operation which enabled the writer to photograph Mount Olympus weather conditions from the air.

TABLE II—COMPARISON OF MOUNT OLYMPUS AND NICOSIA TEMPERATURE AND RAINFALL STATISTICS

	TEMPERATURE						RAINFALL					
	Average daily maximum			Average daily minimum			Monthly average			Wet days* per month		
	Mount Olympus	Nicosia	Difference	Mount Olympus	Nicosia	Difference	Mount Olympus	Nicosia	Difference	Mount Olympus	Nicosia	Difference
			degrees Celsius					*millimetres*				
Jan.	1·7	14·6	12·9	−2·9	5·8	8·7	—	64·6	—	11	9	−2
Feb.	2·2	15·3	13·1	−3·0	5·6	8·6	—	42·9	—	8	7	−1
Mar.	5·2	17·8	12·6	−1·0	6·9	7·9	—	30·5	—	7	6	−1
Apr.	9·7	23·1	13·4	2·3	10·1	7·8	42·7†	17·3	−25·4	5	3	−2
May	14·1	28·2	14·1	6·4	14·2	7·8	50·7	17·9	−32·8	5	2	−3
June	19·6	32·6	13·0	10·7	18·1	7·4	4·3	9·6	5·3	<1	1	<1
July	22·6	35·6	13·0	13·6	20·7	7·1	11·6	0·9	−10·7	1	<1	−<1
Aug.	22·7	35·8	13·1	13·9	21·0	7·1	4·0	1·7	−2·3	<1	<1	0
Sept.	18·9	32·1	13·2	10·3	18·3	8·0	25·2	4·7	−20·5	1	1	0
Oct.	13·1	27·2	14·1	6·0	14·8	8·8	65·0	31·0	−34·0	6	3	−3
Nov.	9·5	22·0	12·5	3·3	11·2	7·9	70·9	29·4	−41·5	6	4	−2
Dec.	3·7	16·7	13·0	−0·9	7·8	8·7	—	76·3	—	13	8	−5
Mean values			13·2			8·0						

* Wet day ⩾ 1·0 mm/24 hours

† Includes 8 days when precipitation was reported but not recorded.

Mount Olympus statistics : April 1961 to March 1971 = 10 years.

Nicosia statistics : January 1943 to December 1968 = 25 years.

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THE DIURNAL VARIATION OF GLOBAL RADIATION ON A HORIZONTAL SURFACE — WITH SPECIAL REFERENCE TO ABERDEEN

By R. W. GLOYNE

Summary. The broad features of the mean diurnal course of global radiation on a horizontal surface — when meaned over a sufficient number of days (say 10 at least) — may be reproduced either by a sine curve or by a (sine)^2 curve.

If S = mean daily integral of global radiation, T = day-length, t = time from sunrise, and $\alpha = \pi\, t/T$, the intensity $G(t)$ at time t is given by

$G(t) = (\pi S/2T)\sin\alpha$ (Monteith) or $G(t) = (2S/T)\sin^2\alpha$ (Gloyne).

The accuracy of the methods were examined (a) by comparing actual and computed monthly values of mean daily peak intensities at Aberdeen for June 1966 to May 1967, (b) by comparing the durations above three threshold levels, and (c) by their success in reproducing the detail of the mean diurnal course for July 1970. (In almost all comparisons a simple arithmetic mean of the estimates by the two methods was superior to either estimate separately.)

Introduction. Information is required by a range of interests on the variation during the day of the intensity of global radiation (and of illumination) on a horizontal surface. Some inquirers require estimates of the length of period when the intensity was above or below or between stated levels.

Centres providing direct data on an hourly basis are relatively few, although there are more which record the daily integral; furthermore, much of the readily available published data is in the form of daily integrals, meaned over varying periods and generally for calendar months. In addition one can — with varying degrees of accuracy — estimate the mean daily integral from data on the duration of bright sunshine.

The present contribution draws attention to certain useful empirical methods of representing the diurnal variation of mean daily global radiation, and tests the accuracy of some derived estimates against 12 months of data obtained from a recently installed solarimeter at the University of Aberdeen. It was the lack of data from regions such as north-east Scotland and the hazard of interpolating from, for example, data from long-period stations, such as the Observatories at Lerwick and Eskdalemuir, which led to the case study from which this paper has been compiled.

In passing it should be noted that it is not necessarily useful if acceptable statistical relationships are obtainable only for mean values over long periods; in many practical cases relationships are needed which can be used for periods of individual months or even shorter duration.

Analysis. For a given latitude and solar declination, global radiation on a horizontal surface is broadly a function of solar altitude which in turn is a function of cos H, where H is the local hour angle.

Trial plots of the diurnal march of global radiation, when meaned over a sufficient number of days (say 7 to 10 at least, and more generally for a month), suggest that the course is approximately sinusoidal. Monteith* has stated that there is a useful relationship with that portion of a sine wave comprised within the argument $\pm\,\pi/2$ from the maximum point, i.e. that at local apparent noon (LAN). The writer, whose immediate interest was in the circumstances at the ends of the day, i.e. at times of relatively low

* MONTEITH, J. L.; Light distribution and photosynthesis in field crops. *Ann Bot, London*, **29**, 1965, pp. 17–37.

intensities, suggests that for certain purposes the relevant portions of the diurnal curve may possibly be better reproduced by a (sine)^2 curve. (See Figure 1 (a) and (b).)

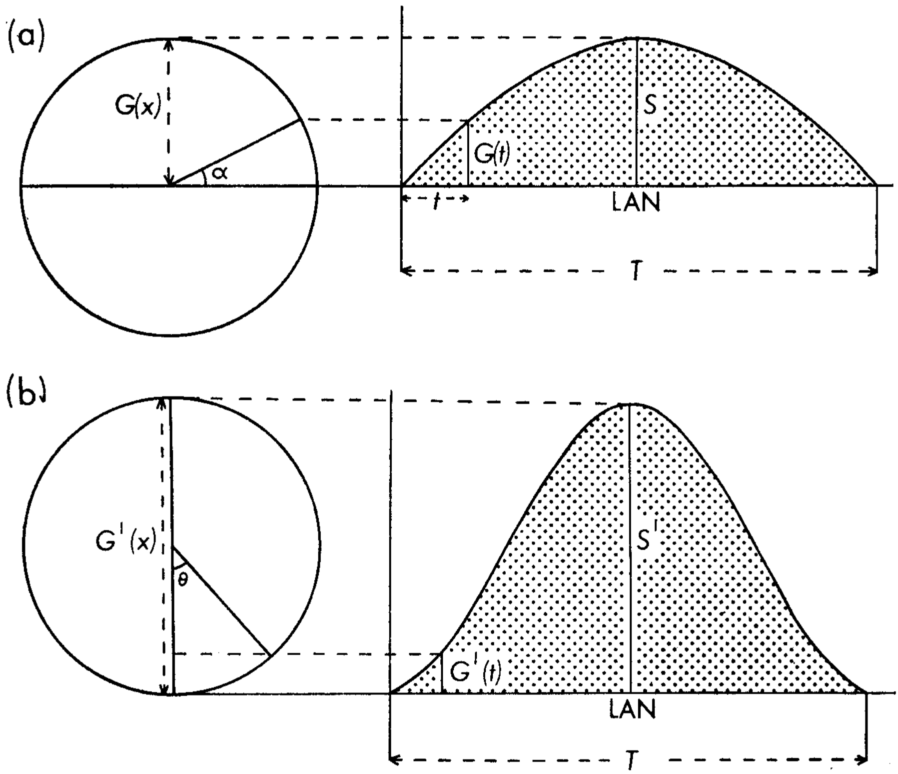


FIGURE 1—CO-ORDINATE SYSTEMS FOR ESTIMATION OF DIURNAL COURSE OF GLOBAL RADIATION ON A HORIZONTAL SURFACE

(a) After Monteith (b) After Gloyne

(a) *Monteith's method.* In Figure 1 (a) let

$G(t)$ = intensity of global radiation on a horizontal surface at time t (measured from sunrise)

$G(x)$ = intensity at LAN and assumed to be the maximum for the day

T = day-length

S = daily integral and equal to the area under the curve

α = $\pi t/T$ $(0 \leqslant t \leqslant T)$.

Then, with origin at sunrise

$$G(t) = G(x) \sin \alpha. \qquad \ldots (1)$$

It is easy to show that

$$S = G(x)\, 2T/\pi$$

and hence

$$G(t) = \frac{S}{T} \frac{\pi}{2} \sin \frac{\pi t}{T}. \qquad \ldots (2)$$

Also for a given threshold intensity G,

$$\tau = (T/\pi)\sin^{-1}(G/G(x)),$$

where 2τ = total period when $G(t) < G$

and $T-2\tau$ = the duration of global radiation of an intensity above the threshold values.

(b) *Gloyne's method.* Using dashed symbols $G'(t)$, $G'(x)$ and S' and $\theta = 2\pi t/T$ $(0 \leqslant t \leqslant T)$ the alternative expressions are (Figure 1 (b)) :

$$G'(t) = \tfrac{1}{2}G'(x)\,(1-\cos\theta), \qquad \ldots (3)$$

$$S' = \tfrac{1}{2}G'(x)\,T,$$

therefore

$$G'(t) = (S'/T)\,(1-\cos\theta), \qquad \ldots (4)$$

$$1-G'(t)\frac{T}{S'} = \cos\theta = \cos\left(\frac{2t}{T}\cdot\pi\right);$$

and for a given threshold G,

$$\tau = (T/2\pi)\cos^{-1}(1-(G/S')T) = (T/2\pi)\cos^{-1}(1-2G/G'(x)),$$

where 2τ is the total period when $G(t) < G$ and $T-2\tau$ is the period with global radiation above the threshold intensity.

Since $\theta = 2\alpha$, equation (4) may be written

$$G'(t) = (S'/T)\,2\sin^2\alpha. \qquad \ldots (5)$$

A preliminary comparison of estimates is informative. Consider the value of the expressions $G(t)/(S/T)$ and $G'(t)/(S'/T)$ at various values of t:

t	0	$T/6$	$T/4$	$T/3$	$T/2$
Method (a)	0	0·79	1·11	1·36	1·57
Method (b)	0	0·50	1·00	1·50	2·00

The difference in the shape of the curves is evident. From $t = 0$ to beyond $T/4$ Method (a) gives the higher value; equality is reached at $\sin^{-1}\pi/4$ (about $51\tfrac{1}{2}°$ or $T/3{\cdot}5$) after which Method (b) gives the higher estimate and an indicated maximum at LAN approaching 1·3 times that for Method (a). Of necessity the bounding curve for Method (b) is narrower than for Method (a). The important point is, of course, which of the two is the better approximation to the observed values. The second representation, i.e. that by a $(\text{sine})^2$ curve, corresponds to a complete sine wave from trough to trough with an oscillation occurring around a base-line equal to half the maximum radiation.

(c) For future reference, if S is assumed equal to S', note the approximate expression relating to the arithmetic mean of the two estimates, namely

$$\tfrac{1}{2}(G(t) + G'(t)) = (S/2T)\sin\alpha\,((\pi/2) + 2\sin\alpha). \qquad \ldots (6)$$

(d) In Figure 2 the basic features of the results are illustrated using data for a month (July 1970) not included in the original data.

Results. Hour-by-hour actual values and estimates by both methods of the mean intensities for each month in the period June 1966 to May 1967 (inclusive) were plotted on convenient scale (specifically: abscissa $\tfrac{1}{2}$ in = 1 hour, and ordinate 1 in = 10 mW/cm², for all except winter months of November to February when a large scale, usually 4 in = 10 mW/cm², was used).

A check on the accuracy of free-hand drawing of the diurnal curves was made by measuring the area under the curves and comparing the results with mean daily integral as recorded; the errors were less than ± 1 per cent for all months except October (+ 1·2 per cent) and January (+ 2·8 per cent).

Examination of graphs — such as Figure 2 — shows that in general the observed daily march of global radiation assumes a course intermediate between the two empirical representations. Method (a) tends to over-estimate, while Method (b) tends to underestimate duration above a threshold intensity except for approximately the middle third of the day; accordingly a simple arithmetic mean of the separate estimates might be expected to give a better representation than either of the individual estimates.

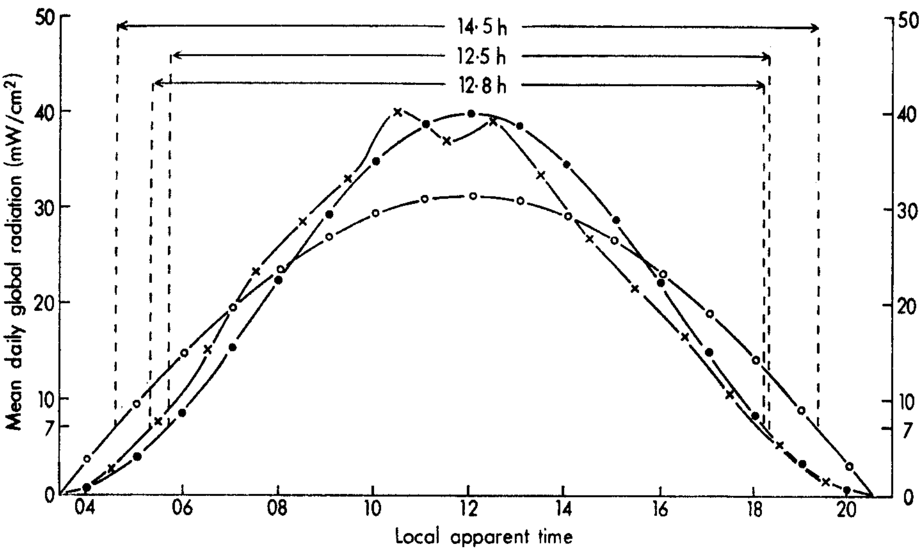


FIGURE 2—DIURNAL COURSE OF MEAN DAILY GLOBAL RADIATION FOR ABERDEEN, JULY 1970

x———x Observed values
o———o Estimated (Monteith)
.———. Estimated (Gloyne)

The adequacy of the empirical representations was examined in three ways.

(a) *Table I.* This compares the peak intensity as recorded (mean value over 60 minutes) with the computed maxima at LAN $(G(x), G'(x))$.

TABLE I—COMPARISON OF MONTHLY MEAN VALUES OF THE MEASURED MEAN DAILY MAXIMUM INTENSITIES WITH EMPIRICAL ESTIMATES AT LOCAL APPARENT NOON (ABERDEEN)

	1967				1966							
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	milliwatts per square centimetre											
Measured	9·6	18·7	33·1	42·6	47·3	40·4	45·6	34·2	30·2	17·8	10·7	5·8
Method (a)	8·3	16·3	31·1	38·3	41·4	30·4	40·1	28·9	28·4	16·1	9·7	5·8
Method (b)	9·6	20·7	39·6	48·8	52·7	38·6	51·0	36·8	35·3	20·5	12·4	7·4
Mean of (a) + (b)	9·0	18·5	35·3	43·5	47·1	34·5	45·6	32·9	31·9	18·3	11·1	6·6
Deviation of mean from measured	−0·6	−0·2	+2·2	+0·9	−0·2	−5·9	0·0	−1·3	+1·7	+0·5	+0·4	0·8

(b) *Table II.* This compares the estimated and measured periods above selected threshold intensities, namely :

(1) 7 mW/cm^2 (equivalent to 800 foot-candles — the requirement which led to the current investigation).

(2) An intensity equal to 50 per cent of the observed maximum. For the estimated periods the threshold used was 50 per cent of the empirical maximum.

(3) As for (2) but at the 75 per cent level.

(c) *Table III.* This shows the complete daily march of global radiation for July 1970 (i.e. a particular month outside the period June 1966–May 1967).

The underestimate by Method (a) reaches a maximum of about 10 mW/cm^2 in June but otherwise is numerically less than 5 mW/cm^2; the largest over-estimate by Method (b) is 6·5 mW/cm^2 in March; otherwise the errors are numerically less than 3 mW/cm^2 in 7 of the 12 months; using a simple arithmetic mean the largest error is in June, otherwise it is less than about 2 mW/cm^2.

On duration above stated levels (Table II), the arithmetic mean of the two estimates leads in most months to an error in duration of one-half hour or less for intensities $\geqslant 7$ mW/cm^2, usually less than one hour (June excepted) associated with the 50 per cent peak intensity, and for the 75 per cent level, 1·0 mW/cm^2 or less for 10 of the 12 months. It should perhaps be emphasized that the actual value of the peak intensity and the estimated values all differ and hence necessarily the 50 and 75 per cent levels; by hypothesis the estimates are to be derived *solely* from a knowledge of the mean daily integral and the day-length.

Since values for short periods are required, 10-day means were also formed (1–10, 11–20, 21–(30, 31 or 28)), and the actual data and the estimates from Method (b) plotted; the intercepts at 7 mW/cm^2 were measured from the 'actual' and the estimated curves. The errors incurred were almost all under-estimates with an absolute value of one hour or less. Accordingly from this particular sample it might be concluded that the method is capable of giving results for means over 10 days as reliably as over a calendar month.

The results illustrated in Figure 2 and set out in Table III merit some attention. In general terms Gloyne's method gives the closer fit for this particular sample, although the use of a simple arithmetic mean between the two estimates gives a close general fit except during the middle of the day. It is perhaps a matter for comment that a rather closer fit in this instance arises if Gloyne's curve is displaced to the left by 30 minutes (i.e. his value for hh + 30 being associated with the actual values for hh). It is perhaps worthy of note that June 1966 — the month giving rise to the largest deviations — was very dull (Aberdeen 55 per cent of possible sunshine) and hence perhaps atypical.

Conclusions.

(a) From a limited sample, it has been found that many features of the diurnal course of mean daily total radiation on a horizontal surface (meaned over periods of at least 10 days) can be reproduced, given mean daily total and day length, either by a sine curve with maximum at LAN (Monteith) or by a $(\text{sine})^2$ curve (Gloyne).

Photograph by M. G. Phillips

PLATE I—TORNADO OVER NICOSIA, 3 AUGUST 1966

See page 53

Photograph by K. M. Jones

PLATE II—HOUSE DAMAGED BY TORNADO

See page 55

Photograph by K. M. Jones

PLATE III—TREE UPROOTED BY TORNADO

See page 55

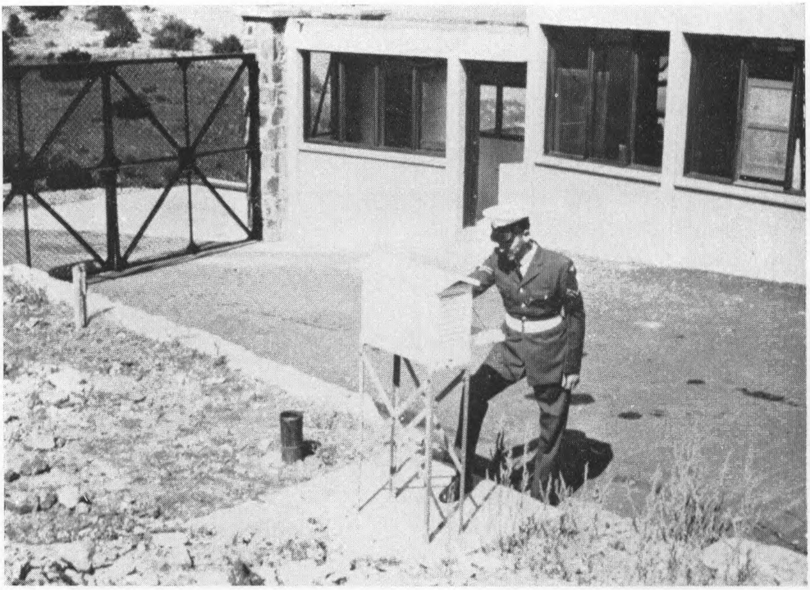


PLATE IV—MOUNT OLYMPUS OBSERVING STATION, CYPRUS, IN SUMMER 1970

See page 40

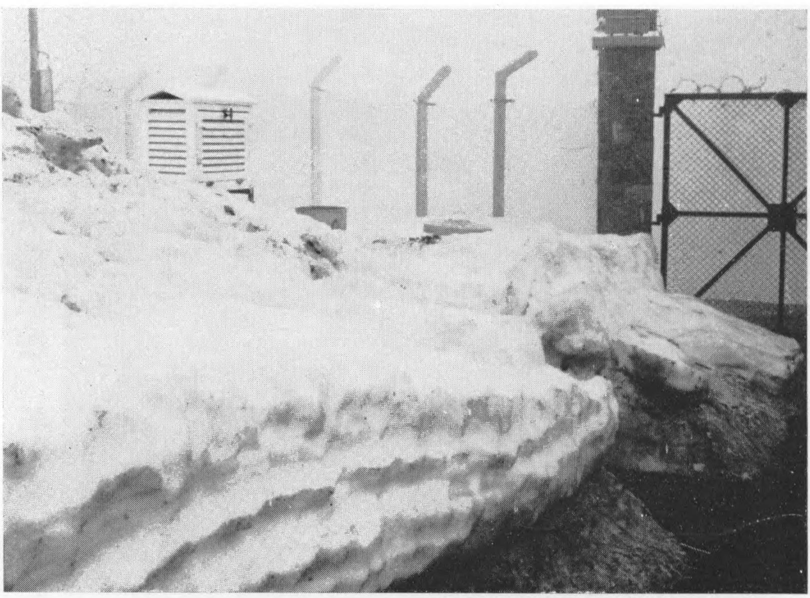


PLATE V—MOUNT OLYMPUS OBSERVING STATION, CYPRUS, 26 MARCH 1971

See page 41

To face page 49

PLATE VI—AWARD WINNERS WITH MAJOR AND MRS K. G. GROVES AND AIR VICE-MARSHAL D. G. EVANS

Left to right: Mr H. H. Lamb, Corporal R. Cotton, Major K. G. Groves, Air Vice-Marshal D. G. Evans, Mrs K. G. Groves, Squadron Leader G. F. Holbrook and Flight Lieutenant T. J. Kenny (see page 62).

TABLE II—COMPARISON OF MEAN MONTHLY VALUES OF DAILY DURATIONS OF INTENSITIES AS MEASURED AND AS ESTIMATED

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
(1) For intensities ⩾ 7 mW/cm²						*hours*						
Measured	2·4	6·4	9·4	11·9	13·5	13·0	13·7	11·9	9·9	6·7	3·8	0·0
Method (a)	2·7	6·9	10·1	12·6	14·7	15·0	15·4	12·9	10·8	7·2	4·0	0·0
Method (b)	2·6	5·7	8·6	10·8	12·6	12·9	13·1	10·9	9·2	6·3	3·8	0·9
Mean of (a) and (b)	2·7	6·3	9·4	11·7	13·7	13·9	14·3	11·9	10·0	6·7	3·9	0·5
Deviation of mean from measured	0·3	−0·1	0·0	−0·2	0·2	0·9	0·6	0·0	0·1	0·0	0·1	0·5
(2) For intensities ⩾ 50 per cent peak intensity, either measured or estimated												
Measured	3·7	5·4	7·3	8·3	9·4	8·7	10·1	8·6	7·7	6·0	4·7	4·7
Method (a)	4·9	6·3	7·9	9·5	11·0	11·9	11·5	10·2	8·5	6·9	5·4	4·3
Method (b)	3·7	4·8	5·9	7·1	8·3	8·9	8·6	7·6	6·4	5·2	4·1	3·2
Mean of (a) and (b)	4·3	5·6	6·9	8·3	9·7	10·4	10·1	8·9	7·5	6·1	4·7	3·8
Deviation of mean from measured	0·6	0·2	−0·4	0·0	0·3	1·7	0·0	0·3	−0·2	0·1	0·0	−0·9
(3) For intensities ⩾ 75 per cent peak intensity, either measured or estimated												
Measured	2·2	3·3	5·0	5·7	5·3	5·2	6·5	5·0	5·6	4·4	3·2	3·3
Method (a)	3·4	4·4	5·4	6·6	7·6	8·2	8·0	7·0	5·9	4·8	3·7	3·0
Method (b)	2·5	3·1	3·9	4·7	5·5	5·9	5·7	5·0	4·2	3·4	2·7	2·1
Mean of (a) and (b)	2·9	3·8	4·7	5·6	6·5	7·1	6·8	6·0	5·1	4·1	3·2	2·6
Deviation of mean from measured	0·7	0·5	−0·3	−0·1	1·2	1·9	0·3	1·0	−0·5	−0·3	0·0	−0·7

TABLE III—INTENSITY OF GLOBAL RADIATION THROUGHOUT THE DAY (MEAN VALUES FOR ABERDEEN, JULY 1970) AT THE HALF HOUR AS MEASURED AND AS COMPUTED; TOGETHER WITH ERRORS OF ESTIMATE

	Time (GMT)															
	0430	0530	0630	0730	0830	0930	1030	1130	1230	1330	1430	1530	1630	1730	1830	1930
Method	*milliwatts per square centimetre*															
Measured	2·4	7·4	14·9	23·0	28·2	32·8	39·8	36·8	39·0	33·5	26·9	21·6	16·7	10·7	5·5	1·8
Method (a)	6·4	11·8	16·8	21·3	25·0	27·9	29·9	31·0	31·0	29·9	27·9	25·0	21·3	16·8	11·8	6·4
Deviation of (a) from measured	4·0	4·4	1·9	−1·7	−3·2	−4·9	−9·9	−5·8	−8·0	−3·6	1·0	3·4	4·6	6·1	6·3	4·6
Method (b)	1·7	5·7	11·6	18·6	25·5	31·9	36·7	39·3	39·3	36·7	31·9	25·5	18·6	11·6	5·7	1·7
Deviation of (b) from measured	−0·7	−1·7	−3·3	−4·4	−2·7	−0·9	−3·1	2·5	0·3	3·2	5·0	3·9	1·9	0·9	0·2	−0·1
Mean of (a) and (b)	4·1	8·7	14·2	20·0	25·3	29·9	33·3	35·1	35·1	33·3	29·9	25·3	20·0	14·2	8·7	4·1
Deviation of mean from measured	1·7	1·3	−0·7	−3·0	−2·9	−2·9	−6·5	−1·7	−3·9	−0·2	3·0	3·7	3·3	3·5	3·2	2·3

(b) For estimates of the LAN (peak) intensity and of the duration above, below or between stated levels of intensity, the value obtained by meaning the two estimates appears the most successful (the error in the duration usually being but a fraction of an hour).

(c) Except perhaps in the winter months, there are indications that the $(\text{sine})^2$ curve gives a somewhat better representation of the daily course — at any rate in higher latitudes.

(d) Obviously the above findings should be subjected to extensive tests before a firm recommendation on the best procedures is possible.

551.524.73:551.551.5

A REPORT OF CLEAR-AIR TURBULENCE ASSOCIATED WITH A LARGE TEMPERATURE CHANGE

By J. D. PERRY

Details of a report of severe clear-air turbulence over the southern Mediterranean, associated with a rapid temperature rise of 8 degC, were given recently by McGinnigle.[1]

A further occurrence of clear-air turbulence also associated with a large temperature change is of interest, in that the upper winds were by no means similar to those previously reported. On this occasion at 0141 GMT on 4 August 1970 a Boeing 707 encountered light to moderate clear-air turbulence at 18 000 ft (5·5 km) during descent into Bahrain Airport with a simultaneous temperature change of 11 degC, while at about 0215 GMT a second aircraft reported moderate to severe turbulence at the same height with a temperature change of 7 degC.

The synoptic situation showed a seasonal pressure pattern with a complex low-pressure area covering West Pakistan, central south Arabia and much of Persia. The reports, which were made within a few hours of the midnight Bahrain radiosonde ascent, Figure 1, were found to have occurred in the transitional zone between low-level north-westerly winds and upper easterly winds (see Table I). A marked inversion had been a feature of this zone for several days and the midnight ascent showed an inversion of 7 degC in 10 mb at about 500 mb.

TABLE I—BAHRAIN UPPER WINDS, 4 AUGUST 1970

mb	00 GMT	06 GMT *degrees knots*	12 GMT
850	335 23	350 21	350 21
800	340 19		335 20
780		335 14	
700	335 08	320 12	315 18
655	345 07		
650		320 13	
600	010 04		320 11
575		320 09	310 06
531	065 05		
500	095 07	155 08	195 10
486			130 14
470		125 18	
450		105 18	
440	100 18		
430			105 19
400	085 18	105 19	100 22
358	080 19		
300	090 20	090 21	110 17

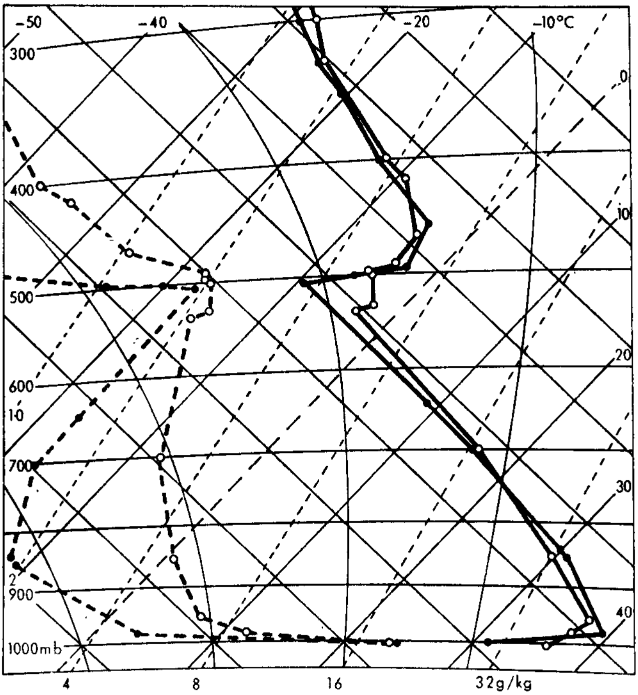


FIGURE 1—BAHRAIN ASCENTS, 4 AUGUST 1970

00 GMT		12 GMT	
.———.	Temperature	o———o	Temperature
. - - - - .	Dew-point	o - - - o	Dew-point

Discussion. A study of the upper air charts shows the air at 700 mb to have originated over the desert and this flow is representative of the virtually dry adiabatic layer which extends from 850 mb to 500 mb, whereas the subsided air above 500 mb is tropical in character.

The wind shear of 30 knots (1 kt ≈ 0·5 m/s) in the dry adiabatic layer between 850 mb and 500 mb is sufficient to produce turbulence (the Richardson number for this layer being about 0·8), and evidence that vertical motion was present on this occasion is given by the working sheets of the midnight Bahrain radiosonde ascent which show a significant increase in the rate of ascent in the layer between 640 mb and 505 mb. The actual rates of ascent were :

Surface to 640 mb	5·9 m/s
640 mb to 505 mb	6·5 m/s
505 mb to 400 mb	6·1 m/s

Dry convection is typical of desert air. However, the turbulence reported occurred in the shallow layer of the inversion in which the aircraft experienced the large changes of temperature. The ascent in the layer below the inversion and the shallow layer of turbulence associated with the marked inversion are indicative of the turbulent motion suggested by Townsend,[2] who used a laboratory model (in which a stably-stratified fluid overlay an unstable layer) to study the disturbance of a stable layer by convective columns. The results of this study showed that convection in the unstable layer is sufficient to produce internal waves within the interface between the two fluids. Townsend further suggested that the energy of these waves would be dissipated in shallow patches of turbulence.

Evidence that mixing was occurring on the occasion on which turbulence was observed is given by the Bahrain radiosonde ascents, Figure 1, which show that considerable mixing had taken place between 540 mb and 460 mb between midnight and midday, resulting in erosion of the previously marked inversion. It is therefore suggested that the main mechanism of the turbulence, which was confined to the shallow inversion layer and was associated with a large temperature change, was the dissipation of convectionally induced internal waves.

Acknowledgement. The author would like to thank Dr W. T. Roach for his constructive comments.

REFERENCES

1. MCGINNIGLE, J. B.; An occurrence of highly localized clear-air turbulence over the southern Mediterranean. *Met Mag, London*, **99**, 1970, pp. 208–211.
2. TOWNSEND, A. A.; Natural convection in water over an ice surface. *Q J R Met Soc, London*, **90**, 1964, pp. 248–259.

551.515.3

TORNADO AT NICOSIA, CYPRUS, 3 AUGUST 1966

By K. M. JONES and R. F. WILLIAMS

Summary. Just before 12 GMT (2 p.m. local time) on 3 August 1966 a tornado developed to the west of the Strovolos district of Nicosia and caused substantial damage to property and vegetation as it subsequently tracked northwards across the western part of the city. Although dust devils are quite common over inland districts of Cyprus during the summer months, tornadoes, which have a similar mechanism, are comparatively rare. The tornado is described in relation to its environment and the synoptic situation prevailing at the time.

Observations and effects of the tornado. One of the Nicosia Meteorological Office staff, Mr M. G. Phillips, was travelling between the airfield and Nicosia city (see the map of the area — Figure 1). He was fortunately able to photograph the tornado and give an eye-witness account of its progress (the tornado could not be seen from the Meteorological Office because of intervening high ground and generally hazy conditions).

The photograph (Plate I) was taken at 1155 GMT from the position shown in Figure 1 with the tornado about 2 miles* away to the east. Although it is not clear from the photograph, Mr Phillips recorded the normal snake-like tornado column rising to the base of the cloud from the low-level umbrella-shaped mass of rising dust and debris. The rotation appeared to be anti-clockwise or cyclonic. The tornado was associated with a thunderstorm which had developed over Nicosia.

Mr Phillips continued his journey towards Nicosia and then northwards out of the city. He recalled that the tornado was still visible to the south-east (approximately in the position shown in Figure 1) when he was passing

* Distances and heights are given in traditional British units. Conversion factors to metric units are: 1 foot = 0·3048 m; 1 mile ≈ 1·6 km; 1 knot ≈ 0·5 m/s.

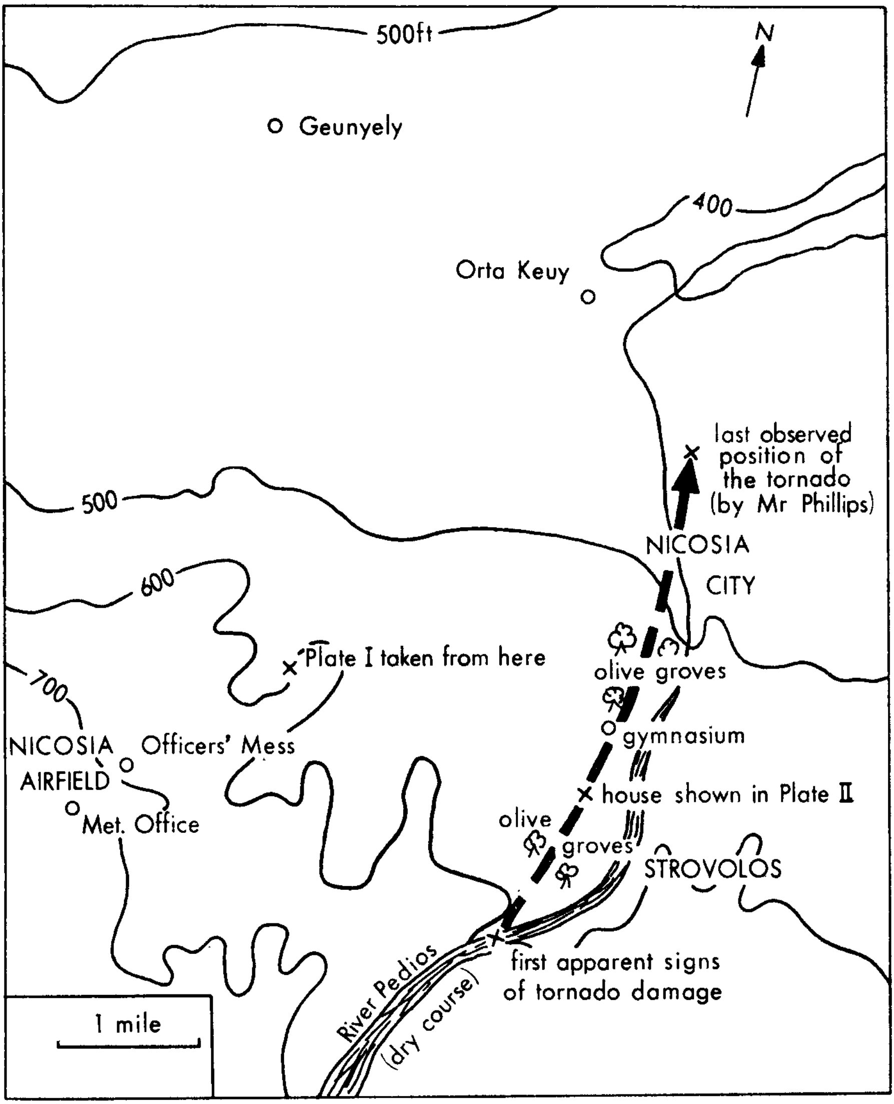


FIGURE 1—MAP OF NICOSIA AREA SHOWING THE TORNADO TRACK

through the village of Orta Keuy at 1220 GMT. Subsequently he drove north-westwards towards Geunyely but could not see any further signs of the tornado itself owing to the large amount of dust haze and general atmospheric obscurity in the direction of Nicosia city. However, he did observe a well-developed dust devil rising from ground-level to about 2000 ft in a position about 5 miles north-east of Geunyely at 1235 GMT. Although this was obviously not the remains of the tornado itself (it was too far north and was divorced from the main cloud system with which the tornado had been associated) its occurrence is relevant to the discussion which follows later.

An attempt to trace the path of the tornado by inspection of the damage inflicted was made the following day. The first signs of damage appeared in the position indicated in Figure 1 amongst the vegetation on the periphery of the dry flat bed of the river Pedios. The trail of damage then led north-north-eastwards into the western part of the Strovolos area through an extensive area of olive groves. Trees in the direct path of the tornado sustained considerable damage with branches as thick as 6 to 12 inches being torn away from the main trunk. The most spectacular area of damage was found about one mile north of the area where the initial damage began and a house in the track of the tornado at this point suffered extensive damage (Plate II). The tiles of the roof were blown outwards, as were the windows of an adjoining house, thus exhibiting the usual signs of explosive damage associated with the rapid reduction of air pressure outside the buildings, as is common with tornadoes. About 25 yards further on from the house a large tree was uprooted (Plate III). As the tornado proceeded north from this position it passed over the buildings of the Kykko gymnasium where structural damage in the form of loss of roofing and blown-out windows was again observed. Further damage to trees was evident where the tornado had passed through another olive grove some 300 yards north of the gymnasium but from eye-witness reports and lack of any further evidence of damage on the northern side of this grove it appears that the tornado had begun to diminish in intensity at this point. Judging from the observations recorded by Mr Phillips it appears that the tornado maintained its identity as a revolving disturbance for at least another mile north of the second olive grove, i.e. 3 miles north of the original area of damage, although the actual length of the trail of damage was about 2 miles. Based on the length of time (40 minutes) between the time that Mr Phillips took his photograph and his final sighting of the disturbance, it appears from the distance the tornado travelled that it was moving quite slowly (about 3 miles per hour), at least in its latter stages of life.

Discussion. Figure 2 shows the surface chart for the eastern Mediterranean at 12 GMT on the day in question. The usual surface pattern at this time of year is a shallow trough of low pressure extending westwards from the seasonal low over Iraq to the vicinity of Cyprus. As can be seen from Figure 2

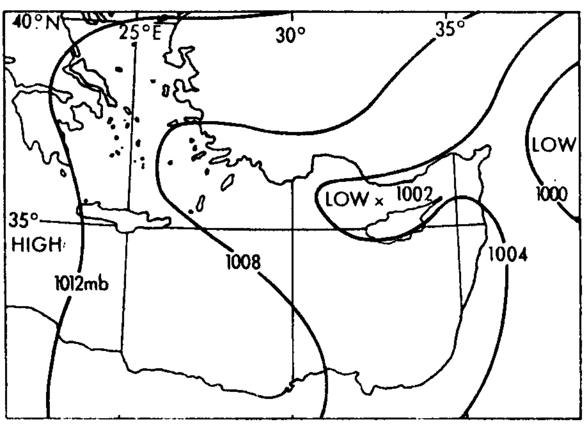


FIGURE 2—SURFACE ANALYSIS, 12 GMT ON 3 AUGUST 1966

this trough was well defined on the day in question with a suggestion of a separate cell of low pressure to the north-west of Cyprus. There was a trough adjacent to the island at all levels up to and including 300 mb and this was well marked at 700 mb. By 00 GMT on 4 August the axis of the 700-mb trough had moved to the south-east of Cyprus and winds at this level over the island had veered from south-west to north-east.

Wallington[1] lists four favourable criteria for the development of a tornado :

(a) The presence of a cold front.
(b) Moist unstable air from the surface to several thousand feet.
(c) A stable layer above the moist air.
(d) A deep layer of unstable and relatively dry air above the stable layer.

The 12 GMT upper air sounding for Nicosia on 3 August 1966 (Figure 3) appeared to satisfy the last three of Wallington's criteria, as detailed above, fairly well. Conditions up to 14 000 ft were very moist and unstable and a stable layer between 14 000 ft and 19 000 ft capped the moist lower levels and in turn was beneath a deep layer of dry unstable air.

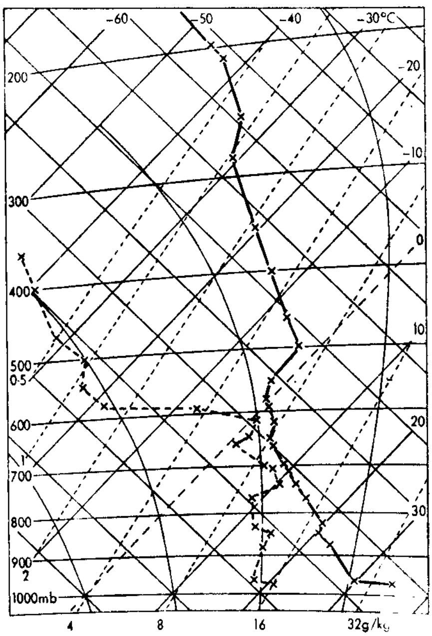


FIGURE 3—NICOSIA ASCENT, 12 GMT ON 3 AUGUST 1966

x———x Temperature x - - - - x Dew-point

Although no surface cold front was evident on the 12 GMT surface chart on the day in question an important factor which must be taken into consideration is the onset of the west-north-westerly sea-breeze in the vicinity of Nicosia. The sea-breeze front appears almost certainly to have been the 'trigger' for the thunderstorm and associated tornado that afternoon. This sea-breeze front appears to have satisfied the first of Wallington's criteria in the manner detailed below.

Conditions prior to the arrival of the sea-breeze at Nicosia were quite moist. The island had been surrounded by very moist stagnating surface air for several days prior to 3 August and dew-points around the coasts of Cyprus were around 24°C. Even well inland at Nicosia the morning dew-point was around 20°C. This was well above normal even for August. Light easterly winds prevailed at Nicosia Airfield during the morning and the approach of the westerly sea-breeze was heralded by a line of cumulus cloud observed just to the west of the airfield at 1045 GMT. The sea-breeze front arrived at the airfield at 1120 GMT with a rapid reversal of the surface wind direction to west-north-westerly and an increase in mean speed from around 7 kt to a mean of 18 kt with gusts to 28 kt. Figure 4 shows the anemograph trace at Nicosia Airfield around this time. At the time of the passage of the sea-breeze front across the airfield the cumulus cloud appeared to be developing with base estimated at 6000 ft and tops 12 000 to 14 000 ft. No precipitation was observed at the Meteorological Office but there was apparently a shower at the Officers' Mess on the camp. As well as halting the morning rise in temperature at 35°C, the sea-breeze front also brought in a supply of moist maritime air and thus further increased the moisture content of the surface layers. In the next half hour the line of cumulus continued its slow eastward progress away from the airfield and towards Nicosia city and rapidly built

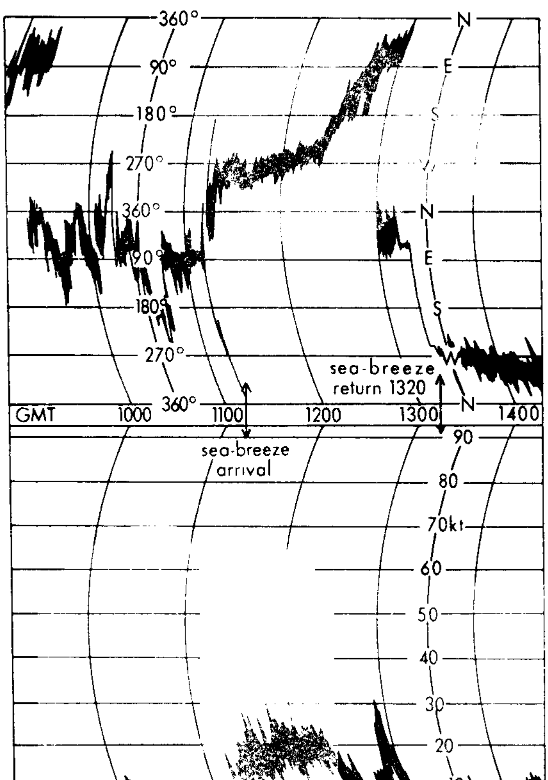


FIGURE 4—DIAGRAMMATIC REPRESENTATION OF ANEMOGRAPH CHART FOR NICOSIA AIRFIELD FOR 3 AUGUST 1966

into cumulonimbus proportions with one estimated top reaching at least 30 000 ft. The 12 GMT tephigram for Nicosia (Figure 3) clearly shows this to be possible. It is feasible that a sea-breeze from the south and east coasts of Cyprus had opposed the westerly sea-breeze and added to the general convergence taking place over Nicosia, but apart from the light easterly wind during the morning at the airfield there is insufficient observational evidence to confirm this.

Unfortunately there were no radar reports of the storm area but the fairly short duration of the thunderstorm (which from accounts lasted for less than one hour in Nicosia itself) and light upper winds with little vertical shear suggest that the tornado was not associated with the formation of a severe storm as described by Browning.[2] On this particular occasion it seems evident that the thunderstorm was entirely due to the normal convergence on the sea-breeze front combined with the abnormally high moisture content of the lower layers of the atmosphere, high temperatures and generally unstable conditions. The sighting of a well-developed dust devil by Mr Phillips in a position almost due north of Nicosia adds to the evidence that local vortices were developing on the sea-breeze front that day. Figure 5 shows

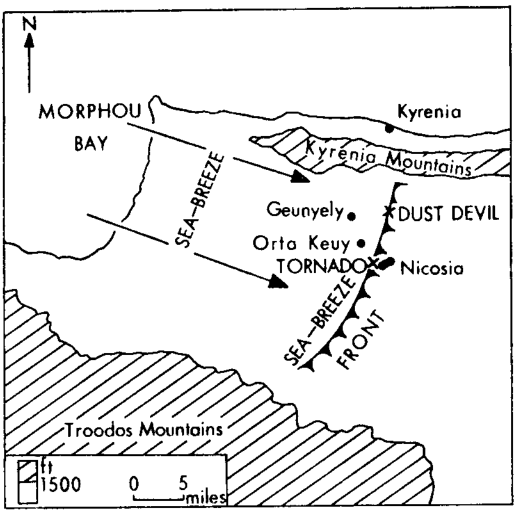


FIGURE 5—ESTIMATED POSITION OF SEA-BREEZE FRONT OVER NORTH-WEST CYPRUS AT ABOUT 12 GMT ON 3 AUGUST 1966

the estimated position of the sea-breeze front over the western plain area of Cyprus at about 12 GMT on 3 August with the positions of the tornado and observed dust devil marked. The trigger action for these revolving disturbances was probably a local unusually large superadiabatic lapse rate in the air close to the ground combined with some local microscale configuration of topography that might be conducive to rotation of the air. These conditions could well be produced in a small hollow or gulley. The appearance of the first signs of damage on the edges of the fairly wide (about 30 yards) dried-up bed of the Pedios river with rising ground on each side (see Figure 1) fits in with this fairly well.

As can be seen from the anemograph trace (Figure 4) the surface wind at Nicosia Airfield changed from the westerly sea-breeze direction to north-east with a gust of 31 knots at 1253 GMT. This was probably a downdraught effect from the thunderstorm to the east. The wind reverted to a westerly direction at 1320 GMT as the thunderstorm decayed and ceased to influence the local winds in the area around it.

Conclusions. On the day in question it would seem that the combination of marked instability, an environment curve fulfilling fairly well those conditions listed by Wallington,[1] high temperatures of both the surface layers of air and the ground, convergence associated with both the upper trough and the sea-breeze front and, finally, sufficiently moist air in the lower layers to allow condensation, produced the necessary conditions for the quite common phenomenon of a dust devil to develop into the comparatively rare phenomenon of a tornado.

Acknowledgement. The authors are grateful to Mr Phillips for his account of the tornado and his photograph.

REFERENCES

1. WALLINGTON, C. E.; Meteorology for glider pilots. London, John Murray, 1961.
2. BROWNING, K. A.; The organization of severe local storms. *Weather, London*, **23**, 1968, pp. 429–434.

REVIEWS

Meteorology: a historical survey, by A.Kh. Khrgian. 245 × 173 mm, pp. iv + 387, *illus.* (translated from the Russian by Israel Program for Scientific Translations, Jerusalem). Keter Press Ltd, 15 Provost Road, London NW3 4ST, 1970. Price: £10.

The only substantial volume on the history of meteorology known to the reviewer is Volume 1 of Napier Shaw's *Manual of meteorology*,* so that there is ample room for Professor Khrgian's new book, which takes the historical survey up to 1920. It is a much longer book than is Shaw's and must be the result of very careful research and reading in the literature of textbooks, papers and reports of international meetings of meteorologists. It also has the advantage of seeing the later period with the hindsight of another 35 years and so of being able to put emphasis in the right place.

The author rightly deals briefly with the first phase of speculation and the introduction of instrumental observation, and gives most space to the phase divided from the first by the acquisition of the ability to communicate observations which led to meteorological institutes, national services, synoptic meteorology and the professional meteorologist. We can see clearly in the narrative the forces which made meteorology important about the mid 19th century: different needs for different nations, illustrated by the state department in which the service found its greatest support — in Russia, the Naval Department and the Department of Mines; in the U.S.A., the Signal Service;

* SHAW, Sir N.; Manual of meteorology. Volume 1 — Meteorology in history. London, Cambridge University Press, 1932.

in the U.K., the Board of Trade — and then the need for international co-operation, so clearly seen and so well founded that today we regard it as natural.

The author also reviews the meteorological thought of the 19th century when synoptic charts were beginning to yield up the typical mid-latitude weather patterns and the problems of explaining the mechanisms became of prime importance. Some remarkably successful ideas, considering the total lack of upper air observations, and some otherwise, were put forward and argued about, and if now some of the controversies seem as irrelevant as the Morphy–Anderssen match, they were nevertheless very real. Cyclones, anticyclones, fronts (though not so named) and the general circulation are some of the subjects that claimed a great deal of attention. Towards the end of the period under survey came the exploration of the upper air, which simplified some old problems but inevitably raised new ones. Throughout the period meteorologists were laying not only the foundations of synoptic meteorology but also of climatology both by the taking and recording of observations and by theorizing about them.

Professor Khrgian gives the history of his period in a lot of detail and it cannot fail to fascinate and educate the meteorologist of today. If he errs occasionally on the side of parochialism by over-emphasizing the contributions of his countrymen, then let it be so, for Shaw was also parochial and the author is simply redressing the balance. The translation reads well with just the odd infelicity of phrase and of retranslating names which have been transcribed into Russian.

E. KNIGHTING

World survey of climatology, Volume 13 Climates of Australia and New Zealand, edited by J. Gentilli. 300 mm × 215 mm, pp. x + 405, *illus.*, Elsevier Publishing Co. Ltd, 22 Rippleside Commercial Estate, Barking, Essex, 1971. Price: £17.

The editor of this volume, Dr J. Gentilli, Reader in Geography at the University of Western Australia, has been carrying out research in climatology in Australia since 1940. Consequently he is well qualified to contribute the vast majority of the description of Australian climate himself.

He has chosen deliberately to write a dynamic account of the spatial relationships of climate, rather than a static description. However, it is claimed that the inclusion of numerous maps still makes it possible to obtain a large amount of detailed factual knowledge by interpolation. This approach leads the reader from a description of the position of Australia in the General Circulation of the Southern Hemisphere (contributed by Dr U. Radok, Department of Meteorology, University of Melbourne), through a discussion of climatic factors such as duration and intensity of sunshine, albedo of the surface and ocean temperatures, to an account of the dynamics of the Australian troposphere. Then follows quite naturally the key chapter on the main climatological elements and a shorter chapter on climatic fluctuations.

The last three chapters of the book deal with the climate of New Zealand and are written by W. J. Maunder of the Department of Geography, University of Otago, Dunedin, New Zealand. A similar treatment is used here, a chapter on the causes of the main types of airflow in New Zealand being followed by a description of the elements of New Zealand's climate and the climatic areas of New Zealand. At the end are over 100 pages of detailed climatological tables for Australia and New Zealand, which some readers would undoubtedly consider the most valuable part of the whole book.

This is a beautifully printed and bound volume, and the style of writing makes it easy to read and to assimilate the information. The maps are very clear but a statement such as 'more than 80 Campbell-Stokes sunshine recorders are now in use' (in the whole of Australia) makes one wonder how accurate are some of the isopleths. In places the underlying physical ideas are woolly, e.g. page 123 'the source of heat is the cloudless interior'. What a pity, too, that a really good topographical map is not included near the beginning of the book.

There is no evidence that the book is aimed at one particular class of reader, but appears rather to be a broad survey which will be of value to a wide spectrum of people interested in the climatology of Australia and New Zealand. To an industrialist considering the location of a new factory, the book could well provide all the information required. To a hydrologist or research climatologist it is an excellent 'launching pad' and the copious references to original sources at the end of each chapter will suggest many profitable avenues of investigation. As a general work of reference it fulfils its role admirably and many librarians will be very anxious to have a copy on their shelves.

P. D. BORRETT

World survey of climatology, Volume 14 Climates of the polar regions, edited by S. Orvig. 300 mm × 215 mm, pp. x + 370, *illus.*, Elsevier Publishing Co. Ltd, 22 Rippleside Commercial Estate, Barking, Essex. Price: £14·75.

Established meteorological observing stations are sparse in the polar regions and a considerable part of the available data come from discontinuous and short-lived series provided by expeditions and drifting ice stations. Observational backing is insufficient for the climatological statistics normally compiled by the meteorological services; on the other hand there is at present little requirement for applied climatology as in the developing countries. So it is to be expected that this volume will differ to some extent, in its approach, from the more conventional and factual texts and climatological handbooks. A substantial part of the book is in fact devoted to climatic tables for a number of stations, but in using them the limitations of the data must be borne in mind.

The volume is in three sections dealing respectively with Greenland, the North Polar Basin and Antarctica. Because of the regions' differing topography, particularly in regard to their effects on the atmospheric circulation, there is a good deal of emphasis on synoptic and dynamic climatology. Synoptic charts are not detailed enough, and upper air observations are too sparse for the study of the structure of individual depressions and anticyclones. The activity of these systems has often to be inferred from derived data, for example 24-hour pressure and temperature changes at fixed stations, zonal and meridional indices, and changes with time of thickness and lapse rate. The section on Greenland provides the clearest example of these methods. Greenland is an elevated ice-sheet extending through more than 20° of latitude, its southern extremity lying on the fringe of the mid-latitude westerlies. Its role as a barrier to the westerlies and to depressions approaching from west or south-west (problems of great interest to European forecasters) is thoroughly discussed from several of the indirect viewpoints mentioned above. Geographical factors, and their climatic effects, are emphasized in the sections on the other two regions. The North Polar Basin is a level, mostly ice-covered, surface, with no topographical complications, so that a single observing station is usually representative of a large area. Antarctica, on the other hand is an elevated ice-cap more or less symmetrical about the pole.

Because a large proportion of the observing stations have been established for scientific rather than purely utilitarian purposes in the reporting network, they are equipped for the more sophisticated as well as the standard observations. So the book deals climatologically with such factors as radiation and the heat balance, and phenomena special to the polar regions such as whiteout, ice crystals in the air, ageostrophic flow caused by rugged topography and sharp temperature differences at the water–ice boundaries.

All this results in a mine of information on a very large number of topics — difficult reading if too much is attempted at once, so essentially a reference book. It is an exhaustive contribution to meteorological knowledge of the polar regions. It is copiously and well illustrated with charts and diagrams, and my only criticism is that a few maps showing the names and locations of places mentioned in the text would have helped the reader.

A. G. FORSDYKE

AWARDS

L. G. Groves Memorial Prizes and Awards

The 25th award of prizes was made on Friday, 26 November 1971, at the Ministry of Defence, Whitehall, by Major and Mrs K. G. Groves. The Assistant Chief of Air Staff (Operations), Air Vice-Marshal D. G. Evans, C.B.E., presided and the ceremony was attended by the Director-General of the Meteorological Office. (See Plate VI.)

The 1971 Aircraft Safety Prize has been awarded to Flight Lieutenant D. R. Clark, RAF Regiment, formerly of Royal Air Force Coningsby. Flight Lieutenant Clark is at present serving overseas and was unable to attend this ceremony, but arrangements have been made for him to receive his prize at his present station. The citation for this award is as follows :

> 'Under existing arrangements, if an aircraft has used the Rotary Hydraulic Arrester Gear (RHAG) on landing, the hookwire is re-tensioned by an 84 lb lever pulley hoist affixed to an ACRT crash vehicle. Flight Lieutenant Clark has devised a lightweight pulley which is not only 63 lb lighter than the present hoist but which also enables the re-cycling process to be effected in about 7 minutes as compared with the present average of 12 minutes. The quicker restoration of runway availability could be vital if other aircraft were simultaneously in difficulty.
>
> He has also successfully tackled another aspect of RHAG operations in devising an Aircrew Indicator Board for conveying signals to pilots. The device consists of a rotatable illuminated sign, for attachment to an

ACRT crash vehicle, to replace the existing arrangement which requires RHAG operators to communicate with pilots by the less satisfactory medium of hand signals.

The lightweight pulley is to be adopted for all RHAG installations in the Royal Air Force and the Indicator Board is also being considered for wide application.

In devising practical improvements to 2 separate aspects of RHAG operations which materially enhance their effectiveness, Flight Lieutenant Clark has made an important contribution to flight safety in the Royal Air Force.'

The 1971 Meteorology Prize has been awarded to Mr H. H. Lamb, Senior Principal Scientific Officer, Meteorological Office, with the following citation :

'Mr Lamb has over many years carried out important studies of past climates and of the causes of climatic change. During the past year his unique and comprehensive study of the effects of volcanic dust on weather and climate was published by the Royal Society. This is of great importance at the present time since it provides an indication of the climatic effects of natural dust against which the significance of man-made dust as a climatic factor can be assessed. Mr Lamb's work is likely to be the standard reference on the subject for many years to come.'

The 1971 Meteorological Observers Award has been awarded to Squadron Leader G. F. Holbrook, D.F.C., formerly of Royal Air Force Farnborough, with the following citation :

'Squadron Leader Holbrook was OC Meteorological Research Flight from July 1966 to August 1970. Throughout this period he spared no effort to understand the scientists' requirements so that he could always give valuable advice on the flying aspects and organize aircrew support in order that these requirements were met as far as aircraft and safety considerations allowed. As a pilot his flying on research projects was always carried out with care and the highest possible accuracy and contributed both directly and by example to the success of the meteorological research flights carried out during his four years with the Flight.'

The second Memorial Award for 1971 has been awarded jointly to Flight Lieutenant T. J. Kenny and Corporal R. Cotton, Royal Air Force Akrotiri, with the following citation :

'In the Lightning flight simulator, the practice of emergencies which involve ejection presently terminates with a token pulling of the ejection handle. In reality however seat ejection does not occur until the canopy has jettisoned, and if because of some malfunction the latter does not happen the pilot is compelled to adopt an alternative drill. Although a thorough knowledge of such procedures is an integral part of pilots' continuation training the simulator makes no provision for a realistic portrayal of this particular situation.

Flight Lieutenant Kenny devoted much effort to resolving this problem and, with the assistance of Corporal Cotton, certain modifications were devised which permit the whole ejection sequence to be realistically simulated and the various emergencies properly rehearsed. In applying themselves to this problem and achieving a workable solution Flight Lieutenant Kenny and Corporal Cotton have made a valuable practical contribution to flight safety.'

NOTES AND NEWS

Retirement of Mr H. H. Lamb

On 31 December 1971 Mr H. H. Lamb retired from the Meteorological Office after more than 30 years' service.

In the earlier years of his career Mr Lamb was largely engaged in aviation forecasting, and in particular with the early stages of transatlantic aviation. He worked as a forecaster at Foynes, then one of the principal transatlantic terminals, from 1939 to 1945. However, from the earliest stage of his meteorological career Mr Lamb has contributed to research; his work on North Sea stratus in particular sprang from his experience as a forecaster at Montrose.

In 1946 Mr Lamb was asked by the Director of the Meteorological Office, Sir Nelson Johnson, to sail on the whaling ship *Balaena* to the Antarctic waters in order to study the requirements of whaling activities for meteorological services. Despite the very limited synoptic data Mr Lamb was able to develop a number of important studies on the weather and climate of the Antarctic seas from his experience of eight months in these waters and has continued to maintain a keen interest in southern-hemisphere meteorology ever since. He is a member of the international working group on Antarctic meteorology of SCAR (the Scientific Committee on Antarctic Research).

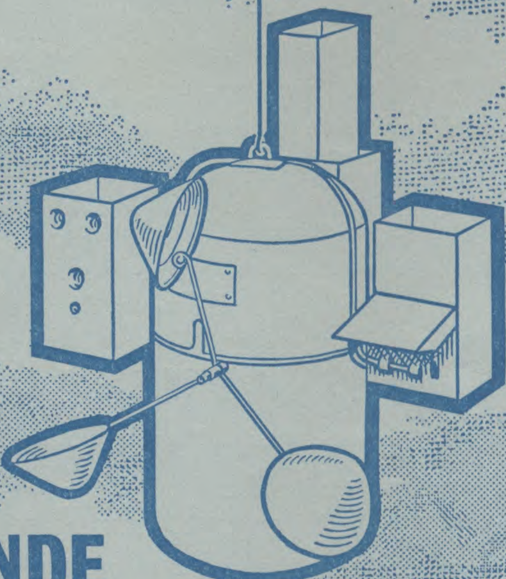
However, it is the study of variations in the general circulation of the atmosphere and of climatic changes in particular to which Mr Lamb has devoted most of his efforts during recent years. He has collected evidence on climatic change on all time scales from a wide variety of sources and by a variety of methods. His catalogues of daily weather types are widely used and his monthly mean pressure charts back to the year 1750 provide a unique means of studying the changes in general circulation. Moreover, his ability to seek out relevant historical and other evidence of climatic change, and to provide a meteorological interpretation has been particularly fruitful in building up a coherent picture of the climate of the past.

Mr Lamb was granted a special merit promotion to Senior Principal Scientific Officer in 1963 in recognition of his research work and in order that he could continue his climatic-change studies without administrative responsiblity. Mr Lamb has now accepted an Honorary Professorship at the University of East Anglia and has left the Office to take up his new post as Director of the Climate Research Unit in the School of Environmental Sciences at the University. His colleagues in the Meteorological Office take this opportunity of expressing their wishes for the fruitful continuation of his studies of climatic change in his new environment.

J. S. SAWYER

OBITUARY

It is with regret that we record the death on 23 October 1971, of Mr R. Jenner, Senior Scientific Officer, Met. O. 8.



THE METEOROLOGICAL MAGAZINE

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NOTICES

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SPRING AND AUTUMN REVERSALS OF STRATOSPHERIC WINDS OVER SCOTLAND

By R. A. EBDON

Summary. Wind data for 30 mb over Scotland have been used to illustrate the behaviour of the spring change from westerly to easterly zonal components for the years 1958–71 and for the autumn change from easterly to westerly for the years 1958–70.

Possible connections between the time of the spring reversal and both the weather of the following summer and the phase of the quasi-biennial oscillation in equatorial stratospheric winds are discussed.

It is suggested that dust from the Jan Mayen volcanic eruption in September 1970 may have influenced high-latitude stratospheric events in 1971.

Introduction. In 1902 when Teisserenc de Bort 'discovered' the stratosphere and for the following 50 years or so, meteorologists generally were of the opinion that conditions above the tropopause were comparatively calm and rather uninteresting. Then in 1952 the late Professor Scherhag reported the phenomenal 'Berlin warming'[1] and from that time on much more interest has been focused on events which take place above the tropopause. The pursuit of this interest has been made possible by the steady improvement in the number of radiosonde ascents reaching levels above 50 mb (approximately 20 km) and it has been stimulated by the increasing need to improve our understanding of stratospheric events. The need for this knowledge arises in two ways: (a) to meet the demands of those engaged in theoretical studies of the general circulation and (b) to meet the demands of those concerned with the operation of aircraft at mid-stratospheric levels.

In recent years two particular stratospheric phenomena have featured very prominently in the literature, namely, the 'quasi-biennial oscillation', which is most marked in low latitudes and the 'final warming', which is restricted to higher latitudes. Both of these phenomena are referred to in a paper entitled 'The structure and dynamics of the stratosphere' by Murgatroyd.[2]

The main purpose of this note is to draw attention to a particular aspect of the final warming. It is now a well-established fact that in winter the high-latitude stratosphere is dominated by two features — a cold circumpolar vortex with a strong westerly circulation, and a warm high centred over the Aleutian/Kamchatka area. In summer there is a complete reversal of the flow and the dominant feature in the stratosphere is a warm high centred near the North Pole, with a very light easterly drift over high latitudes. The time at which this warming of the stratosphere and reversal of the circulation takes place and the way in which it happens can and does vary quite considerably from year to year.

The spring reversal. There are many ways of examining the breakdown of the winter polar stratospheric vortex and a variety of ways of defining the time at which the event happens. One simple parameter which can be used (although no claim is made that it is better than any other) is the pentad, i.e. 5-day, mean zonal wind component at 30 mb (approximately 24 km) over Scotland. The averages of the pentad mean values for January to October for the period 1958–70 are shown in Figure 1. The winter westerlies which

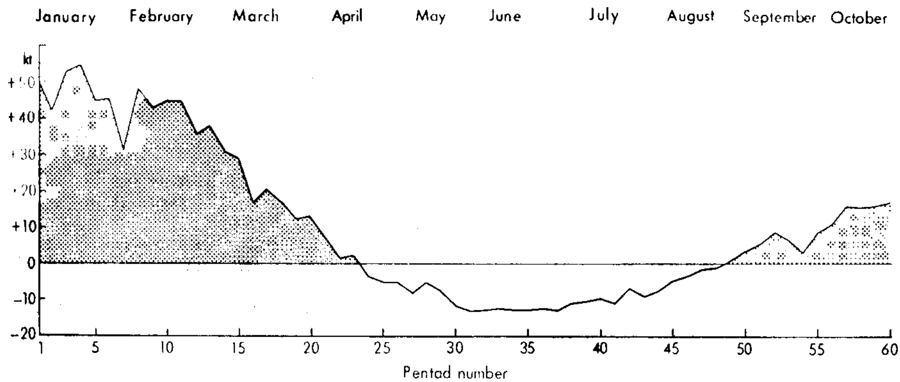


FIGURE 1—PENTAD AVERAGE ZONAL WIND COMPONENTS AT 30 mb OVER SCOTLAND FOR JANUARY–OCTOBER (1958–70)

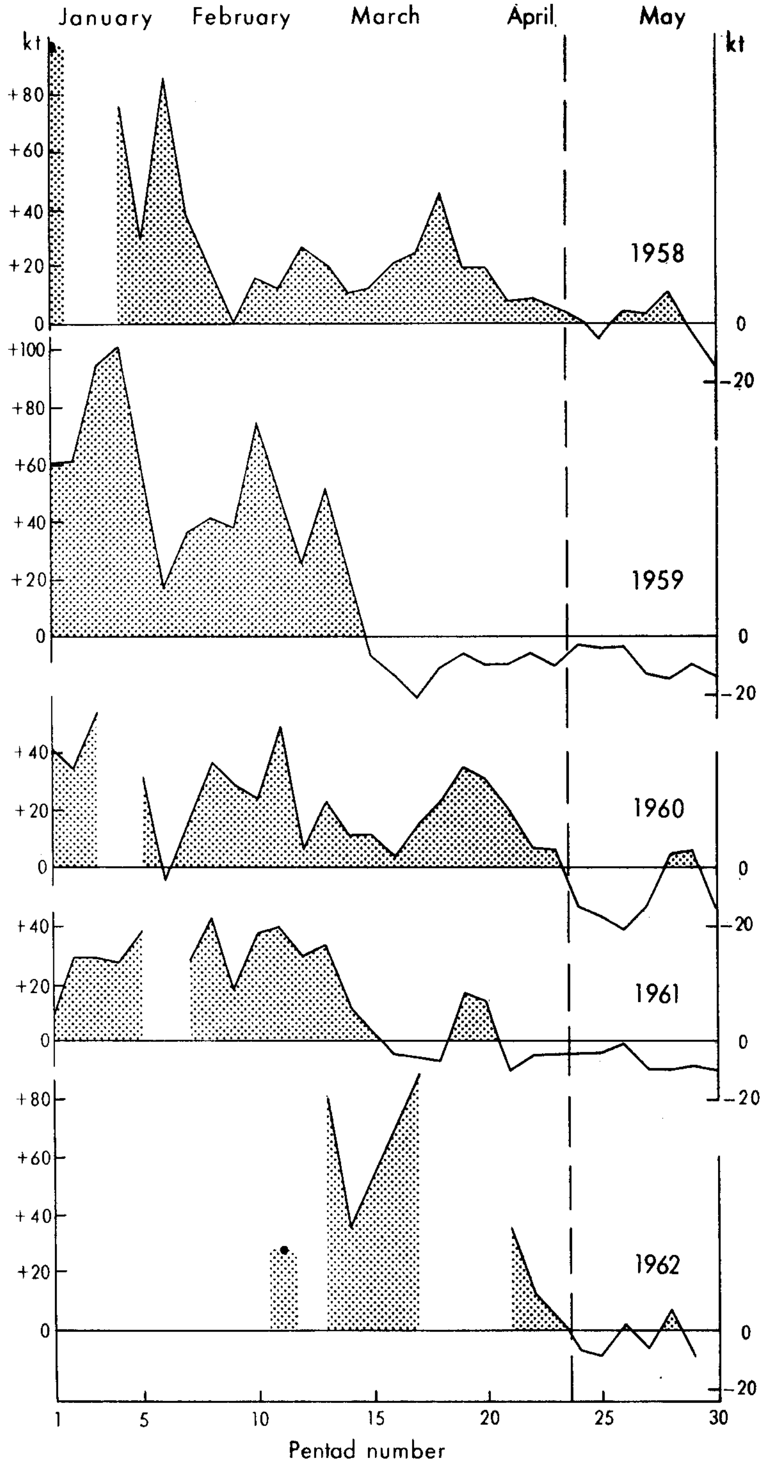
Components towards the east are positive and stippled. Data for Leuchars/Shanwell combined with Stornoway.

are stronger than 40 kt for most of January and February decrease in the spring and change to light easterly towards the end of April. The pentad average zonal component remains about 10 kt easterly throughout the summer and changes back to westerly again by late August or early September. However, as can be seen in Figure 2, the time of the change-over to easterlies does vary considerably from one year to another.

It is not easy to devise a completely satisfactory definition of the date of change, particularly when dealing with the data from only one station. Indicators which can be used are :

(a) the last pentad mean zonal wind component > 5 kt westerly,
(b) the first pentad mean zonal wind component > 5 kt easterly,
(c) the first easterly pentad mean zonal wind component, and
(d) the first pentad mean zonal wind component > 5 kt easterly, after which the pentad mean remains either easterly or less than 5 kt westerly.

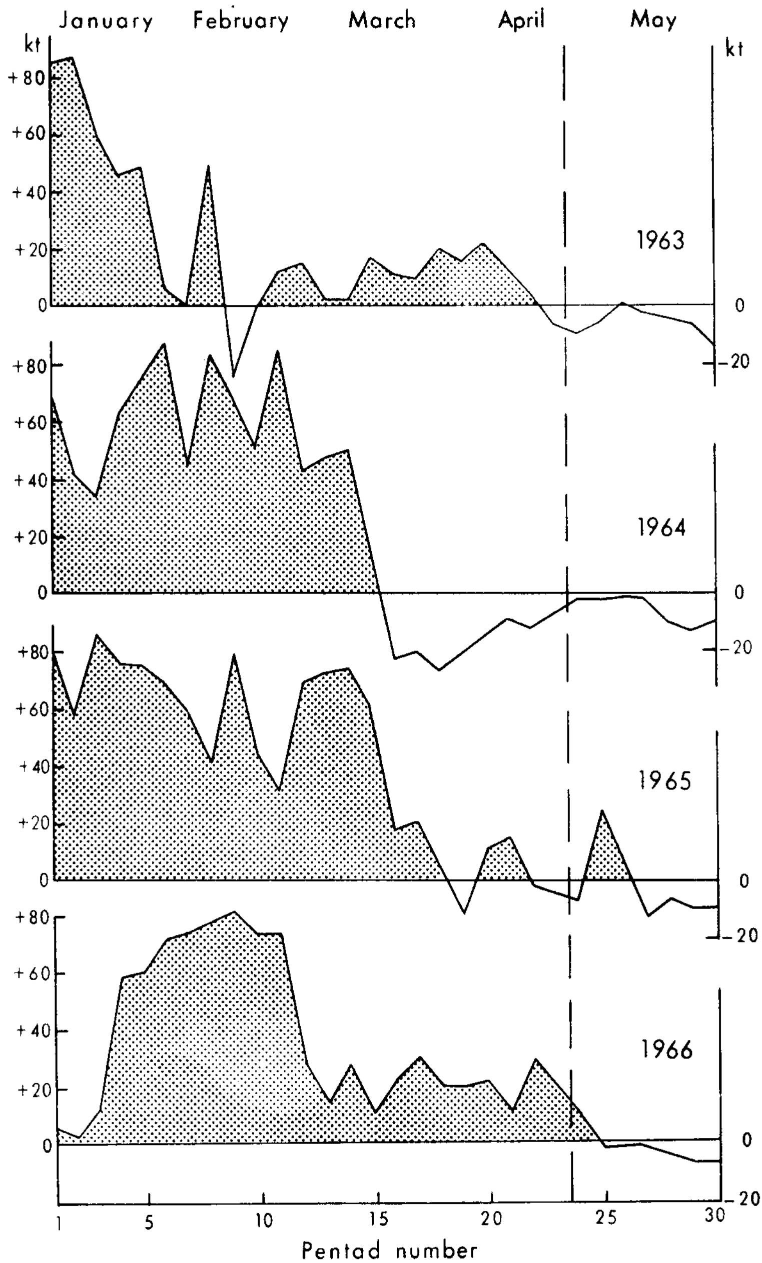
Clearly there are some years when all of these indicators suggest either an 'early' or a 'late' change-over. In such cases it is probable that other indicators using other parameters would usually — but not necessarily always — give similar indications for hemispheric events (e.g. the date when a high was first established near the North Pole or the date when 'summer' temperature values were first recorded in polar latitudes). Nevertheless



(a) 1958–62

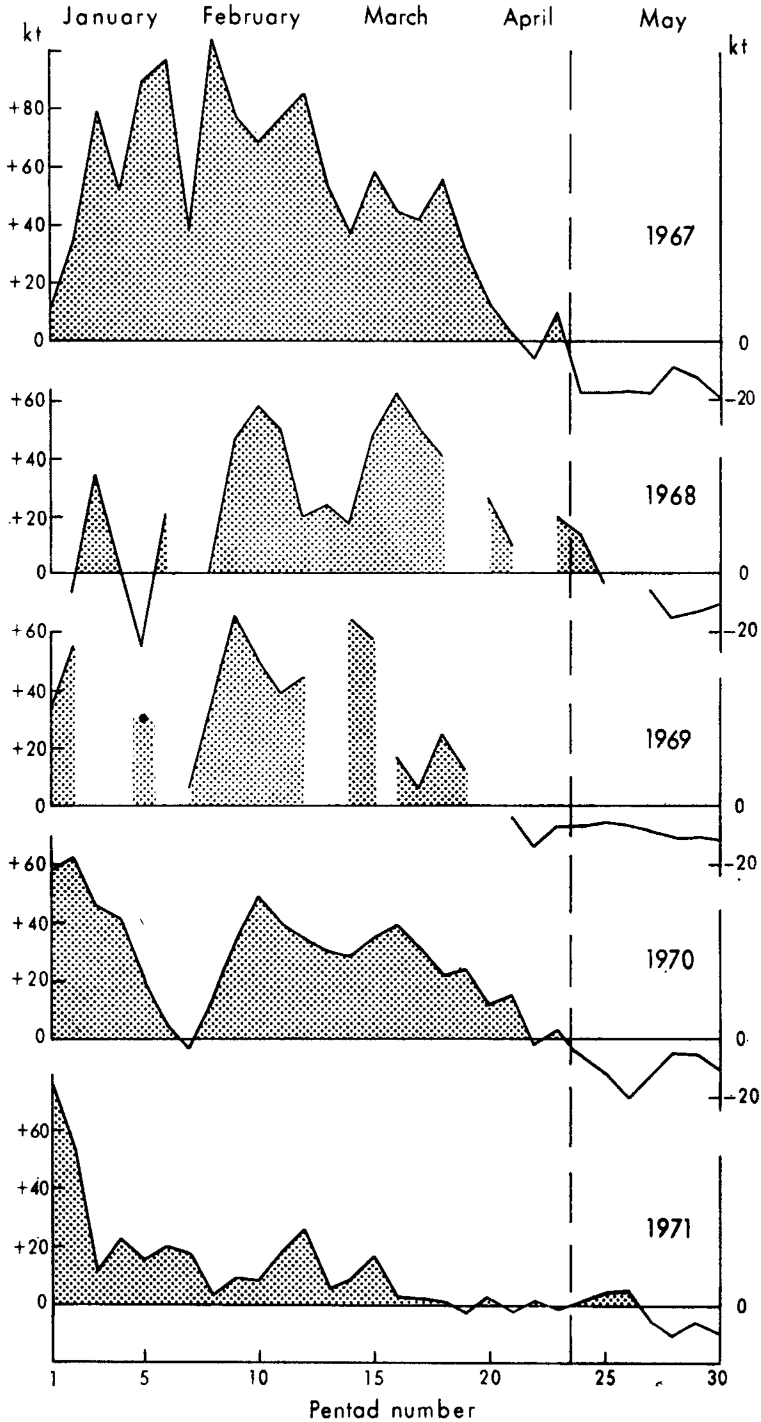
FIGURE 2—PENTAD MEAN ZONAL WIND COMPONENTS AT 30 mb OVER SCOTLAND FOR JANUARY TO MAY OF EACH OF THE YEARS 1958–71

Components towards the east are positive and stippled. The average time of the change-over to easterly is shown by the pecked line.



(b) 1963–66

FIGURE 2—*contd.*



(c) 1967–71

FIGURE 2—*contd.*

there are years when it is extremely difficult to classify the change-over as either 'early' or 'late' and these years also tend to be difficult to classify on a hemispheric scale. If the criteria listed above are applied to Figure 2 then there are years, such as 1959, 1961, 1964 and 1969, when it is seen that the easterlies are definitely established early. There are other years, such as 1958, 1960, 1962, 1966 and 1968, when the change-over can be said to be late. There is another group of years, 1963, 1965, 1967, 1970 and 1971, when it is difficult to classify the onset of the easterlies with any degree of certainty although some of these might be considered as average.

The spring reversal and possible indications of the weather of the following summer. In an earlier paper[3] it was suggested that there might be some correlation between the time of occurrence of this event in the stratosphere in spring and the weather of the following summer, as measured by Poulter's index of the summer at Kew; this index is defined as $10T + S/6 - R/5$, where, for June, July and August, T = mean temperature (°F), S = total sunshine hours, and R = total rainfall (mm). Table I shows the values of the summer index at Kew for the years 1958–70.

TABLE I—VALUE OF POULTER'S SUMMER INDEX AT KEW FOR 1958–70

	1958	1959	1960	1961	1962	1963	1964
Kew summer index	650	759	683	700	671	670	690
	1965	1966	1967	1968	1969	1970	
Kew summer index	658	670	708	647	701*	716	

* Approximate value as no north-wall screen temperatures available in June.

In the five years — 1958, 1960, 1962, 1966 and 1968 — which can be classified with reasonable certainty as a late change-over, the average summer index was 664. The four years which were quite definitely early give an average summer index at Kew of 712. As has been stressed already, it is quite difficult in some years to classify the change-over but Table II was prepared using the criteria in (d) on page 66.

TABLE II—RELATIONSHIP BETWEEN SPRING REVERSAL OF 30-mb WINDS OVER SCOTLAND AND INDEX OF THE FOLLOWING SUMMER AT KEW

Time of spring reversal	Kew summer index ≥690	689 – 671	≤670
Late	0	2 (60) (62)	4 (58) (66) (65) (68)
Average, pentads 23/24	2 (67) (70)	0	1 (63)
Early	4 (59) (64) (61) (69)	0	0

Years are indicated in brackets.

The four years with an early change-over to easterlies at 30 mb have all been followed by above-average summers. On the other hand, a late change-over has never been followed by an outstandingly good summer and, in fact, all six of the years in that category have a summer index at Kew below the 13-year average of 686.

Charts of the departure from average of the optimum summer index for a large number of stations in the United Kingdom, prepared by N. E. Davis, show that in years with an early final stratospheric warming the summer is better than average over a large part of the country (with the exception of north-west Scotland). The improvement is greatest in an area which includes east Devon, east Somerset, south Wiltshire, Dorset, Hampshire and West Sussex. In years with a late final stratospheric warming the summers are below average over most of the country except north-west Scotland. The largest departures from the average occur in Norfolk, Suffolk and Essex.

Japanese workers[4] have found that the breakdown of the stratospheric vortex and the time of the final warming provides guidance for their forecasting of the summer season in Japan.

Using an index of meridionality at 10 mb in the spring stratosphere as an indicator, Ugrjumov[5] has produced maps of the mean June pressure over temperate- and high-latitudes of Eurasia for the 'early' years 1959, 1961 and 1964 and the 'late' years 1958, 1963 and 1965. These maps varied considerably and in the 'early' years the circulation was determined largely by the ridge from the Azores anticyclone whereas in the 'late' years cyclones predominated over Europe. He found that in years which were 'average' as regards the spring reversal the surface-pressure situations fell between these two patterns.

Hemispheric charts of surface pressure and their anomalies have been produced for the months of June, July, August and September, based on years when the spring change-over of 30-mb winds over Scotland was (a) early, (b) late and (c) not possible to classify with any confidence. The years used in preparing the average charts were :

(a) 1959, 1961, 1964 and 1969.
(b) 1958, 1960, 1962, 1965, 1966 and 1968.
(c) 1963, 1967 and 1970.

These charts show that, over the British Isles, there is little difference in the average pressure charts for June but in July, August and September the ridge from the Azores anticyclone is a more prominent feature, particularly over southern England and pressures are appreciably higher than in the years following a late warming. The pressure differences (mean of 'early' years – mean of 'late' years) amount to 2 or 3 mb in July, 4 mb in August and 4 mb in September. In July the maximum difference (3 mb) is centred off south-west England but in August and September the maximum (up to 4 mb) lies between approximately 50° and 55°N.

Clearly, on the basis of the few years of available data, it is not possible to form any reliable rule for obtaining a forecast of the summer index. If the evidence of the past 13 years continues then perhaps the time will come when it will be possible to infer with some confidence that the date, and perhaps the manner, of the stratospheric-wind reversal and final warming does have a bearing on the character of the following summer in some parts of the northern hemisphere. This is, of course, a purely statistical relationship and, to date, little or no work has been done on the more interesting aspect of trying to determine the underlying physical causes for such a possible relationship.

The spring reversal and possible links with the quasi-biennial oscillation. It has been suggested that the phase of the quasi-biennial oscillation in equatorial stratospheric winds has a bearing on the time of the final warming in high latitudes.[6,7] That this may be so can be seen from Table III.

TABLE III—30-mb MONTHLY MEAN ZONAL WIND COMPONENTS AT CANTON ISLAND (2°46′S 171°43′W), 1958–67, AND AT GAN (00°41′S 73°09′E) FROM 1968 ONWARDS

	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971
							knots							
Jan.	+12·8	−51·9	−3·6	−6·6	+12·6	−54·1	+6·6	+1·4	−59·9	+29·4	−41·3	−3·5	−18·9	−0·8
Feb.	+11·1	−54·7	−5·6	+6·0	+14·4	−62·1	+4·1	−1·6	−42·3	+24·9	−36·5	+9·1	−27·0	+6·9
Mar.	+7·8	−48·5	−12·6	+8·6	+12·8	−67·1	+10·5	−8·2	−14·3	+20·9	−48·8	+19·7	−32·9	+19·0
Apr.	−9·0	−42·4	−25·7	+22·9	−1·7	−64·2	+10·3	−31·0	+12·7	+22·3	−52·6	+30·5	−46·0	+17·9
	w	e	E	W	w	E	W	E	e	w	E	W	E	W
	L	E	L	E	L	Av	E	L	L	Av	L	E	Av	

Components towards the east are positive.

E, W signify an increasing easterly or westerly component from February to March and e, w signify decreasing easterly or westerly components.

L, E or Av show whether the spring reversal at 30 mb over Scotland was early, late or average.

Kac[8] has shown that in the stratosphere there are considerable differences in the global circulation patterns depending on whether the flow is easterly or westerly in the equatorial zone. He suggests that the way in which the rearrangement of the high-latitude stratospheric circulation takes place depends on the type of circulation pattern prevailing in the tropics and that the different ways in which redistribution of air masses vary in association with the fluctuations in the equatorial stratosphere lead to differences in the zonal and meridional circulation indices in the stratosphere in higher latitudes. It does seem to be the case that if the phase of the equatorial quasi-biennial oscillation in the 30-mb zonal wind component is such that in the spring there is an increasing westerly (or decreasing easterly) component, then there is a marked tendency for the change-over to stratospheric summer easterlies over Scotland to occur early. The converse is also true and a decreasing westerly (or increasing easterly) in the spring at 30 mb over the equator usually appears to be associated with a later-than-usual reversal to easterly at 30 mb over Scotland. The outstanding exception is 1966 when the phase of the equatorial quasi-biennial oscillation at 30 mb was unquestionably decreasing easterly but the change-over to summer easterlies at 30 mb over Scotland was certainly not early. In 1963, 1967 and 1970 the change-over occurred very close to the average date and, as mentioned earlier, these years are difficult to classify as either 'early' or 'late'.

On the evidence for the years 1958–70 it might have been expected that the spring reversal would have occurred early in 1971 as the equatorial winds showed an increasing westerly component. However, Figure 2 shows that this did not happen and it is clear that the curve for 1971 bears little resemblance to those for the other years. The 30-mb pentad mean zonal wind components were comparatively light for most of the period and exceeded 20 kt in only four pentads. From mid-March to late May the winds were very light indeed — sometimes easterly and sometimes westerly. In some respects it might be argued that the 1971 final warming was early if considered on a hemispheric scale. In the second half of March there was a very marked warming (of about 30 degC) over the Russian Arctic and there was a high centre near the North Pole. There was also a warming over the Canadian Arctic but it was noticeable that the temperatures did not quite reach summer values in April. The events leading up to the breakdown of the stratospheric vortex and the final warming in 1971 were certainly most unusual and no doubt papers will appear describing in detail the synoptic and dynamical events which took place.

The 1971 spring reversal and possible effects of volcanic dust. At this point it is tempting to speculate whether the unusual course of events in the stratosphere might have been influenced by an event which occurred in the previous year. In September 1970 there was a volcanic eruption at Jan Mayen (71°N 8°W) and it has been suggested by Lamb and Parker[9] that the dust cloud from this eruption was probably located above the 10-mb (30 km) level. Their method of locating the height of the dust cloud by examining gradient winds is very subjective and consequently some doubt remains as to the height reached by the dust in the days immediately following the eruption. If their estimate is correct then volcanic dust could have been present in the high-latitude upper stratosphere during the early months of 1971.

When Mount Agung, Bali (8°S 115°E), erupted in 1963 meteorologists were provided with very definite evidence and measurements concerning the dust cloud[10,11] and it was established that the presence of the dust had a very noticeable effect on the stratospheric temperatures.[12,13] Sparrow[14] has suggested that the observed rise in temperature may have been contributed to by a change in the phase of the quasi-biennial oscillation associated with the solar minimum or, on the other hand, that the dust may have been responsible for the observed changes in the behaviour of the oscillation. As the dust from this eruption reached 20 km it is reasonable to assume that temperatures near that level (i.e. 50 mb) would be higher owing to increased absorption of solar radiation. In fact the 50-mb monthly mean temperatures at Ascension Island (07°58'S 14°24'W) for September 1963 (the annual maximum) and for March 1964 (the annual minimum) were both warmer than usual and were both extreme values. The average rise in 50-mb monthly mean temperatures from the minimum (January–March) to the maximum (June–September) is 5·8 degC but in 1963 the rise amounted to 14·2 degC and much of this anomaly was almost certainly due to the presence of dust from the Bali eruption. In the case of the Jan Mayen eruption there was no sampling of the dust by aircraft and there is much less evidence regarding the height and extent of the dust cloud. However, if the dust did rise to 10 mb as suggested by Lamb and Parker then it is possible that its presence had an effect on stratospheric temperatures.

In the absence of any direct measurement of the height, composition and extent of the dust it is not possible confidently to associate any observed temperature anomalies in the stratosphere with the presence of the dust from Jan Mayen as was done following the Bali eruption. However, in assembling the relevant facts it should be remembered that the dust from Jan Mayen was ejected into the stratosphere at 71°N and that the area north of this represents only about 3 per cent of the earth's surface. Mean meridional motions in the stratosphere are very small indeed but it is known that at these latitudes, in winter in particular, there are eddy motions capable of transporting stratospheric particles over wide bands of latitude. Consequently, whilst some of the dust would be transported into lower latitudes some would probably be carried polewards and remain in the circulation around the vortex. Any volcanic dust in the high-latitude stratosphere during the winter months would also, of course, be subjected to some very pronounced vertical motions associated with 'sudden warmings'; it is known that one such warming took place in late December 1970 / early January 1971. If the dust did not reach levels above 30 mb in the days immediately after the eruption then particles in the lower stratosphere could well be carried to higher levels in such a warming. Nevertheless, in spite of the uncertainties concerning some of the statements made, it may well be possible that a relatively small quantity of dust injected into the high-latitude stratosphere is capable of having a significant effect on stratospheric temperatures in high latitudes.

The effect on the 30-mb temperatures in high latitudes (below the level of the top of the dust veil) could be to reduce the temperature as a result of increased absorption of solar radiation at the higher levels. As mentioned earlier, the stratospheric temperatures over the Canadian Arctic did show a warming in March but the values recorded were some 5 degC below the summer values to be expected after a warming. During the first few months of the year the high-latitude temperature patterns at 30 mb are subject to wide variations both within a particular month and from one year to another but by May the monthly mean chart always shows a fairly typical summer pattern and so comparison of different years is easier then. It is of interest to note that at two stations in the Canadian Arctic (see Table IV) the monthly mean temperatures in May, June and July 1971 were well below the 10-year (1960–69) average.

TABLE IV—30-mb TEMPERATURES AT ALERT (82°30′N 62°20′W) AND EUREKA (80°00′N 85°56′W)

Station	Month	T_m	σT	δT	
		degrees Celsius			
Alert	May	−42·3	2·2	−3·2	equal to previous extreme in 1957
	June	−40·0	0·9	−2·4	extreme
	July	−39·8	0·6	−1·2	equal to previous extreme in 1955
Eureka	May	−42·5	2·2	−3·6	equal to previous extreme in 1955
	June	−39·9	1·0	−2·2	coldest apart from extreme of −42·7 in 1955
	July	−39·9	0·5	−1·1	coldest apart from extreme of −41·8 in 1955

T_m is monthly average for 1960–69. σT is standard deviation of the monthly means for the period 1960–69. δT is the departure of the monthly mean for 1971 from the 1960–69 average.

In most cases the negative anomalies in 1971 were extremes or equal to previous extremes but, as indicated in the table, if a previous monthly mean anomaly equalled or exceeded the 1971 value then it occurred in the early years of the record when the hours of ascent were different (in June 1957 there was a change from 03 and 15 GMT to 00 and 12 GMT). From 1960 the records at both stations are completely homogeneous and all the 1971 anomalies quoted in Table IV are cold extremes for that 11-year period. It is perhaps more significant that the 30-mb monthly mean temperature charts for May, June and July for the years since 1964 suggest that this anomalous cold was not confined to the Canadian Arctic. In May and June 1971 the highest temperatures in the warm area near the pole were lower than in most of the other years for which charts are available and in July 1971 the area enclosed by the −40°C isotherm appears to be appreciably smaller than in the other years.

Obviously this evidence is somewhat circumstantial, and there are some who will reject it, but it is worth bearing in mind that the presence of volcanic dust might have influenced the final warming and the stratospheric wind reversal in the spring of 1971 and also that it may have contributed to the three months of below-normal 30-mb temperatures in high latitudes from May to July 1971. It may even be that but for the presence of the dust the final warming would have taken place much earlier and this would add support to the idea that an increasing westerly phase of the quasi-biennial oscillation at 30 mb is associated with an early spring reversal of stratospheric winds over Scotland. Unfortunately it is unlikely that any direct measurements of the dust cloud will become available to prove or disprove this suggestion but it does seem to be more than coincidental that arguments can be advanced which suggest that the dust reached levels above 30 mb, that the mid-stratospheric temperatures over the Arctic in May, June and July 1971 should be colder than usual and also that the onset of stratospheric easterlies at 30 mb over Scotland should have taken place in what appears to have been a very unusual way.

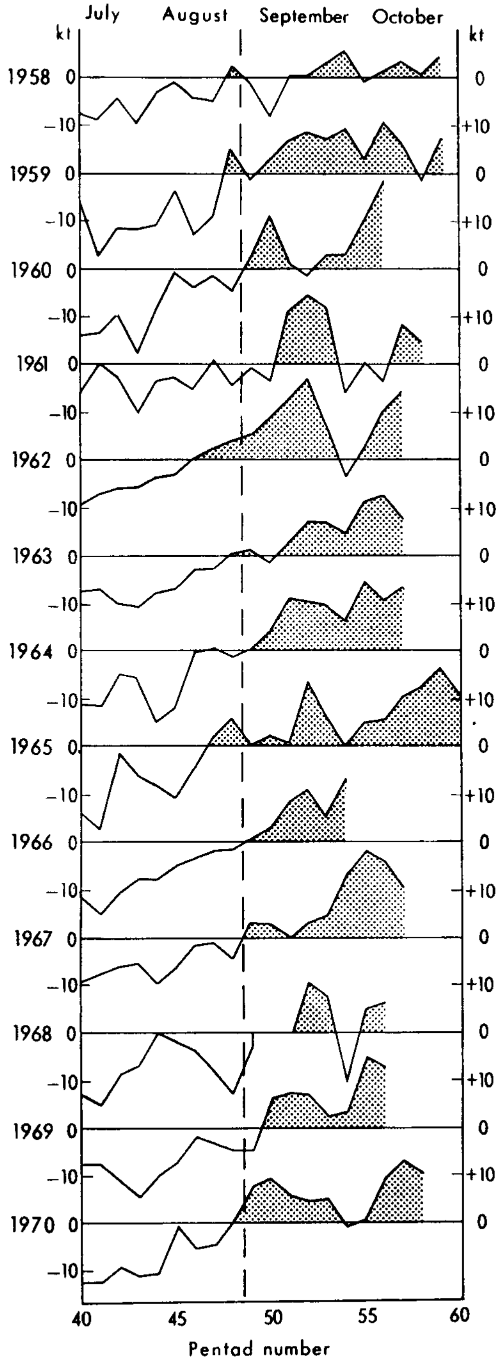


FIGURE 3—PENTAD MEAN ZONAL WIND COMPONENTS AT 30 mb OVER SCOTLAND FOR JULY TO OCTOBER FOR EACH OF THE YEARS 1958–70

Components towards the east are positive and stippled. The average time of the change-over to westerly is shown by the pecked line.

The autumn reversal. The average 30-mb pentad zonal wind components in Figure 1 show that over Scotland the summer easterlies are replaced by westerlies around late August or early September. Although there is some year-to-year variation in the time at which this autumn change-over takes place it can be seen from Figure 3 that it is a much more regular event than the spring reversal. Perhaps it could be said that the westerlies were established early in both 1962 and 1965, and it may or may not be significant that in 1961 and 1968 there were brief periods when easterlies were re-established in late September. However, in most years the change-over takes place within a short period near the average time of late August and, perhaps because of this more regular behaviour, the autumn reversal has so far attracted less interest than the spring reversal. The behaviour of the polar-night stratospheric vortex in autumn does, apparently, provide the Japanese long-range forecasters with an indicator for the following winter.[15] As more data become available, further study of the autumn reversal may reveal interesting stratospheric/tropospheric relationships about which little is known at present.

REFERENCES

1. SCHERHAG, R.; Die explosionsartigen Stratosphärenerwärmungen des Spätwinters 1951/1952. *Ber Dt Wetterd U.S. Zone, Bad Kissingen*, 1952, pp. 51–63.
2. MURGATROYD, R. J.; The structure and dynamics of the stratosphere. CORBY, G, A, (editor); The global circulation of the atmosphere. Joint conference, 25–29 August 1969. London, Royal Meteorological Society and Boston, Mass., American Meteorological Society, 1970, pp. 159–195.
3. EBDON, R. A.; A summer predictor? *Weather, London*, **21**, 1966, p. 259.
4. WADA, H. and ASAKURA, T.; Studies on the seasonal forecasting of the summer season in Japan (Part I).* *J Met Res, Tokyo*, **19**, 1967, pp. 124–159.
5. UGRJUMOV, A. I.; The biennial oscillation in the troposphere over temperate latitudes in the northern hemisphere.* *Met Gidrol, Leningrad*, **12**, 1968, pp. 24–32.
6. LABITZKE, K.; On the mutual relation between stratosphere and troposphere during periods of stratospheric warmings in winter. *J Appl Met, Lancaster, Pa*, **4**, 1965 pp. 91–99.
7. HOEBBEL, W.; Schwankungen des totalen Ozongehaltes der Atmosphäre im Zusammenhang mit stratosphärischen Erwärmungen.* 75 Jahre Meteorologisches Observatorium Potsdam: 1892–1967, Potsdam, Meteorologischer Dienst der Deutschen Demokratischen Republik, 1969, pp. 108–111.
8. KAC, A. L.; The two-year periodicity in the equatorial stratosphere and the general circulation of the atmosphere.* *Met Gidrol, Leningrad*, **6**, 1964, pp. 3–10.
9. LAMB, H. H. and PARKER, B. N.; Volcanic eruption in Jan Mayen, September 1970. *Weather, London*, **26**, 1971, pp. 263–267.
10. MOSSOP, S. C.; Volcanic dust collected at an altitude of 20 km. *Nature, London*, **203**, 1964, pp. 824–827.
11. DYER, A. J. and HICKS, B. B.; Stratospheric transport of volcanic dust inferred from solar radiation measurements. *Nature, London*, **208**, 1965, pp. 131–133.
12. EBDON, R. A.; Possible effects of volcanic dust on stratospheric temperatures and winds. *Weather, London*, **22**, 1967, pp. 245–249.
13. NEWELL, R. E.; Stratospheric temperature change from the Mt. Agung volcanic eruption of 1963. *J Atmos Sci, Lancaster, Pa*, **27**, 1970, pp. 977–978.
14. SPARROW, J. G.; Stratospheric properties and Bali dust. *Nature, London*, **229**, 1971, p. 107.
15. ASAKURA, T., KUBOKI, K. and KUBOTA, I.; Studies on the seasonal forecasting of the winter season in Japan.* *J Met Res, Tokyo*, **18**, 1966, pp. 271–296.

* Translation available in Meteorological Office Library, Bracknell.

551.515.1

A STUDY OF RAPID CYCLONIC DEVELOPMENT OVER THE CENTRAL MEDITERRANEAN IN SEPTEMBER 1969

By L. DENT and D. C. MASON

Summary. An account is given of the development of a disastrous late summer storm with gale-force winds over the central Mediterranean. The case study is used to illustrate the part played by several dynamical factors in cyclogenesis.

Introduction. The seasonally settled weather over the central Mediterranean, which normally breaks down in October, was brought to an abrupt end on 23 September 1969 by the sudden development of a depression and gale-force winds. Following a day and a night of prolonged heavy rain (Figure 1) at Malta the wind veered sharply to north-easterly and increased to gale force, producing conditions known locally as a gregale. Heavy seas were soon whipped up by the storm which caused considerable damage to shipping around the island, particularly to small craft moored in the many

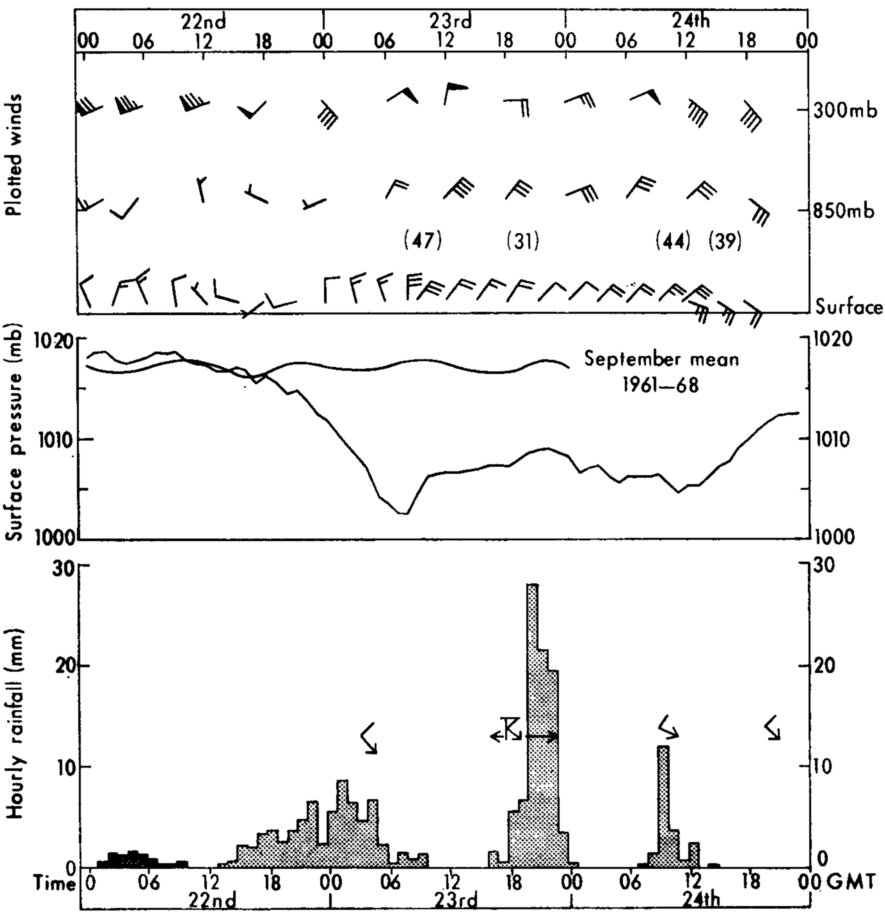


FIGURE 1—CHANGES IN WIND, PRESSURE AND RAINFALL AT LUQA ON 22–24 SEPTEMBER 1969

International plotting symbols are used. Figures in brackets in top diagram are maximum surface gusts.

creeks facing north-east. As the wind veered, the 22 000-ton tanker *Angel Gabriel* was driven on to rocks off St Thomas's Point, at 08 GMT on the 23rd, and broke in two with the loss of one crew member. The remainder of the crew were brought safely ashore in a joint civil and military rescue operation.

Heavy rain fell over Malta between 22 and 25 September when 194·7 mm were recorded at Luqa, of which 154 mm fell in the 36 hours after 12 GMT on the 22nd (Figure 1). Taken together, 22 and 23 September 1969 were the two wettest consecutive days in any month at Luqa since records began in 1946.

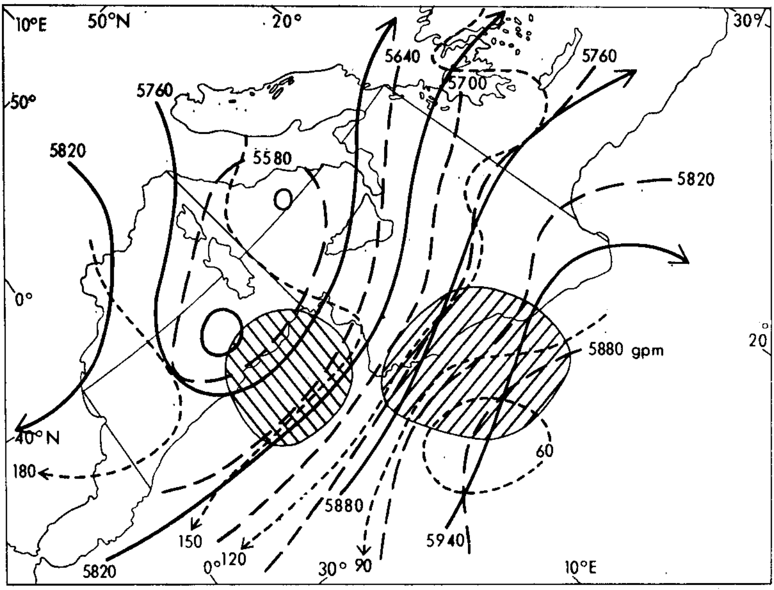
The evolution of this storm was an extremely complex process, as will be described later, but the authors' conclusions are that it formed quite suddenly to the east or south-east of Malta in the early hours of 23 September. It remained slow moving during the 23rd and began to move westwards on the 24th, crossing south-westwards into southern Tunisia on the 25th. The widespread devastation and loss of life from flooding which then occurred in Tunisia and Algeria has been described by Winstanley.[1]

Synoptic evolution. Two of the major contributing factors which led to the development of this remarkable storm were the south-eastward movement from Sardinia of a deep low in the upper layers of the troposphere, which passed to the south of Malta, and the movement from Libya to the Gulf of Sidra of a mobile, desert depression in the lower atmospheric layers. Other important factors were the non-adiabatic heat supply from the sea surface and latent-heat releases during heavy rain.

Associated with the upper low was a strong field of vorticity advection, which would be accompanied by ascending motion, and which advanced ahead of the centre. Simultaneously the desert depression, moving east-north-east, was instrumental in maintaining a thermal ridge and warm air advection field over the Gulf of Sidra and the Ionian Sea, and would also be accompanied by ascending motion where the warm advection was a maximum.[2]

The evolution of these synoptic features is shown in Figures 2–5, from which it will be noted that the shaded area of vorticity advection began to overtake the warm air advection field soon after 12 GMT on the 22nd. By 00 GMT on the 23rd there was an appreciable overlap of the two advection fields to the east and south-east of Malta. On the surface chart for 00 GMT on the 23rd (not shown) a cold front separated cool maritime north-west winds over Tripolitania from warmer desert air over Cyrenaica and extended northwards over the Ionian Sea to Sicily. This front had moved south-east across Libya during the previous 24 hours but had remained almost stationary near Sicily. A broad isobaric trough and light winds covered the Ionian Sea and Malta.

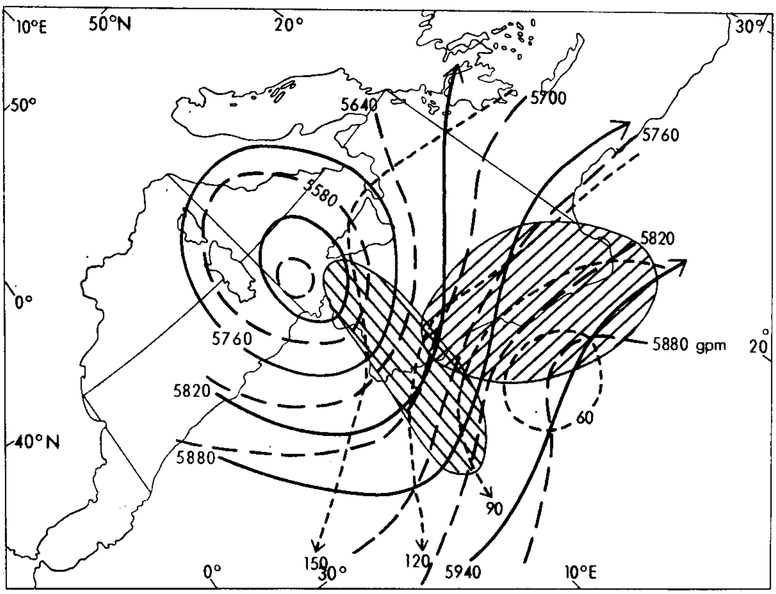
The difficulty at this stage of the analysis is the absence of observations to the south-east of Malta, and for this reason it is not possible to specify precisely where the depression developed, but it seems that a new separate circulation formed in the lower layers of the atmosphere between 00 and 03 GMT somewhere to the east or south-east of Malta. Three-dimensional analysis tends to support this supposition which is also consistent with observations of pressure and wind at Malta (Figure 1) and over Sicily on intermediate charts.



Area of vorticity advection — Area of warm-air advection

FIGURE 2—CONTOURS AND THICKNESS AT 00 GMT ON 22 SEPTEMBER 1969

- - - 1000-mb contours ——— 500-mb contours
— — 500–1000-mb thickness



Area of vorticity advection — Area of warm-air advection

FIGURE 3—CONTOURS AND THICKNESS AT 12 GMT ON 22 SEPTEMBER 1969

- - - 1000-mb contours ——— 500-mb contours
— — 500–1000-mb thickness

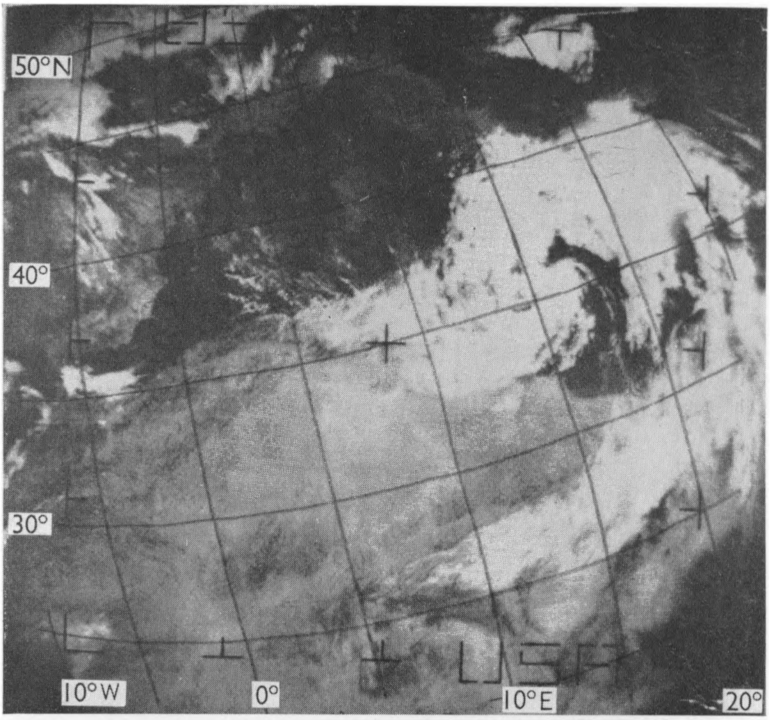


PLATE I—ESSA 8 SATELLITE PICTURE FOR 09 GMT ON 23 SEPTEMBER 1969

See page 82.

PLATE II—THE METEOROLOGICAL OFFICE COLLEGE AT SHINFIELD PARK, WHICH WAS OPENED IN OCTOBER 1971

(a) Classroom

PLATE II—*continued*

(b) Library

To face page 81

PLATE II—*continued*

(c) Observation area with enclosure in background

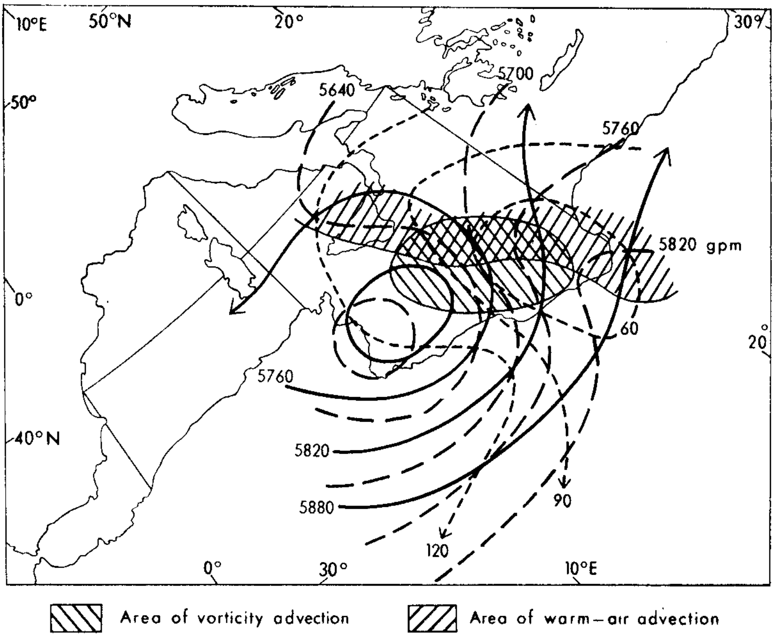


FIGURE 4—CONTOURS AND THICKNESS AT 00 GMT ON 23 SEPTEMBER 1969

– – – 1000-mb contours ——— 500-mb contours

— — 500–1000-mb thickness

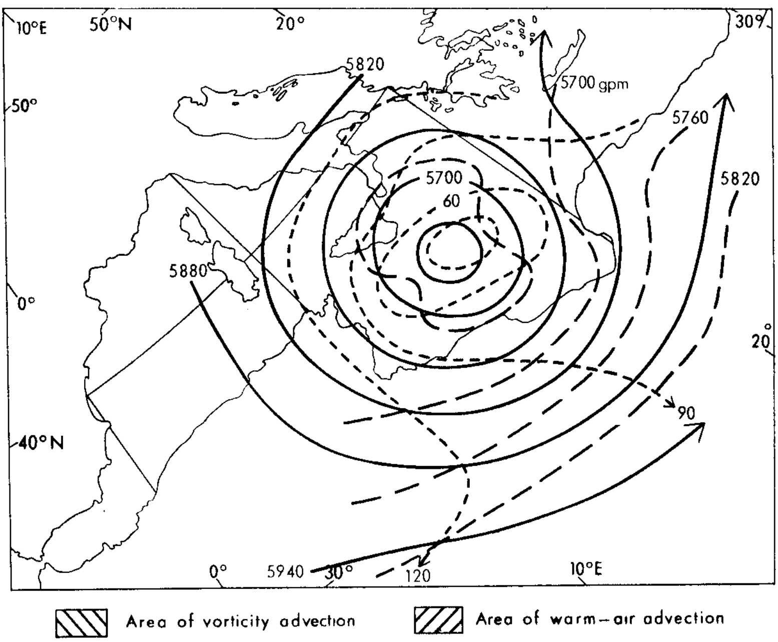


FIGURE 5—CONTOURS AND THICKNESS AT 12 GMT ON 23 SEPTEMBER 1969

– – – 1000-mb contours ——— 500-mb contours

— — 500–1000-mb thickness

In the event, on the 03 GMT chart for 23 September a deep depression appeared over the central Mediterranean to the east of Malta (Figure 6). The desert depression then moved away across Cyrenaica and filled. The ESSA 8 satellite picture for 09 GMT on 23 September (Plate I) shows the vortex to the east of Malta with an extensive mass of cloud extending into Tunisia, and the frontal band of cloud trailing south-westwards across Cyrenaica. The new centre quickly became concentric with the upper low, and deepening ceased. Considerable convective activity remained however to give further heavy rainfall, including over 80 mm in 5 hours at Malta late on the 23rd, and subsequently to devastate a large part of Tunisia and Algeria.

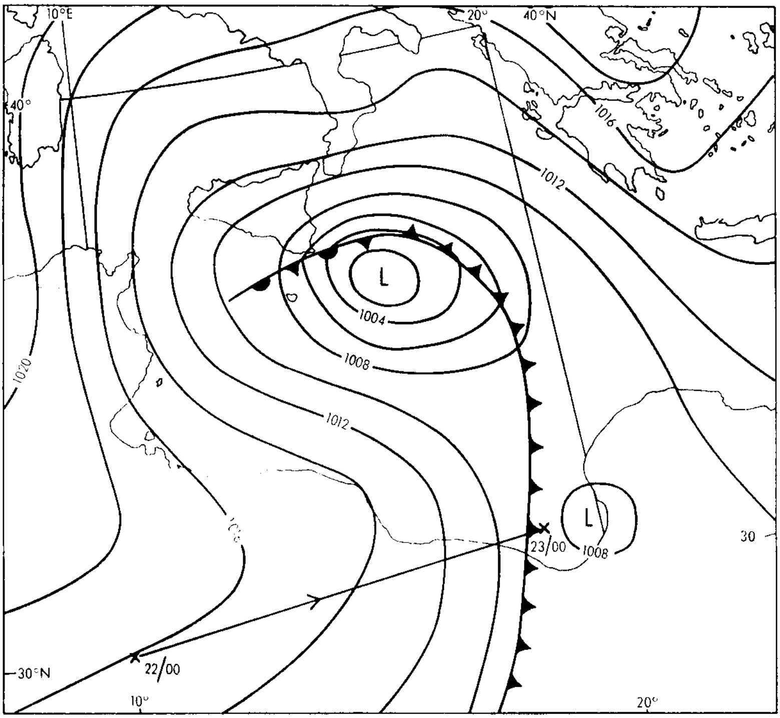


FIGURE 6—SURFACE CHART AT 03 GMT ON 23 SEPTEMBER 1969
Arrow shows 24-hour movement of desert low.

Dynamical aspects. Whilst describing the synoptic evolution it is instructive to refer to the dynamical factors which are responsible for changes in vorticity at sea level. Petterssen[2] has derived an equation as follows :

$$\frac{\mathrm{d}}{\mathrm{d}t} Q_{10} = -\mathbf{V}_5.\nabla Q_5 - \frac{R}{f}\nabla^2\left[-\frac{g}{R}(\mathbf{V}_{10}.\nabla h_{TT}) + S + H\right] \quad \ldots (1)$$

where S and H are meaned over the layer 1000–500 mb and

$$S = \text{the static stability term, } \omega(\Gamma_a - \Gamma)\log\frac{1000}{500},$$

$$H = \text{the non-adiabatic heating term, } \frac{1}{c_p}\frac{\mathrm{d}W}{\mathrm{d}t}\log\frac{1000}{500},$$

V is the wind velocity on an isobaric surface, Q is absolute vorticity and h_{TT} is the 1000–500-mb thickness field. ∇, ∇^2, are operators denoting respectively the gradient and Laplacian of a function on the isobaric surfaces. Subscripts 5 and 10 refer to 500 mb and 1000 mb respectively.

Equation (1) is similar to equation (3) in a recent paper by Morris[3] but omits terms representing vorticity advection at 1000 mb and vertical advection of vorticity, and twisting terms. For a full explanation the reader is referred to Chapter 16 of Petterssen,[2] in particular to his equation 16.2.11 from which the immense complexity of development is evident and at sea level emerges as an imbalance between the vorticity advection at the level of non-divergence and the Laplacian of the thermal components. Thus briefly equation (1) implies that sea-level cyclogenesis is favoured by: advection of cyclonic vorticity at 500 mb, a maximum of warm air advection, an unstable environment and the release of latent and sensible heat.

During 21 and 22 September (see Figures 2 and 3) the desert depression moved east-north-eastwards across north Africa and by 12 GMT on the 22nd had passed to the south of Wheelus Field in Libya and was approaching the Gulf of Sidra, with a prominent area of warm air advection extending northwards from the low centre towards Malta. The prominence of the thermal advection is demonstrated on the hodograph for Wheelus Field in Figure 7. During the same period the upper tropospheric cold vortex had moved south-east from Spain and by 12 GMT on the 22nd the 500-mb vortex was south-east of Sardinia with a trough to the south. The probable area of cyclonic vorticity advection is depicted in Figure 3.

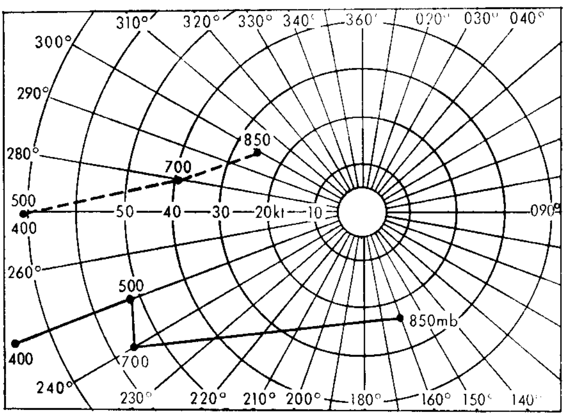


FIGURE 7—HODOGRAPH ANALYSIS FOR WHEELUS FIELD IN SEPTEMBER 1969
——— 12 GMT on 22nd   – – – 00 GMT on 23rd

It will be seen that the independent movement of the upper trough and the Libyan depression would lead to an increase in the area of overlapping of the warm air advection field by the cyclonic advection aloft. In accordance with equation (1) this implies an increase of cyclonic vorticity at sea level. This overlapping of upper and lower systems would also enhance the amount of upward motion.[3] Accordingly the air in the middle and lower troposphere might be expected to cool adiabatically so that by 00 GMT on the 23rd (Figure 4) it is likely that a near moist adiabatic lapse rate was present in the environmental air over a limited region just east or south-east of Malta.

Figure 8 depicts the upper air sounding for Wheelus Field at 12 GMT on 22 September and for Malta at 00 GMT on the 23rd. The Wheelus sounding is representative of the air within the thermal ridge (Libyan cyclonic system) and it is important to note the potential instability shown by the decrease of wet-bulb temperature upwards to 700 mb. The Malta sounding was colder and more moist than Wheelus and also unstable to sea temperatures of 23°C. If it be assumed that the Malta sounding above 600 mb was representative of the upper cold trough, the overlapping of the warm advection field by the upper cyclonic vorticity advection field at 00 GMT on 23 September was synonymous with the overrunning of the Wheelus lower air mass by the Malta upper air mass. In view of the enhanced upward motion within this composite environment it would not take long to remove the dry layer between 800 and 600 mb through adiabatic cooling and also perhaps by evaporation of rain falling from upper levels. Hence the potential instability of the environment would be released with copious supplies of sensible and latent heat within a relatively small area east and south-east of Malta. Thus it may be seen that all the terms in equation (1) were probably combining to produce sea-level cyclogenesis at 00 GMT on the 23rd.

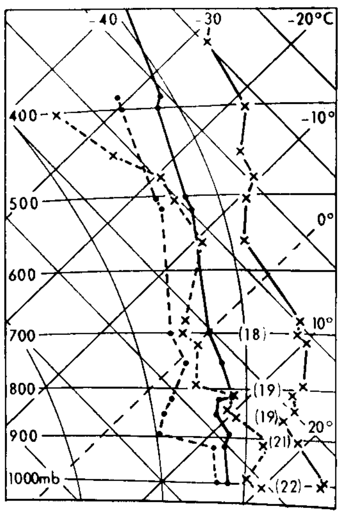


FIGURE 8—UPPER AIR ASCENTS FOR WHEELUS FIELD AND MALTA IN SEPTEMBER 1969

Wheelus Field, 12 GMT on 22nd
x——x Temperature
x– – –x Dew-point

Malta, 00 GMT on 23rd
·——· Temperature
·– – –· Dew-point

The evidence of surface pressure changes supports the theoretical expectations, with the accelerated fall of pressure first observed at Malta at 00 GMT on 23 September and subsequently in Sicily as the area of development moved towards Malta and Sicily, and culminated in the rapid formation of a cyclonic storm centre to the east or south-east of Malta.

Figure 5 shows the synoptic situation at 12 GMT on the 23rd. It will be seen that 'development' had also occurred at 500 mb which probably reflects the role of the feedback terms which were neglected in equation (1).

Acknowledgement. The authors wish to thank Mr R. M. Morris for his help in writing the section on dynamical aspects.

REFERENCES

1. WINSTANLEY, D.; The north African flood disaster. *Weather, London*, **25**, 1970, pp. 390–403.
2. PETTERSSEN, S.; Weather analysis and forecasting. Volume 1. Motion and motion systems. 2nd edn. New York, McGraw-Hill, 1956, Chapter 16.
3. MORRIS, R. M.; A case study of the spectacular developments and movement of a February storm. *Met Mag, London*, **100**, 1971, pp. 14–27.*

551.558.21

TILTED OR ASYMMETRIC MOUNTAIN WAVES

By T. A. M. BRADBURY

Summary. Observations from gliders over Scotland show that there is sometimes a marked degree of upwind tilt to the wave front in mountainous areas. On such occasions the changes in the horizontal and vertical components of wind are not symmetrical through the wave pattern. Where the wave appears tilted the band of ascending air is relatively narrow and the horizontal component of the wind is often relatively weak. In contrast, over and particularly downstream of the wave crest the horizontal component of the wind can be unexpectedly strong. The vertical component on the lee side is then likely to be weaker than on the upwind side. The width of the zone of descending air is however wider than the zone of ascending air.

Introduction. For some years glider pilots who have flown in lee waves over Scotland have reported certain interesting features of the airflow which may be summarized as follows :

(a) The area of lift on the upwind side of the wave often appears to slope forward. The slope is sometimes so great that at high levels the wave appears to overlap the low cloud marking the next upstream wave.

(b) The horizontal wind encountered during the climb is sometimes much less than expected. Some reports suggest that the occasions of light wind occur when the vertical currents are particularly strong. This decrease of wind is occasionally so marked that the glider is able to circle for a brief period instead of flying almost directly into wind to remain on the forward side of the wave. (In normal circumstances a glider which attempts to circle in wave lift is quickly carried into the region of descending air.)

(c) The band of lift on the upstream side of the wave appears narrow, while the region of sinking air on the lee side is unusually broad.

These observations suggest that the streamlines of the airflow through the waves are not simple oscillations but part of a more complex pattern producing a tilted wave front.

There have been a number of earlier observations of tilted wave fronts and the first published diagram showing some degree of tilt appeared in a paper by Küttner.[1] Tilted waves also appear in mathematical studies by Lyra,[2] Queney,[3] Corby and Sawyer,[4] and Scorer.[5] Pao[6] computed a number of flow patterns for a stably stratified inviscid fluid and published diagrams of these patterns at various Richardson numbers. His pattern when $(Ri)=0{\cdot}833$ shows a number of features which appear to fit the observations of Scottish

* See also the correction on p. 96.

glider pilots. A simplified version of this flow pattern is given in Figure 1, with pecked lines showing the tilt of wave crests, and troughs added to emphasize the point. It may be noted that the streamlines show that the horizontal component decreases at middle levels on the upwind side of the wave, but there is also a region of much stronger flow over the crest and for a considerable distance downstream from it.

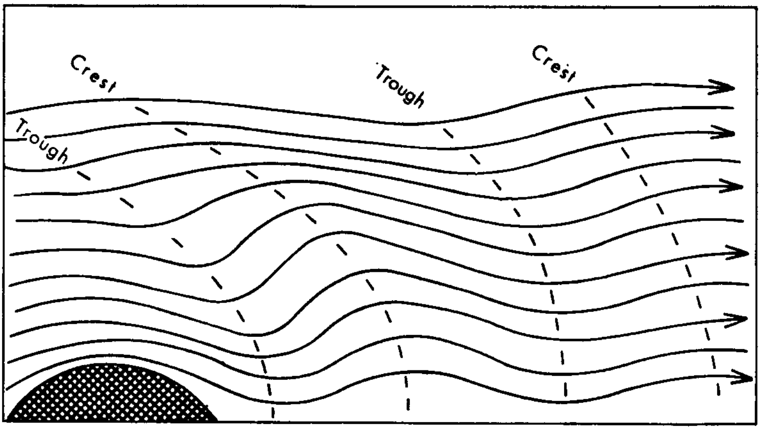


FIGURE 1—TILTED WAVE FLOW PATTERN (after Pao[6])

Glider observations over Scotland. In March 1971 an opportunity arose to make notes during a period of lee-wave flow over Scotland. A number of gliders were then visiting Portmoak, the site of the Scottish Gliding Union (56°12′N 03°20′W). On 9 and 10 March numerous flights were made to heights between 18 000 and 25 000 ft.* On the 9th a cold front passed southwards through the area and the associated increase of cloud made it impossible to keep an accurate visual plot of position. On the 10th there were sufficient areas of clear air to allow pilots to establish their positions for much of the time. In the account which follows certain important positions were established from subsequent study of a series of photographs which showed ground details identifiable on large-scale maps.

The general pattern of the waves was deduced from radio reports amplified by subsequent verbal and written descriptions. These reports were not sufficient in themselves. They formed the framework within which the more detailed personal notes made in flight could be worked up, with some confidence that the data from a single glider were not unrepresentative.

Rates of climb for this glider were calculated from stop-watch and altimeter readings and also from the barograph trace. The rate of sink of the glider was calculated from the published performance curves after correcting the indicated airspeed for changes of density. It has been assumed that the true vertical velocity of the air can be determined by adding the calculated sinking speed in still air to the achieved rate of climb. This is only practicable when the airspeed has been kept constant for the period of measurement. However,

* Conversion factors to metric units are : 1 foot = 0·3048 m; 1 knot ≈ 0·5 m/s.

in the very smooth conditions often encountered during a wave climb it is frequently possible to trim the glider to fly almost 'hands off' and then the airspeed can be kept within two knots of a constant value. Furthermore, since control movements are then at a minimum the actual sinking speed is likely to be close to that established on test. (Any control motion increases drag and hence alters the sinking speed.)

Instrumental errors were unlikely to be great enough to influence results: the airspeed indicator has been recalibrated at annual intervals and the readings were within official tolerance before and after the flight; the barograph was calibrated by an official observer and heights were taken from the curve prepared by him; the altimeter, when compared with the barograph, showed a small but consistent under-reading at high levels.

The flight on 10 March consisted of two main climbs together with a number of exploratory searches. The first climb covered the period 1036 to 1130 GMT when the nearest wave system was used to gain height for more extensive exploration. At this stage there were four other gliders, all in radio contact, using the same wave. It was therefore possible to establish the main area of rising air with some confidence. The lowest part of the wave was marked by a line of cloud just to the lee of the Ochils. Since this cloud remained almost stationary throughout the climb it is probably true to assume that the wave too was almost stationary. During the climb the band of lift was found to be tilted forward, as shown in Figure 2, which also shows the underlying cross-section of the Ochils north-west of Kinross.

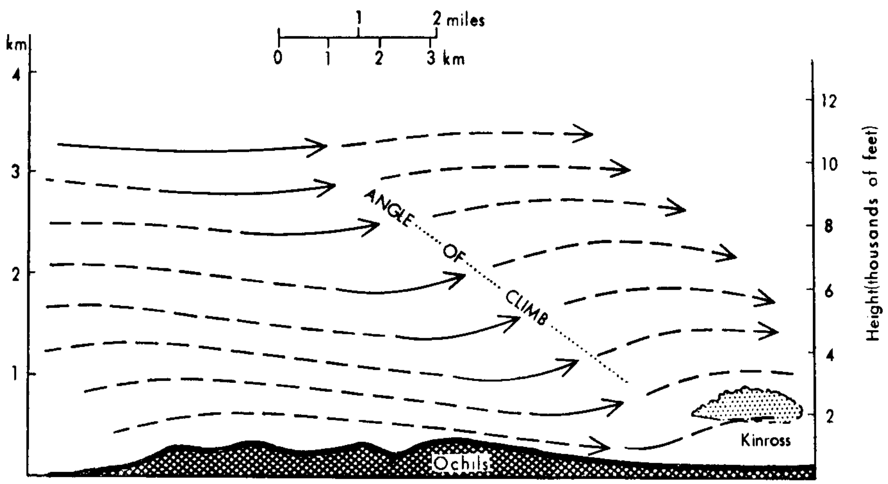


FIGURE 2—WAVE FLOW PATTERN OVER THE OCHILS NORTH-WEST OF KINROSS ON THE MORNING OF 10 MARCH 1971

Not only did the zone of rising air tilt forward with height but it was also found that the air over the leading edge of the cloud, 3000 ft above the cloud top, was descending. Had the wave front been vertical, one would have expected to find a small upward component above the leading edge of such a cloud.

From interchange of information between a number of gliders flying over an area stretching from near Leuchars in the north-east to Dollar in the south-west, it appeared that the wave flow was still rather weak and pilots were unable at that time to climb much above 12 000 ft. A change occurred after 12 GMT when lenticular clouds began to form at many levels as moister air ahead of a frontal wave began to spread over from the north-west. Figure 3 shows the surface chart with the 1000–500-mb thickness lines superimposed. Until that time there had been little visible indication of the location of lee waves but during the afternoon the positions were clearly marked by some very extensive lenticular clouds.

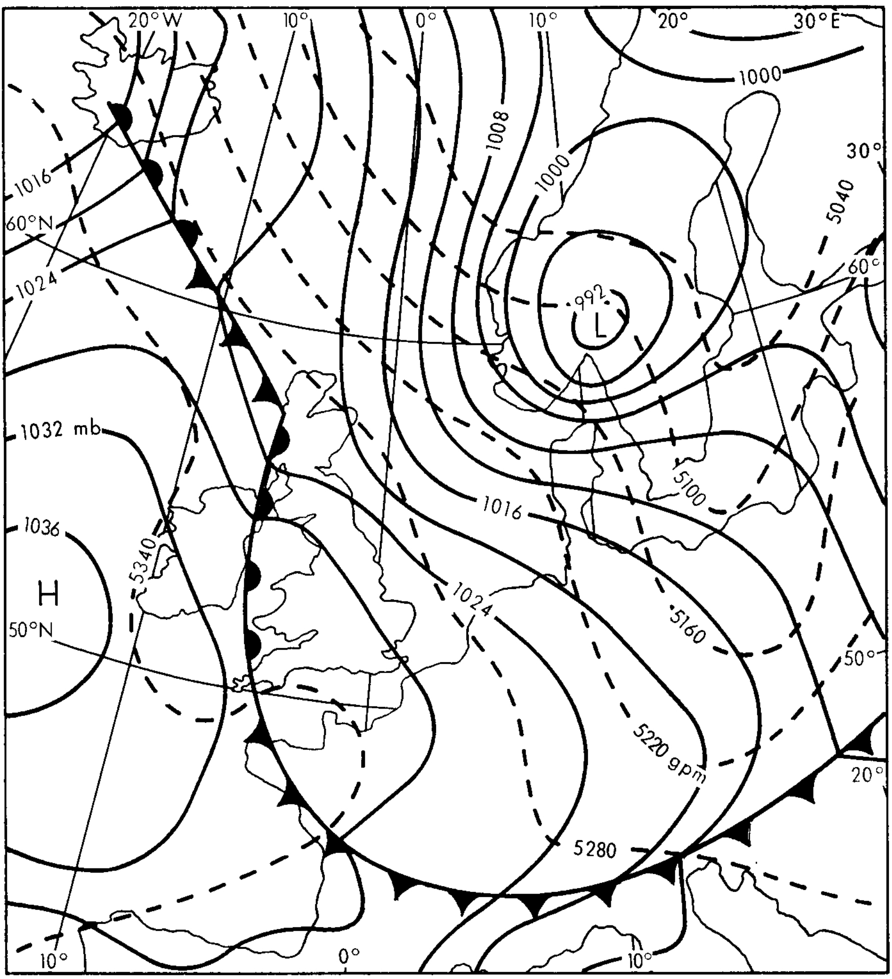


FIGURE 3—SURFACE AND 1000–500-mb THICKNESS CHART AT 12 GMT ON 10 MARCH 1971

At 13 GMT it was decided to head for Crieff where these clouds appeared most marked. The route traversed a wide area of descending air over the lower section of the Ochil range south-east of Perth. However, although the area was broad the vertical component of the airflow was relatively weak. The upstream wave was marked by a band of stratocumulus and once again the wave front tilted forward so that the region of upcurrents was not encountered until the glider was several hundred yards ahead of the cloud below. In contrast to the broad area of descending air the rising air occupied a very narrow band, but the upward velocity was approximately twice the downward velocity observed on the lee side of the wave crest.

The main climb was made in the area near Crieff during the period 1336 to 1500 GMT, starting at 7000 ft and ending at 23 000 ft. During this climb it was necessary to advance approximately six miles (≈9·5 km) upwind to remain in front of the wave crest. Figure 4 shows the cloud structure and apparent tilt of the wave front. In both cases where this tilt could be plotted the slope had a gradient of about 1 :2. For most of the time the true airspeed was 47–55 kt, not all of which was flown directly into wind. Since the glider was actually making some progress upwind it is unlikely that the mean horizontal component exceeded 50 kt and it may have been appreciably less.

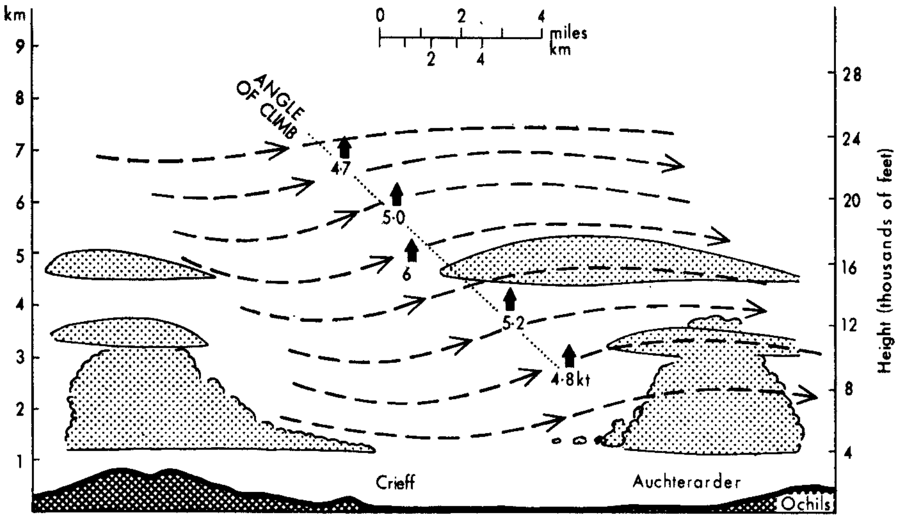


FIGURE 4—WAVE FRONT AND CLOUD STRUCTURE NEAR CRIEFF ON THE AFTERNOON OF 10 MARCH 1971

Vertical velocities on the climb are shown by short arrows with speeds below.

From the top of the climb near Crieff it was possible to fly cross-wind at a true airspeed of 90 kt without experiencing excessive drift, but quite a different wind field was encountered near Loch Lomond. The glider was then at nearly 20 000 ft and an attempt was made to fly into wind to reach the next wave. Speed was increased to within a few knots of the maximum permitted. At one stage the true airspeed reached 136 kt but even so no appreciable forward progress was made during a descent of 7000 ft and the attempt was abandoned in order to remain clear of cloud. It appeared that there was an unusually strong band of winds on the lee side of the next wave between the levels of 19 500 and 12 500 ft. It was necessary to return to the original wave where the wind velocity returned to normal. Although cloud cover made it impossible to estimate a drift angle the plot of the return track showed no further sign of unusual wind strength. Certainly the wind velocity along the upwind side of this wave front, which extended from near Loch Lomond (approximately 56°04′N 04°30′W) to Leuchars (56°22′N 02°52′W), did not exceed 40 kt at levels between 10 000 and 12 000 ft.

Further evidence of localized strong winds. Figure 1 shows that with this type of flow, unusually strong winds may be experienced at low levels, as well as higher up on the lee side of waves. Table I shows the upper winds of the midday soundings from Stornoway and Shanwell. It can be seen that whereas the Stornoway wind profile is fairly typical of conditions for wave flow, the Shanwell wind profile is distorted by a narrow band of anomalously strong winds at the 850-mb level. If this wind is taken to be representative of the undisturbed wind field, it implies a thermal wind in the 850–500-mb layer reciprocal to the thickness lines, and also suggests that lee waves would be unlikely. Since there is no reason to doubt the accuracy of the Shanwell report it may be presumed that the balloon was penetrating one of the layers of anomalously strong winds as it passed the 850-mb level.

TABLE I—UPPER WINDS FOR 12 GMT 10 MARCH 1971 AT SHANWELL AND STORNOWAY

Shanwell			Stornoway		
Pressure level	Wind Direction	Speed	Pressure level	Wind Direction	Speed
mb	*deg*	*kt*	*mb*	*deg*	*kt*
200	320	43	200	320	52
272	295	46			
300	295	45	300	325	57
			312	325	61
400	305	46	400	330	57
440	310	45	411	335	56
500	325	45	500	325	47
600	330	40	600	310	38
			677	305	32
700	315	41	700	310	31
800	325	48	800	310	33
850	325	53	850	310	30
876	315	45			
914	295	32	918	320	30
1021	220	14	1022	330	14

Similar anomalous winds, also implying a reversal of the expected thermal (or partial thermal) wind, are occasionally reported over Norway and it may be that the smoothing applied to wind measurements does not always mask genuine singularities caused by lee waves.

Conclusions. One of the flow patterns calculated by Pao[6] for an inviscid fluid seems also to occur in the free atmosphere when lee waves develop in a mountainous area. Generalized reports from a number of glider pilots, combined with a more detailed study of a single occasion, appear to confirm the existence of tilted asymmetric waves. There is so far no evidence to show how commonly such waves occur, nor is it known if the same effect can be found in the waves further downstream when the air passes out to sea.

REFERENCES

1. KÜTTNER, J.; Zur Enstehung der Föhnwelle. *Beitr Phys Frei Atmos, Leipzig,* 25, 1939, pp. 251–299.
2. LYRA, G.; Theorie der stationaren Leewellströmung in freier Atmosphäre. *Z Angew Math Mech, Berlin,* **23,** 1943, pp. 1–28.
3. QUENEY, P.; Theory of perturbations in stratified currents with applications to air flow over mountain barriers. *Misc Rep Inst Met Univ, Chicago,* No. 23, 1947.
4. CORBY, G. A. and SAWYER, J. S.; The air flow over a ridge — the effects of the upper boundary and high-level conditions. *Q J R Met Soc, London,* **84,** 1958, pp. 25–37.
5. SCORER, R. S.; Natural aerodynamics. London, Pergamon Press, 1958, p. 237.
6. PAO, Y.-H.; Inviscid flows of stably stratified fluids over barriers. *Q J R Met Soc, London,* **95,** 1969, pp. 104–119.

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WORLD METEOROLOGICAL ORGANIZATION COMMISSION FOR AGRICULTURAL METEOROLOGY FIFTH SESSION – GENEVA, OCTOBER 1971

By C. V. SMITH

In some ways, this fifth meeting of the Commission for Agricultural Meteorology (CAgM) represented a watershed, or even a climax as far as the United Kingdom was concerned. It is perhaps unlikely that either of the U.K. delegates, Dr Gloyne or C. V. Smith, will in fact be able to be present at future meetings of the Commission, whilst the man so closely associated with the development of the Commission over the past 20 years, and who has done so much to lead the Commission to maturity, both in the scientific and organizational sense, chose to bring his close association with the Commission to an end at this time — Mr L. P. Smith, President for the past 9 years, left Geneva with no formal duties within the Commission. Many delegates from the 50 countries represented were slightly incredulous; I think they may rest assured that his passionate interest in the problems that the Commission sets out to resolve will not keep his pen from paper for long.

The delegates came with divergent interests and difficulties. In a few countries the problem in recent years has been one of the disposal of agricultural surpluses; the fortunes of agricultural meteorology are inevitably linked with those of agriculture and in these countries they are in decline. Established patterns of capital intensive farming in such regions are only marginally affected by the introduction of alternative crops; the expertise of the individual farmer is already high and governmental intervention is perhaps more social than economic, interested neither in simple production nor yet in productivity. Projections of the future world demand for food would suggest that this lack of interest can only represent a short-term difficulty for agricultural meteorology in the countries now carrying a food surplus.

At the other extreme there were those who were concerned primarily with the development and expansion of national agricultural output, through an extensive rather than an intensive approach. The infra-structure necessary for intensive production is perhaps inadequate at the present time and the emphasis brought by delegates from such countries was on land-use planning, on agro-climatic mapping, on zoning for new plant and animal introductions, and on training in agrometeorology. This demand, in developing countries, for agrometeorological advice at governmental level on the feasibility and advisability of investment projects, must dominate the subject during the next few years. The reasons for the demand for such advice are quite pragmatic; they stem from difficulties and unanticipated side effects found in existing expansion projects, where early agrometeorological consultation was inadequate.

This need to influence the thinking of those concerned with the allocation of resources, and with decision making at all levels of management, was reflected in the discussions of the Commission.

A Working Group was established to revise the *Guide to agricultural Meteorological practices* and among the agreed new chapter headings are:

(6) Agricultural forecasts (meteorology-based).

(8) Weather risk assessment for agricultural planning decisions.

A U.K. recommendation aimed at generating credibility for agrometeorology at the highest level, through illustrative case studies employing conventional middle-level management techniques, found expression in the establishment of a rapporteur on this topic (though perhaps not quite with the terms of reference which a U.K. rapporteur would have written). The importance the Commission was persuaded to attach to this subject resulted in this rapporteur being specifically entered into the President's Advisory Working Group and charged primarily to keep a watching brief on the economic aspects of agrometeorology.

It was also agreeable to find that another U.K. recommendation on the need to initiate further work on the meteorological aspects of aerobiology was taken up and expanded and resulted finally in a new Working Group.

Among the papers called for by the previous meeting in Manila (CAgM IV — 1967) and approved for publication in the World Meteorological Organization *Technical Note* series are :

Weather and animal diseases by L. P. Smith.

Some problems of intensive animal houses by C. V. Smith.

Protection of plants against adverse weather by G. W. Hurst and R. P. Rumney.

Publication of U.K. work on the Colorado beetle was held up pending the inclusion of information to be made available from Eastern Europe and the European Plant Protection Organization.

A further U.K. report on minimum temperatures brought to light so many more questions than the original terms of reference anticipated, that three rapporteurs and international experiments have been instituted.

Current U.K. commitments are fewer than in the past. The U.K. is to provide the rapporteur on mulches, whilst Dr Gloyne is to chair a Working Group on soil deterioration and erosion; help will probably also be given to an Animal Disease Working Group.

Soil deterioration is but one example of the factors leading to a falling off in production, an area of work for the agrometeorologist emphasized by the President in his report to the Commission. A concern for the environment may be topical but is not new to agricultural meteorologists who have long since learned that they must identify problems from the bottom up and not from the top down, if their work is to be effective. Erosion may represent an irreversible process and if one may anticipate a likely quotation at CAgM VI — 'It is already later than you think'.

Other areas of work for the Commission were summarized by the President under the headings of :

Techniques to improve food production.

Meteorological factors involved in problems of plant and animal physiology.

Meteorological factors involved in field operations.

Meteorology as an input to strategic decision making.

Micrometeorological research and soil/plant/animal/atmosphere interactions.

Past and current reports, future rapporteurs and working groups are to be found under all these headings.

It would be wrong to close any report on the meeting without reference to the emphasis that the Commission gave to collaboration with FAO, UNESCO, UNDP, ISB, ISSS, IGU, IUGG.* Surveys of climatic resources of large parts of the globe, experimental projects involving several countries in studies on the introduction of new plant varieties, training through the establishment of seminars — none of these past and present activities would have been possible without the combined initiative and efforts of CAgM and these other bodies. Such collaboration is not by any means purely organizational. For example, coffee leaf rust, a fungal disease, currently constitutes a significant threat to many countries in southern and central America and the Caribbean. A further spread on any large scale could have disastrous economic consequences for countries where coffee is the main cash crop. UNDP and FAO, as a matter of urgency, are preparing plans to reduce the impact of the disease. CAgM has set up a Working Group to assist. It is just possible that these few men could point the way to save the economic livelihood of a subcontinent. Conscience dictates that all possible international assistance should be provided. Self interest in a shrinking world leads to the same conclusion. In the end agrometeorology is concerned with people, and with results as well as ideas.

REVIEWS

Thermal interaction of the atmosphere and the hydrosphere in the Arctic, by Yu. P. Doronin. 245 mm × 173 mm, pp. viii + 244, *illus.* (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), Keter Press Ltd, 15 Provost Road, London NW3 4ST, 1970. Price: £8.

The author's Institute has been concerned for many years with the interaction between the atmosphere and the underlying water/ice layer in the Arctic. Perhaps its best-known data-gathering expeditions have been those on drifting ice stations and results from these have been used extensively in the book. The text is divided into eight main sections, beginning with a chapter on turbulent exchanges of momentum, heat and water vapour between surface and atmosphere. Chapter 2 discusses the surface radiation balance and is followed by a section dealing with vertical heat exchange in the sea. Most of the remainder of the book uses these ideas to develop treatments of ice accretion and the annual freezing/thawing cycle but there is also a section on the effect of surface exchanges on the tropospheric temperature and pressure fields and a final short chapter on the possibility of artificially modifying the Arctic climate.

The middle part of the book discusses topics most closely allied to the author's own researches and is written with some authority but other sections are less convincing. Chapter 1 is especially confusing and the formulae for vertical turbulent transfer developed here by using the turbulent kinetic energy equation without its divergence term have little credibility. Most of this chapter is in any case irrelevant since in the remainder of the book Doronin uses conventional bulk-aerodynamic formulae for representing vertical exchanges at the surface. In Chapter 3 the discussion of vertical mixing in a stably stratified sea ignores completely the layered structure

* i.e. Food and Agriculture Organization; United Nations Educational, Scientific and Cultural Organization; United Nations Development Programme; International Society for Biometeorology; International Society for Soil Science; International Geographical Union; International Union for Geodesy and Geophysics.

observed in these conditions in the absence of wave mixing and includes an uncritical reference to the well-known Kattegat observations of turbulent mixing with an apparent Richardson number around 10.

The book will probably have only limited appeal to anyone not actively involved in the field, as it goes into considerable mathematical detail. Additionally, its value as a definitive text is reduced considerably by the author's frequent presentation of conflicting results from different sources without guidance on which are the more plausible.

The volume may perhaps be of most value as a source of references to predominantly Russian work, but unfortunately, although published in its original form in 1969, it lists very few references beyond 1966 and must be considered already somewhat out of date. Printing is in a cramped format and symbols in the formulae are far too small for easy reading.

N. THOMPSON

Interpretation of observational data from meteorological satellites, by K. Ya. Kondrat'ev, E. P. Borisenkov and A. A. Morozkin. 245 mm × 173 mm, pp. v + 370, *illus.* (translated from the Russian by Israel Program for Scientific translations, Jerusalem), Keter Press Ltd, 15 Provost Road, London NW3 4ST, 1970. Price: £5·50.

This monograph, written at a relatively high technical level, was first published in the U.S.S.R. in 1966. At that time it must have fulfilled its purpose admirably — 'a first attempt to summarize the latest advancements in applied satellite meteorology'. The translation, published in 1970, comes too late to do real justice to the book. So much has happened in the world of meteorological satellite technology, as indeed in most other meteorological activities, that one cannot avoid the criticism that much of the book is now sadly out of date. Nevertheless, there is of course much useful information and comment to be derived from it.

The title of the book is an excellent one; an up-to-date version of a book of this kind is necessary in any large meteorological organization. At the time of its original publication, it made available to its readers in the U.S.S.R. a vast amount of information from sources in the U.S.A. A puzzling thought is why the authors have made so little reference to Soviet meteorological satellites. We are told in the foreword :

> 'The discussion is restricted to data from American meteorological satellites, since most experience has been gained by interpreting these data. The authors have benefited much from the WMO Seminar on the interpretation and use of meteorological satellite data held in Tokyo during 1964. Different problems of applied satellite meteorology were discussed in great detail during the Seminar in which one of the present authors participated. Two interesting and fully illustrated volumes of data and methodically well-designed exercises on nephanalysis were prepared by members of the staff of the U.S. Weather Bureau for practical work at the Seminar. Part of this material was used by the authors in preparing this book.'

This international basis adds value to the book in a broad sense but makes the translation of less importance, for surely a great part of the value of a translation from U.S.S.R. sources lies in the knowledge to be gained from an independent approach to common problems.

The book is divided most logically into four chapters, followed by a good selection of satellite photographs. The chapters are :

(1) The potentialities of satellite-borne equipment for meteorological research.
(2) The use of radiation data obtained with meteorological satellites.
(3) The processing of meteorological satellite data.
(4) The practical use of television and infra-red pictures obtained from meteorological satellites.

The first chapter has a large historical content including details of the U.S. satellite programme, starting with VANGUARD II and EXPLORER VII and ending with NIMBUS I. As might be expected, much of this has little application to present needs. The best part is a section entitled 'Global meteorological observation system'. The authors' opinion is that a global meteorological system should be based on the following component elements :

(a) The totality of conventional observation methods (ground-based meteorological, aerological, radiometric, ship- and aircraft-instrument observations, etc.).
(b) Meteorological satellites.
(c) A system of meteorological sounding balloons (and radiosondes), ocean buoys, and ground-based automatic weather stations operated jointly with satellites that carry out collection and transmission of the received data.
(d) Manned orbiting space laboratories.
(e) Lunar meteorological stations for Earth observations.

It is interesting to quote the comments on the last two items. Manned orbiting space laboratories provide the following advantages :

'(1) the possibility of deliberate choice of the object to be investigated,
(2) supervision (monitoring) of the complex instrumentation,
(3) the testing of new instruments (and the checking of calibration which is difficult to carry out automatically),
(4) visual observations.'

With regard to item (e) :

'A lunar meteorological observatory (LMO) for Earth observations . . . can play an important role in the visual or instrumental tracking of large-scale atmospheric processes. The absence of atmosphere on the Moon makes it possible to carry out on the lunar surface measurements of the solar constant; data of such measurements are instrumental for solving the problem of the Sun's influence on weather. Of considerable interest are also measurements of the Earth surface. This same installation could also be used to measure components of the radiation budget on the lunar surface and the radiation temperature of the latter. Since the Moon always turns the same face toward the Earth it suffices to set up on its surface a single station for the observation of the entire Earth surface and atmosphere as the Earth rotates about its axis. Of particular meteorological interest will be the transmission of infra-red pictures of the Earth which will permanently supply data on the distribution of cloud cover, temperature, and height of cloud tops, as well as information on the temperature of the underlying surface in cloud-free regions for the whole hemisphere.'

Chapter 2 begins by outlining the radiation balance of the Earth surface–atmosphere system and the spatial structure of the outgoing-radiation field and then proceeds to more practical aspects such as the analysis of infra-red cloud pictures, radiation forecasting and the determination of surface temperature, cloud height and moisture in the troposphere. The recent breakthrough achieved with the use of satellite infra-red spectrometer data is of course not mentioned.

Chapter 3 is concerned wholly with what may be called the housekeeping aspects of satellite data interpretation. These comprise the geographical correlation of television pictures and the elimination of distortion factors, the geographical orientation of automatic picture transmission data, the interpretation of nephanalysis data and the processing of outgoing-radiation data.

Then follows the most useful part of the book, Chapter 4, which deals with those aspects of satellite data likely to be of most value to meteorologists at outstations. This is the part that has suffered least from the ravages of time. The detailed treatment of the interpretation of satellite pictures is supplemented by numerous illustrations and examples. This section can be recommended.

As a whole, the book provides plenty of evidence of the qualities that are connoted by the term 'scholarship'. Extensive references in each chapter suggest that more than usual care has been taken. It is unfortunate that this translation, apparently an admirable one, will not prove exciting reading for meteorologists who are moving with the times.

T. H. KIRK

HONOUR

The following award to a member of the Meteorological Office was announced in the New Year's Honours List, 1972 :

O.B.E.

J. Harding, Assistant Director (Agricultural Meteorology and Hydrometeorology).

OBITUARY

Mr J. Durward, C.M.G., died on 2 December 1971 on the eve of his 79th birthday. He was Deputy Director (Services) when he retired in 1954 and was one of the best-known meteorologists in the international field. He was closely associated with civil aviation at a time of rapid development and he played a major part in the establishment of upper air networks and in the organization of ocean weather stations on the North Atlantic. Our deepest sympathy is extended to his widow and sons.

P. J. MEADE

CORRECTION

Meteorological Magazine, January 1971, p. 15, line 15 to read :

H = the non-adiabatic heating term . . .

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CONTENTS

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RECENT PUBLICATIONS

Scientific Paper No. 31 The three-dimensional analysis of meteorological data.

By R. Dixon, B.Sc. and E. A. Spackman, M.Sc.

The advent of modern observational devices such as satellites and long-life free drifting balloons has greatly complicated the process of data analysis by computer. This paper presents a possible method for effecting this data analysis by fitting a high-power polynomial to all the observations from within a large volume of the atmosphere.

37½p (40p by post)

Scientific Paper No. 32 The Bushby-Timpson 10-level model on a fine mesh.

By G. R. R. Benwell, M.A., A. J. Gadd, Ph.D., J. F. Keers, B.Sc., Margaret S. Timpson, B.Sc., and P. W. White, Ph.D.

A full description is given of the 10-level numerical weather prediction model which has been developed by the Meteorological Office during the past few years for use in investigating the dynamics of fronts and in predicting rainfall. The formulation includes representation of the effects of surface friction, topography, surface exchanges of sensible and latent heat, sub-grid-scale convection, and lateral diffusion. An example of a recently computed forecast is included.

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THE METEOROLOGICAL MAGAZINE

Vol. 101, No. 1197, April 1972

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AN OBJECTIVE METHOD OF FORESHADOWING WINTER RAINFALL AND TEMPERATURE FOR ENGLAND AND WALES

By R. MURRAY

Summary. Nearly 100 years of monthly mean pressure anomaly data for the northern hemisphere are analysed in order to pinpoint areas where anomalous circulation features in the autumn are of importance in determining the broad type of winter weather over England and Wales. Simple indices of anomalous circulation in key areas are combined to produce several useful and objective rules for predicting mean winter temperature over England and winter rainfall over England and Wales. On many occasions useful indications of winter rainfall and/or temperature are shown to occur in early autumn. Even better and more generally applicable predictive rules are presented on the basis of anomalous circulation features in the three autumn months.

Introduction. The economic value to the community of accurate forecasts of winter temperature and rainfall is obvious. Even the prediction for the 3-month period from December to February of mean temperature and total precipitation in the rather broad classes of quintiles and terciles respectively would be enormously useful to the transport, fuel and building industries, to agriculture and to the general public.

In recent years some experimental work has been done in the British Meteorological Office on seasonal foreshadowing, as recently reported by Murray.[1] Hay[2] has suggested that October is a key month for predicting winter temperature over central England in the so-called 'blocked' epoch (1873–95 and since 1940) but his results were not satisfactory in the 'westerly' epoch (1896–1939). Hay[3] also showed that rainfall over Britain in the early autumn was a useful indicator of winter temperature under certain circumstances. Murray[4] drew attention to some associations between rainfall and temperature in the winter and preceding months.

The present paper is mainly concerned with describing and illustrating objective forecasting procedures derived from analysing mean monthly pressure anomalies over the northern hemisphere preceding various types of winter; some synoptic climatology of relevance in seasonal foreshadowing is also presented.

Large-scale mean surface pressure anomaly patterns are closely related to broad-scale anomalous circulations near the surface and also to anomalous circulation in the middle troposphere. Indeed, Sawyer[5] recently drew attention to the high correlation between the mean geopotential at 1000 mb and that at 500 mb on the monthly time-scale, especially over the Atlantic–European sector. There is also a practical attraction in exploiting mean pressure since the Meteorological Office holds such data in conveniently processed form on magnetic tape, with adequate completeness over the northern hemisphere back to 1873. However, perhaps the main reason for attempting to extract the maximum information from monthly mean pressure anomaly data is the belief that there must be some pattern in the behaviour of anomalous circulation between autumn and winter, reflecting many complex feedback processes. Studies of the ways in which the broad-scale circulation patterns have developed and evolved in the past must be rewarding in view of our present ignorance, but such investigations are themselves difficult and time-consuming even when carried out for particular case-studies. The present empirical approach was concerned with picking out in the autumn months those key areas where anomalous circulation features seem to show some relationship with winter rainfall or temperature. Then several simple but objective relationships of predictive value were developed.

In this paper the central England mean winter temperature is taken from Manley's[6] compilation and the general rainfall over England and Wales refers to the long series of rainfall records maintained by the Meteorological Office. The percentile boundaries employed are based on the 90-year period 1874 to 1963; the rainfall terciles are given by Murray[4] and the temperature quintiles by Murray.[7]

Circulation, rainfall and temperature in winter. The average winter circulation may be represented by the mean surface pressure map for the 3-month period December to February based on data from 1873 to 1968, shown in Figure 1. The mean pressure anomaly map in Figure 2(a) represents

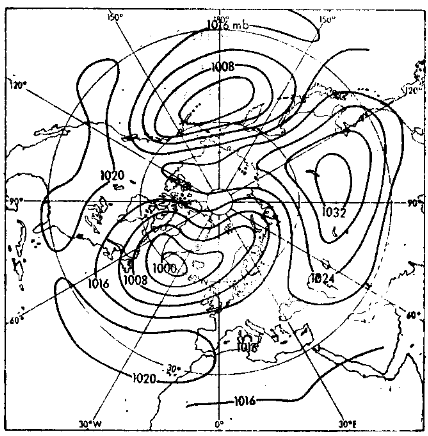

FIGURE 1—MEAN SURFACE PRESSURE IN WINTER, PERIOD 1873 TO 1968

the anomalous circulation in winter associated with dry winters over England and Wales. In this connection dry winters were those in the lowest tercile of rainfall in the 90-year period from December 1873 to February 1963, i.e. those with general rainfall over England and Wales less than or equal to 8·5 inches (216 mm) or 87 per cent of the 90-year average. The most striking feature of Figure 2(a) is the large area of above average pressure over the

Atlantic north of 40°N and most of Europe, with a centre near Ireland; a weaker but significant area of below average pressure is situated near Novaja Zemlja in the Russian Arctic. Wet winters, i.e. those with general rainfall greater than or equal to 10·9 inches (267 mm) or 111 per cent of the 90-year average, are typically associated with the mean pressure anomaly pattern shown in Figure 2(b), which is noteworthy for the large area of below average pressure centred near Ireland. Reversing the signs of the anomalies in Figure 2(a) gives a pattern quite like that in Figure 2(b). The mean pressure anomaly pattern associated with the middle tercile of rainfall (i.e. average rainfall) is featureless and is not shown.

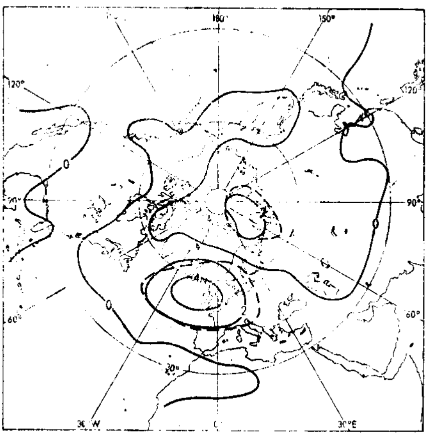

FIGURE 2(a)—MEAN PRESSURE ANOMALY PATTERN ASSOCIATED WITH DRY (TERCILE 1) WINTERS OVER ENGLAND AND WALES

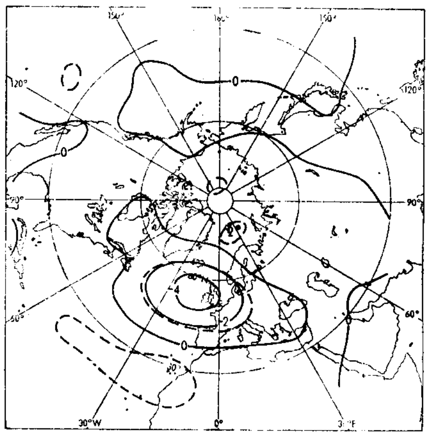

FIGURE 2(b)—MEAN PRESSURE ANOMALY PATTERN ASSOCIATED WITH WET (TERCILE 3) WINTERS OVER ENGLAND AND WALES

Pressure anomalies (2-mb intervals) from 1873–1968 average. Broken lines enclose areas where anomalies are significantly different from zero at the 5 per cent level according to *t*-test.

The mean pressure anomaly map associated with very cold winters, as specified by central England mean winter temperatures (T_m) less than or equal to 2·9°C, is shown in Figure 3(a). For this purpose the central England temperatures of Manley[6] in quintile form derived from the same 90-year period as for rainfall have been employed. Figure 3(a) shows a powerful blocking pattern in the Atlantic sector and a weaker blocking pattern in the Pacific sector. The strong east to north-east anomaly of flow over the British Isles is particularly worthy of note.

Three other mean pressure anomaly maps are presented in Figures 3(b), (c) and (d), which are respectively based on groups of winters classified as quintile 2 ($2{\cdot}9 < T_m \leqslant 3{\cdot}9$°C), quintile 4 ($4{\cdot}4 < T_m \leqslant 5{\cdot}1$°C) and quintile 5 ($T_m > 5{\cdot}1$°C). These diagrams speak for themselves, but it is worth mentioning that Figure 3(d) is quite like Figure 3(a) with the signs of the anomaly patterns reversed. Particularly noteworthy in Figure 3(d) is the strong south-westerly anomaly of flow over the British Isles. The composite pattern associated with quintile 3 winters ($3{\cdot}9 < T_m \leqslant 4{\cdot}4$°C) is not shown; it is weaker than but rather like Figure 3(c), except that the North Atlantic negative anomaly centre is in the Denmark Strait.

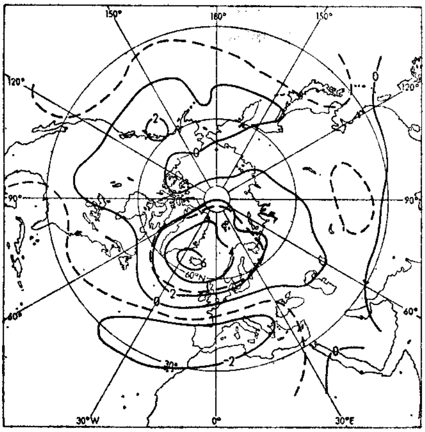

FIGURE 3(a)—MEAN PRESSURE ANOMALY PATTERN ASSOCIATED WITH VERY COLD (QUINTILE 1) WINTERS OVER CENTRAL ENGLAND

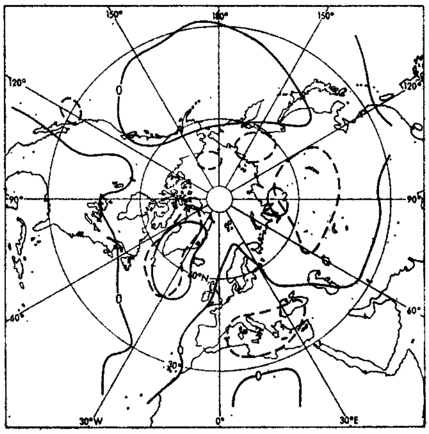

FIGURE 3(b)—MEAN PRESSURE ANOMALY PATTERN ASSOCIATED WITH COLD (QUINTILE 2) WINTERS OVER CENTRAL ENGLAND

See notes at foot of Figure 2.

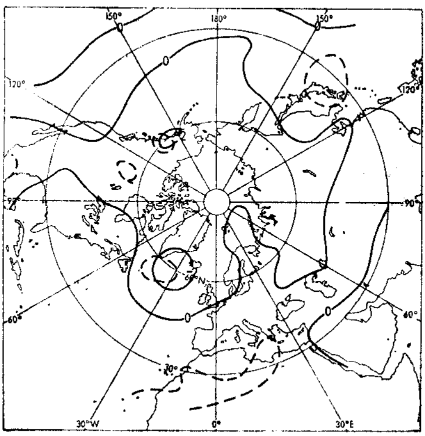

FIGURE 3(c)—MEAN PRESSURE ANOMALY PATTERN ASSOCIATED WITH MILD (QUINTILE 4) WINTERS OVER CENTRAL ENGLAND

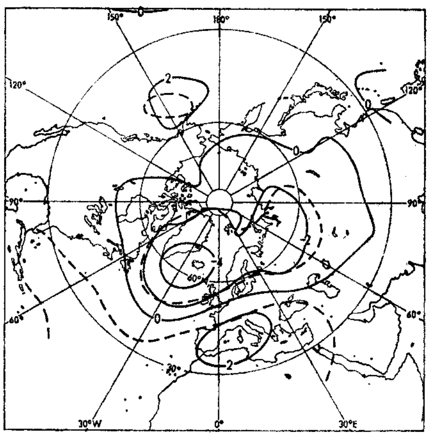

FIGURE 3(d)—MEAN PRESSURE ANOMALY PATTERN ASSOCIATED WITH VERY MILD (QUINTILE 5) WINTERS OVER CENTRAL ENGLAND

See notes at foot of Figure 2.

Figures 2 and 3 clearly show that large-scale anomaly patterns typically occur over the Atlantic–European sector and these generally dominate the hemisphere whenever the winter temperature or rainfall over England and Wales is appreciably different from average.

Procedure. The procedure was quite simple. Five groups of winters were selected according to their mean winter temperature in quintile form in central England. In each class the mean pressure anomaly maps in

September, October and November preceding the winters in question were computed. Areas where the mean monthly pressure anomaly was significantly above or below zero were picked out by application of the *t*-test. An example is given in Figure 4 which is the composite mean pressure anomaly map in

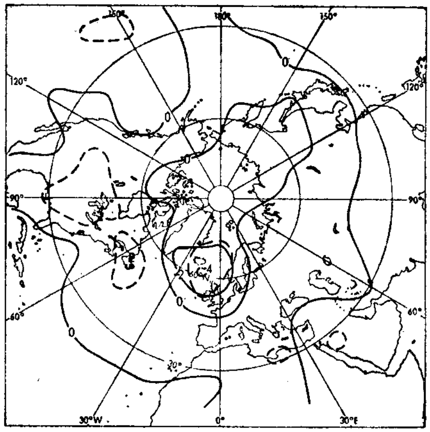

FIGURE 4—MEAN PRESSURE ANOMALY PATTERN IN OCTOBER PRECEDING COLD (QUINTILE 2) WINTERS OVER CENTRAL ENGLAND

See notes at foot of Figure 2.

October preceding cold (quintile 2 or T_2) winters (broken lines enclose areas significant at 5 per cent level). It appears from this figure that below average pressure off north-west Scotland and above average pressure from Newfoundland to the central U.S.A. typically occur before T_2 winters; in a few other small areas in low latitudes, significance is also indicated but these are rather doubtful in view of uncertainties in the basic data. The fact that mean pressure is below average near Scotland in Octobers preceding T_2 winters does not, of course, imply that Octobers in which the mean pressure near Scotland is below average are necessarily followed by T_2 winters. However, composite maps such as Figure 4 suggest that certain areas might well be key areas as regards circulation in helping to determine the type of winter to follow. The next step was to take the pressure anomaly at one (occasionally more than one) grid point within the significant area for each October since 1873 and to relate these values to the quintiles of the following winter. In many cases it seemed probable that an anomalous pressure gradient (e.g. an abnormally strong or weak westerly flow) might be more relevant than the pressure in a particular area; in such cases the differences between the anomalies at two points were computed for each month. In some cases a point was used where the pressure anomaly was not statistically significant but this was generally in order to obtain differences between this point and another point where the pressure anomaly was significant. The broad relationship between pressure anomaly data and subsequent winter temperature was readily seen by forming 5 × 5 contingency tables between the two quantities in quintiles. The chi-square value may, of course, be computed for such tables but the normal test of significance cannot strictly be applied owing to uncertainty concerning the number of degrees of freedom since the data have been pre-selected. In such cases, 'apparently significant at the 5 per cent level' means that the table would have been significant if the data had not been specially selected. However, it was not found satisfactory merely to accept contingency tables which were apparently statistically significant according to the chi-square test. In a few cases, apparently significant tables contained a very complex distribution of frequencies in the cells and in such cases it would not have been possible to derive any usable rule for predictive purposes. At the present stage in long-range forecasting only contingency tables in which at least one wing of the pressure distribution shows a bias in terms of subsequent winter temperature can be used in prediction — if the other wing shows a bias in the opposite sense so much the better.

When both wings of the pressure distribution show a bias the contingency table is usually significant and useful. In some cases one wing might have a potentially useful association with winter temperature even though the whole 5×5 table was not statistically significant at the 5 per cent level.

It was therefore decided to examine the ranked pressure data in more detail. It was clear by inspection that there was often a more natural point in the ranked pressure anomalies than the quintile boundary for useful classification when the object was to associate a class of pressure anomaly data with a strongly biased distribution of quintiles of winter temperature. For this purpose objective criteria were adopted in selecting the classification boundary. These criteria are :

(a) The class must contain at least 15 years.
(b) If both ends of the pressure anomaly distribution appear to have an association with winter temperature then the Sutcliffe score* *(SS)* for each class must equal at least 1·2.
(c) If only one end of the pressure anomaly distribution appears to have an association with winter temperature then $SS \geqslant 1{\cdot}4$.
(d) For practical purposes the pressure class was taken so that the critical pressure anomaly boundary was a whole number (e.g. pressure anomaly $> 3{\cdot}0$ mb) provided also that (a) and (b) or (c) were satisfied.

The criteria (a) to (d) are arbitrary but objective. The so-called Sutcliffe score has been in use in the Meteorological Office for many years. Forecasts with mean $SS \geqslant 1{\cdot}2$ are generally regarded as satisfactory and those with $SS \geqslant 2{\cdot}2$ as very good. For convenience the scoring tables for temperature and rainfall are reproduced in Table I.

In the search for circulation predictions of winter rainfall (i.e. rainfall plus snowfall) the same general procedure was adopted as for temperature. In the rainfall case the pressure anomaly pattern before the three groups classified by terciles of rainfall and before the driest 10 per cent and the wettest 10 per cent of winters were investigated.

Unless otherwise stated the criteria (a) to (d) were adopted in selecting the predictors of winter temperature and rainfall which are discussed in the following sections. Occasionally the positions where pressure anomaly predictors were taken were rather near each other and clearly measured the

* Professor R. C. Sutcliffe originally put forward this simple scoring system; an example of its use is given by Freeman.[8]

TABLE I—SUTCLIFFE SCORES (*SS*) FOR TEMPERATURE FORECASTS IN QUINTILES AND RAINFALL FORECASTS IN TERCILES

(a) Temperature (quintiles)

Forecast	Actual 1	2	3	4	5
1	4	2	0	−2	−4
2	1	4	1	−2	−4
3	−3	1	4	−1	−3
4	−4	−2	1	4	1
5	−4	−2	0	2	4

(b) Rainfall (terciles)

Forecast	Actual 1	2	3
1	4	0	−4
2	−2	4	−2
3	−4	0	4

same type of circulation feature (e.g. pressure anomaly at 50°N 20°W and at 50°N 10°W); in such cases one was selected on the basis of its overall significance.

Forecasting winter rainfall. The analysed data indicate clearly that anomalous atmospheric circulation generally appears to be more important in September and October than in November in determining the winter rainfall over England and Wales. Predictions based on anomalous features of the circulation in each month of autumn are summarized in Table II. In this table positions are given in abbreviated form, e.g. 55 10 is 55°N 10°W and 55 10E is 55°N 10°E.

The positions at which the PA, or PA differences, are important in September are shown in Figure 5. Anomalously high or low pressure in

TABLE II—PRESSURE ANOMALIES OR PRESSURE ANOMALY DIFFERENCES FOR KEY AREAS IN SEPTEMBER, OCTOBER AND NOVEMBER, RELATED TO WINTER RAINFALL IN ENGLAND AND WALES

Rule No.	Pressure anomaly (PA) or difference	Normal	Critical anomaly	Rainfall (terciles) 1	2	3
(a) September		*millibars*				
1	PA(55 10E)	1014·4	<−3	1	5	12
2	PA(55 10E)	1014·4	> 3	11	7	2
3	PA(35 40)−PA(55 10E)	1021·5−1014·4	<−2	14	12	2
4	PA(35 40)−PA(55 10E)	1021·5−1014·4	> 3	1	4	12
5	PA(80 100E)−PA(55 10E)	1012·0−1014·4	<−1	18	16	6
6	PA(80 100E)−PA(55 10E)	1012·0−1014·4	> 6	1	2	12
7	PA(85 180)−PA(50 180)	1015·9−1011·2	<−3	8	6	1
8	PA(85 180)−PA(50 180)	1015·9−1011·2	> 5	3	3	12
(b) October						
9	PA(80 100E)	1011·5	<−5	8	8	2
10	PA(80 100E)	1011·5	> 3	4	9	15
11	PA(80 100E)−PA(50 140)	1011·5−1010·7	< 0	20	14	7
12	PA(80 100E)−PA(50 140)	1011·5−1010·7	> 3	7	10	17
13	PA(25 120)−PA(45 160)	1014·8−1012·3	> 4	2	4	11
(c) November						
14	PA(60 50)	1002·5	<−4	11	5	3
15	PA(45 20E)	1018·1	> 3	10	4	2
16	PA(65 10E)−PA(60 60)	1007·6−1006·0	> 6	9	7	1

Normal monthly pressure or pressure difference is based on the period 1873 to 1968.
Note : Tercile boundaries are : $R_1 \leqslant 216$ mm; $216 < R_2 \leqslant 276$ mm; $R_3 \geqslant 277$ mm.

the polar region with the opposite type of anomaly in the Aleutians and also near Denmark are clearly of importance in September. Anomalous flow (S/SE or NW/N) in the Atlantic, measured objectively by the PA difference

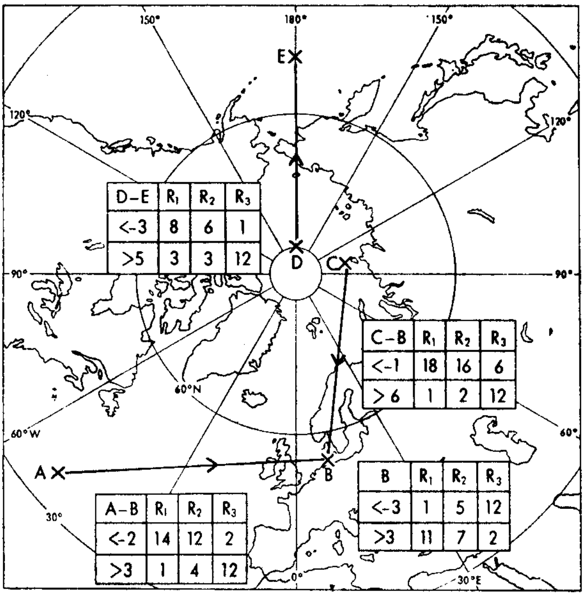

FIGURE 5—INDICATORS OF WINTER RAINFALL OVER ENGLAND AND WALES FROM PRESSURE ANOMALIES IN SEPTEMBER

Anomalies from 1873–1968 average pressure at positions A, B, C, D and E. Boxes contain frequencies of rainfall terciles in following winter; tercile boundaries are given in Table II.

between the points 35°N 50°W and 55°N 10°E, is also a relevant feature. It is of interest that the whole 3 × 3 contingency table of which rules 3 and 4 are the main part was apparently statistically significant at the 0·1 per cent level according to the chi-square test.

Table II also indicates that the October circulation contains features of importance. However, the November circulation appears to be useful for predicting dry winters, although no worthwhile rules (based on criteria (a) to (d) of the previous section) have come to light for predicting wet winters.

Application of the rules of Table II to a particular case usually means that some are satisfied but their predictions may not agree. It might be thought that more weight should be given to a rule based on circulation in November (i.e. nearer to the winter) than to one based on circulation in September, but the facts of the past century do not agree with this supposition. Moreover, it is far from clear that anomalous circulation features in the Atlantic sector should be given more (or less) weight than anomalous circulation features in, say, the polar basin. Weights could be given to the different rules on the basis of frequency of occurrence of individual years in each rule, or according to the total number of years in the frequency distribution, or according to the mean *SS*, or to some combination of all these. In the end it was decided to stick to a quite simple discriminant procedure which will be made clear in the tables which follow.

It is clear from Table III that the September predictors $N_d-N_w \geqslant 2$ and $N_d-N_w \leqslant -1$ give, respectively, very strong indications of dry ($SS = 2{\cdot}6$) and wet ($SS = 2{\cdot}5$) winters to follow. Indeed in these cases only 3 out of 45 years were two terciles different from expectations. However, prediction of average rainfall is less satisfactory ($SS = 0{\cdot}8$). Moreover, 18 years were not considered in Table III since none of the primary predictions of Table II applied.

TABLE III—LAG ASSOCIATIONS BETWEEN VARIOUS COMBINATIONS OF RULES BASED ON MONTHLY PRESSURE ANOMALIES IN SEPTEMBER, OCTOBER AND NOVEMBER OVER THE NORTHERN HEMISPHERE AND WINTER RAINFALL OVER ENGLAND AND WALES

Month	Predictor	Winter rainfall (terciles) 1	2	3	Totals	*SS*
(a) September	$N_d - N_w$					
	$\geqslant 2$	14	7	0	21	2·6
	0 or 1	10	16	8	34	0·8
	$\leqslant -1$	3	3	18	24	2·5
(b) October	$N_d - N_w$					
	$\geqslant 1$	19	14	3	36	1·7
	0 or −1	6	8	9	23	—
	$\leqslant -2$	3	7	14	24	1·8
(c) November	N_d					
	0	15	19	26	60	0·7
	1	11	9	5	25	0·9
	$\geqslant 2$	8	4	0	12	2·6

N_d and N_w are the number of individual monthly rules (see Table II) which indicate dry (tercile 1) and wet (tercile 3) winters respectively. *SS*=Sutcliffe score. Tercile boundaries are given in Table II.

As regards predictions based on October circulation, $N_d-N_w \geqslant 1$ and $N_d-N_w \leqslant -2$ are clearly useful predictors; in this case only 6 out of 60 years differed from expectation by two terciles. However, some 12 years were not incorporated into Table III since the individual predictors of Table II were not applicable.

In November the criterion $N_d \geqslant 2$ apparently gives a useful prediction in a small minority of years (12 only). Moreover, no November predictors were available for wet winters.

Table III gives some useful predictions, especially in September and October, but there are evidently a fairly large number of occasions when no satisfactory rule based on any single month is applicable. The next step is to combine the separate monthly indications. This is done for September and October and also for the three autumn months in Table IV.

Table IV (a) shows that the specified anomalous features of the circulation in September and October are closely associated with the raininess of the following winter. The 3×3 contingency table contains nearly 95 per cent of the data. In rows 1 and 3 there are only five cases which differ by 2 terciles from the expected value of tercile 1 or 3 respectively. Even stronger indications are given if more stringent criteria are employed; these are shown in brackets.

Table IV (b) summarizes the results using objective predictors based on the three autumn months. In general the addition of November does not add much, but some gain is obtained in, for instance, applying the rule given in the bottom row. Once again, very strong indications are in evidence on those occasions when the stringent criteria shown in brackets are laid down.

TABLE IV—LAG ASSOCIATIONS BETWEEN VARIOUS COMBINATIONS OF RULES BASED ON MONTHLY PRESSURE ANOMALIES IN (a) SEPTEMBER AND OCTOBER AND IN (b) SEPTEMBER, OCTOBER AND NOVEMBER OVER THE NORTHERN HEMISPHERE AND WINTER RAINFALL OVER ENGLAND AND WALES

Period	Predictor $N_d - N_w$	Winter rainfall (terciles) 1	2	3	Totals	SS
	$\geqslant 1$ ($\geqslant 3$)	26 (11)	15 (6)	3 (0)	44	2·0
(a) September	0 or −1	4	12	5	21	1·4
and October	$\leqslant -2$ ($\leqslant -4$)	2 (0)	5 (0)	20 (9)	27	2·6
(b) September,	$\geqslant 1$ ($\geqslant 3$)	28 (15)	19 (9)	3 (0)	50	2·0
October and	0 or −1	5	9	6	20	0·7
November	$\leqslant -2$	0	4	19	23	3·3

N_d and N_w are the number of individual monthly rules (see Table II) which indicate dry (tercile 1) and wet (tercile 3) winters respectively. SS = Sutcliffe score. Tercile boundaries are given in Table II.

Note : For a predictor value given in brackets the tercile distribution is shown in brackets.

The stability of relationships such as those shown in Table IV can be tested to some extent by breaking down the whole period and examining the associations in the separate periods. The associations between $N_d - N_w$ and winter rainfall in (a) the so-called 'westerly epoch' (normally taken as 1896 to 1939) and (b) the 'blocked epoch' (taken as before 1896 and after 1939) for the autumn are summarized in Table V.

TABLE V—LAG ASSOCIATIONS BETWEEN VARIOUS COMBINATIONS OF RULES BASED ON MONTHLY PRESSURE ANOMALIES IN SEPTEMBER, OCTOBER AND NOVEMBER OVER THE NORTHERN HEMISPHERE AND WINTER RAINFALL OVER ENGLAND AND WALES IN THE 'WESTERLY' EPOCH (1896–1939) AND THE 'BLOCKED' EPOCH (1873–95 AND 1940–69)

Epoch	Predictor $N_d - N_w$	Winter rainfall (terciles) 1	2	3
(a) Westerly	$\geqslant 1$	10	6	1
	0 or −1	2	5	4
	$\leqslant -2$	0	2	13
(b) Blocked	$\geqslant 1$	18	13	2
	0 or −1	3	4	2
	$\leqslant -2$	0	2	6

N_d and N_w are the number of individual monthly rules (see Table II) which indicate dry (tercile 1) and wet (tercile 3) winters respectively. Tercile boundaries are given in Table II.

It is clear from Table V that the same types of associations between $N_d - N_w$ and winter rainfall hold in both the westerly and the blocked epochs. The different frequencies of cases with $N_d - N_w \geqslant 1$ and $\leqslant -2$ in the two epochs are simply due to the climatological tendency for blocking to be associated with dry rather than with wet winters and, of course, occurrences of blocking were less frequent in group (a) and more frequent in group (b).

The prediction of dry or wet winters does not imply that each month of the winter will be dry or wet. Indeed a feature of the climatology of dry or wet winters is that only a small minority of such winters have all their months either dry or wet. In the case of rules contained in Table IV (b) a few facts are worth noting. For $N_d - N_w \geqslant 1$, (1) the strongest bias to dry is in January (24 R_1, 21 R_2 and 5 R_3) and the weakest bias in February; (2) over 90 per cent of winters have two or more dry or average months; (3) if December is wet, then January is very likely to be dry and February has a somewhat weaker tendency to be average. For $N_d - N_w \leqslant -2$, (1) the strongest bias to wet is in December, the next strongest is in January whereas February is more likely to have average rainfall; (2) 100 per cent of winters have two or more wet or average months. For $N_d - N_w = 0$ or -1, there is little bias in each month except for a tendency for average rainfall in December.

Forecasting winter temperature. Following the same general procedure various predictors in each autumn month were selected as shown in Table VI with a view to predicting winter mean temperature in central England.

TABLE VI—PRESSURE ANOMALIES OR PRESSURE ANOMALY DIFFERENCES FOR KEY AREAS IN SEPTEMBER, OCTOBER AND NOVEMBER RELATED TO WINTER MEAN TEMPERATURE IN CENTRAL ENGLAND

Rule No.	Pressure anomaly (PA) or difference	Normal	Critical anomaly	Temperature (quintiles)				
		millibars		1	2	3	4	5
(a) September								
1	PA(55 20)	1011·0	<−3	5	11	1	0	2
2	PA(35 20)−PA(55 20)	1020·4−1011·0	≥ 3	4	13	2	0	2
3	PA(45 60E)−PA(55 20)	1016·1−1011·0	> 4	4	11	1	0	2
4	PA(55 10)−PA(60 70)	1012·9−1009·1	<−4	5	10	3	0	4
(b) October								
5	PA(65 20)	1004·9	<−5	2	10	4	2	1
6	PA(40 90)	1018·3	> 1	3	14	8	1	4
7	PA(60 10)−PA(40 10)	1007·2−1017·3	<−6	4	11	3	3	1
8	PA(55 00)	1012·3	<−3	6	12	6	4	1
9	PA(80 160E)	1015·8	> 4	1	4	5	3	10
10	PA(80 160E)−PA(60 40)	1015·8−1004·7	<−6	9	5	3	3	1
11	PA(80 160E)−PA(60 40)	1015·8−1004·7	> 6	0	4	5	2	8
12	PA(55 00)−PA(60 40)	1012·3−1004·7	<−7	5	7	7	2	1
13	PA(80 80E)	1010·2	<−6	6	5	0	4	0
14	PA(80 80E)	1010·2	> 5	1	2	4	2	8
15	PA(65 20)−PA(80 80E)	1004·9−1010·2	> 8	9	2	1	4	0
(c) November								
16	PA(60 50)−PA(65 10E)	1002·5−1007·6	> 7	3	9	3	4	0
17	PA(55 10)	1009·7	>−6	2	4	1	10	1

Normal monthly pressure or pressure difference based on period 1873 to 1968.
Note : Quintile boundaries, based on period 1874 to 1963, are as follows : $T_1 < 3{\cdot}0$°C; $3{\cdot}0 \leqslant T_2 < 4{\cdot}0$; $4{\cdot}0 \leqslant T_3 < 4{\cdot}5$; $4{\cdot}5 \leqslant T_4 < 5{\cdot}2$; $T_5 \geqslant 5{\cdot}2$°C.

It is evident from Table VI that more predictors occur in October than in the other two months. This is in accord with a suggestion of Hay[1] that October is the most critical autumn month in determining winter temperature over central England. An attempt is made to combine the predictors from each month as indicated in Table VII.

Table VII summarizes the rules which have been developed on the basis of all the indications contained in Table VI. Using only September data, one useful rule is obtained for predicting T_2 winters but it can be invoked on less than 25 per cent of the years. Using only October data, predictions of T_5 and T_1 or T_2 can be made on about 60 per cent of occasions, and the accuracy of the forecasts of very mild winters is likely to be very high. Using only November data, worthwhile predictions of T_4 and T_2 winters can be made on 34 per cent of occasions. However, the overall rule derived from the September, October and November circulation data (i.e. (d)) appears likely to be usable on nearly 80 per cent of occasions, but with a high degree of accuracy on some 60 per cent of occasions when the conditions in rows 1, 4 and 5 are satisfied. In these 60 cases there are only 5 with negative values

TABLE VII—LAG ASSOCIATIONS BETWEEN VARIOUS COMBINATIONS OF RULES BASED ON MONTHLY PRESSURE ANOMALIES IN SEPTEMBER, OCTOBER AND NOVEMBER OVER THE NORTHERN HEMISPHERE AND MEAN WINTER TEMPERATURE IN CENTRAL ENGLAND

	Period	Predictors	Winter temperature (quintiles) 1	2	3	4	5	Totals	*SS*
(a)	September	$N_c \geq 2$	6	13	2	0	2	23	2·2
(b)	October	$N_c - N_m \geq 2$	13	16	5	8	1	43	1·4
		$N_c - N_m = 0$ or 1	7	7	12	6	5	37	—
		$N_c - N_m \leq -1$	0	0	2	4	11	17	3·0
(c)	November	$N_c - N_m > 0$	3	8	3	3	0	17	1·9
		$N_c - N_m = 0$ or 1	15	12	15	6	16	64	—
		$N_c - N_m < 0$	2	3	1	9	1	16	1·5
(d)	September,	$N_c - N_m \geq 3$	10	17	4	2	2	35	2·0
	October	$N_c - N_m = 2$	4	5	5	4	1	19	0·9
	and	$N_c - N_m = 0$ or 1	5	1	7	3	2	18	—
	November	$N_c = N_m = 0$	1	0	2	3	1	7	1·5
		$N_c - N_m \leq -1$	0	0	1	6	11	18	3·1

N_c and N_m are the number of individual monthly rules (see Table VI) which indicate cold (T_1 or T_2) and mild (T_4 or T_5) winters respectively. *SS* = Sutcliffe score.

of the Sutcliffe score (i.e. seriously in error). It is less satisfactory that when $N_c - N_m \geq 3$ the prediction is cold (T_2) rather than very cold (T_1).

The value of the rule (d) in Table VII in the 'blocked' and 'westerly' epochs was next examined. The results are shown in Table VIII.

TABLE VIII—LAG ASSOCIATIONS BETWEEN VARIOUS COMBINATIONS OF RULES BASED ON MONTHLY PRESSURE ANOMALIES IN SEPTEMBER, OCTOBER AND NOVEMBER OVER THE NORTHERN HEMISPHERE AND WINTER MEAN TEMPERATURE IN CENTRAL ENGLAND IN THE 'WESTERLY' EPOCH (1896–1939) AND THE 'BLOCKED' EPOCH (1873–95 AND 1940–69)

	Epoch	Predictor	Winter mean temperature (quintiles) 1	2	3	4	5
(a)	Westerly	$N_c - N_m \geq 3$	0	8	3	1	2
		$N_c - N_m \leq -1$	0	0	1	2	9
(b)	Blocked	$N_c - N_m \geq 3$	10	9	1	1	0
		$N_c - N_m \leq -1$	0	0	0	4	2

N_c and N_m are the number of individual monthly rules which indicate cold (T_1 or T_2) and mild (T_4 or T_5) winters respectively.

Substantially the same types of predictions apply in both epochs. Not unexpectedly there are more cold winters and fewer mild ones in the 'blocked' epoch compared with the 'westerly' epoch. Moreover, in the 'blocked' epoch, when $N_c - N_m \geq 3$ the following winters are just as likely to be quintile 1 as quintile 2. In the 'westerly' epoch, when $N_c - N_m \geq 3$, no quintile 1 was observed.

As regards the individual winter months the prediction of the seasonal mean temperature as cold (T_1 or T_2) or mild (T_4 or T_5) does not signify that each month will have the same quintile classification. There are some interesting features connected with the overall autumn rule (d) of Table VII. For $N_c - N_m \geq 3$, (1) some 60 per cent of winters have at least two cold (T_1 or T_2) months; (2) if December is cold (T_1 or T_2), then February is also quite likely to be cold (8 T_1, 3 T_2, 4 T_3, 2 T_4 and 3 T_5) but January has little bias to cold; (3) if December is mild (T_4 or T_5) then the distribution of quintile frequencies in the other months is random. For $N_c - N_m \leq -1$,

(1) no very cold (T_1) month occurs and only two T_2 Decembers occur; (2) all Januarys and Februarys have near or above average temperatures (T_3, T_4 or T_5).

So far in this section anomalous circulation features in autumn over the northern hemisphere have been employed in deriving objective rules for predicting winter temperature. Several years ago, following the derivation of the *PSCM* indices of Murray and Lewis,[9] the writer noted that progressive cyclonic autumns were related to cold winters in central England and this rule was illustrated in an article by Murray.[1] It is worth mentioning a few elaborations of the progressive cyclonic autumn rule in predicting cold winters, and these are summarized in Table IX.

TABLE IX—VARIOUS ASSOCIATIONS BETWEEN CIRCULATION NEAR THE BRITISH ISLES AS MEASURED BY *PSCM* INDICES IN AUTUMN AND MEAN TEMPERATURE IN CENTRAL ENGLAND IN WINTER

Rule No.	Predictors	Winter temperature (quintiles) 1	2	3	4	5	Totals	*SS*
1	P_{45} C_{45} autumn	3	13	5	3	1	25	2·0
2	S_{12} C_{45} autumn	5	6	5	1	0	17	1·8
3	P_{45} C_{45} and/or S_{12} C_{45} autumn (counting common years once)	6	15	6	4	1	32	1·9
4	P_{45} C_{45} in autumn and also in at least one of September, October or mid-September to mid-October	3	11	4	1	0	19	2·5

P_{45} C_{45} signifies quintiles 4 or 5 in *P* (progressive) index and in *C* (cyclonic) index; similarly for S_{12} C_{45} (northerly cyclonic). *SS* = Sutcliffe score.

On a limited number of occasions these *PSCM* values in Table IX are applicable and useful. Number 4 in particular shows a very close connection between the specified pre-conditions and quintile 2 winters. The *PSCM* indications add a little on a few occasions to the broader-based rules contained in Table VII. There are no strong *PSCM* rules for predicting mild winters.

Before ending this section it must be said that the prediction of severe winters is not satisfactory, and much more work needs to be done on this particular problem.

Concluding remarks. Experience and judgement have gone into certain aspects of this work, particularly in deciding the levels at which possible criteria should be accepted or rejected, but once the basic predictors in Tables II and VI were accepted the rules derived are quite objective and readily used in practice. No doubt better rules may subsequently be derived, especially by bringing in other physically based predictors and by elaborating the statistical treatment, e.g. by the use of discriminant analysis. However, the present rules set a standard which more sophisticated procedures in the future must exceed in accuracy if they are to be worth while in practical forecasting.

It is also worth stressing that there are inevitably some occasions when none of the rules can be applied. In such cases other methods must be adopted or no forecast should be issued. It should be noted in addition that even the most strongly based rule may fail on a few occasions. Prediction on all time-scales is a question of probability rather than certainty. Even the most sophisticated procedures of the distant future will not always predict correctly on the seasonal or any other time-scale.

Acknowledgement. The writer is grateful to several members of the Synoptic Climatology Branch and particularly to Mr P. Collison and Mr M. J. Weller who were responsible for writing the computer programmes.

REFERENCES

1. MURRAY, R.; Recent developments in long-range forecasting in the Meteorological Office. *Q J R Met Soc, London*, **96**, 1970, pp. 329–336.
2. HAY, R. F. M.; The association between autumn and winter circulations near Britain. *Met Mag, London*, **96**, 1967, pp. 167–178.
3. HAY, R. F. M.; Relationships between autumn rainfall and winter temperatures. *Met Mag, London*, **97**, 1968, pp. 278–282.
4. MURRAY, R.; Some predictive relationships concerning seasonal rainfall over England and Wales and seasonal temperature in central England. *Met Mag, London*, **97**, 1968, pp. 303–310.
5. SAWYER, J. S.; Observational characteristics of atmospheric fluctuations with a time scale of a month. *Q J R Met Soc, London*, **96**, 1970, pp. 610–625.
6. MANLEY, G.; The mean temperature of central England 1698–1952. *Q J R Met Soc, London*, **79**, 1953, pp. 242–261.
7. MURRAY, R.; A note on central England temperatures in quintiles. *Met Mag, London*, **99**, 1970, pp. 292–294.
8. FREEMAN, M. H.; The accuracy of long-range forecasts issued by the Meteorological Office. *Met Mag, London*, **95**, 1966, pp. 321–325.
9. MURRAY, R. and LEWIS, R. P. W.; Some aspects of the synoptic climatology of the British Isles as measured by simple indices. *Met Mag, London*, **95**, 1966, pp. 193–203.

551.510.53:551.557.5

A NOTE ON EQUATORIAL STRATOSPHERIC WINDS*

By R. A. EBDON

Summary. Stratospheric (30-mb) wind data are used to illustrate how the monthly mean patterns vary during selected Januarys and Julys when the winds in the equatorial stratosphere are established easterlies or westerlies. Charts are presented for two selected days — one during an easterly and the other during a westerly régime in the equatorial stratosphere. On both the monthly and the daily time-scales the wind régimes associated with the quasi-biennial oscillation appear to be such that easterly or westerly winds can encircle the earth in the equatorial stratosphere.

Introduction. Since 1960 when the quasi-biennial oscillation (QBO) in the zonal component of equatorial stratospheric winds was first reported, many papers have been written which describe its main characteristics. It is usually stated that the alternating easterly and westerly currents encircle the earth in the equatorial zone and that the effects of the oscillation decrease with increasing latitude. Very often questions are asked regarding the latitudinal extent of the actual easterly and westerly régimes and whether or not the easterlies and westerlies are continuous around the equatorial zone. Lack of an adequate network of stratospheric wind observations makes it difficult to answer these questions with complete confidence, but in an attempt to do so, the available 30-mb (24 km) data have been used to examine the wind régimes in the northern and southern hemispheres for particular months, and in the equatorial zone for particular days, when the phase of the QBO

* This note is based on a paper presented at a symposium on 'Equatorial currents in atmospheres and oceans' held on 21 May 1971 and organized by the Royal Astronomical Society jointly with the Royal Meteorological Society and The Challenger Society.

was easterly or westerly. The choice of months to be examined was determined by the availability of data as well as by the phase of the QBO. Also, the investigation was restricted to the months of January and July which are representative of the established winter (westerly) and summer (easterly) wind régimes in middle and high latitudes.

The monthly mean zonal wind components at 50 mb (20·5 km) and 30 mb (24 km) for Canton Island (2° 46′S 171° 43′W) from May 1954 to August 1967 and for Gan (00° 41′S 73° 09′E) from September 1967 onwards are shown in Figure 1, and the months referred to later in the text are indicated for ease of reference. The QBO itself is very clearly defined in these curves

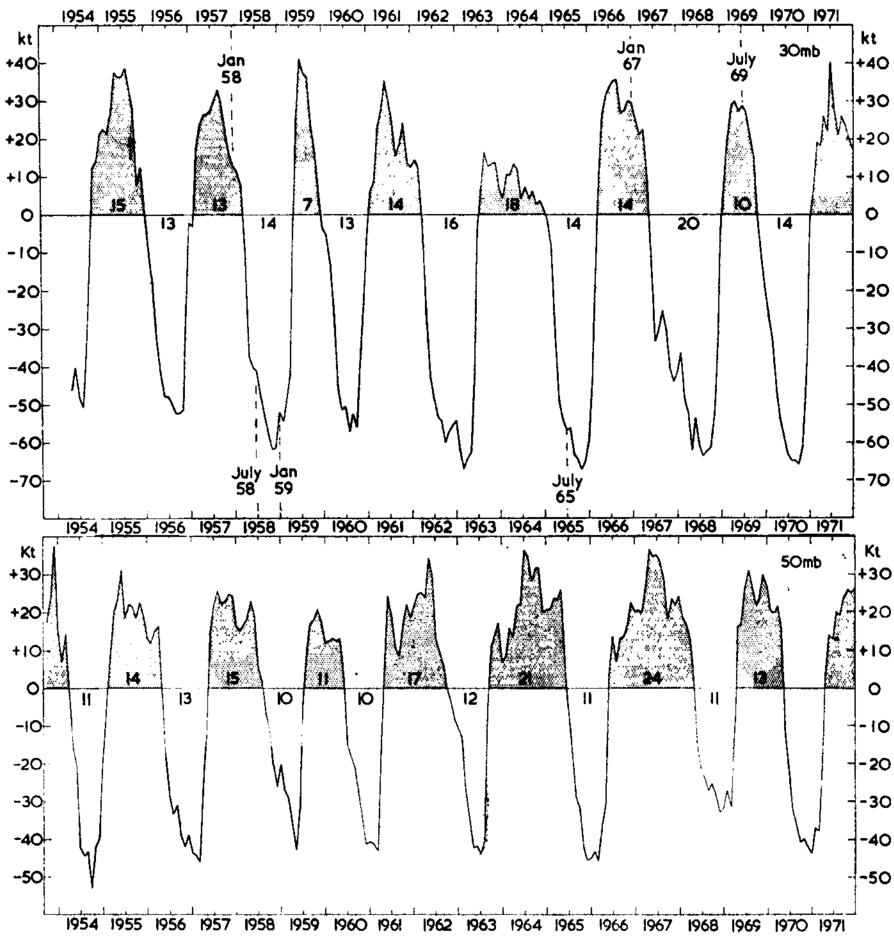

FIGURE 1—MONTHLY MEAN ZONAL WIND COMPONENTS AT 30 mb AND 50 mb FOR CANTON ISLAND, OCTOBER 1953 TO AUGUST 1957 AND FOR GAN, SEPTEMBER 1967 ONWARDS

Components towards the east are positive and stippled. Figures along the zero line indicate the duration, in months, of westerlies or of easterlies. Months mentioned in the text are annotated.

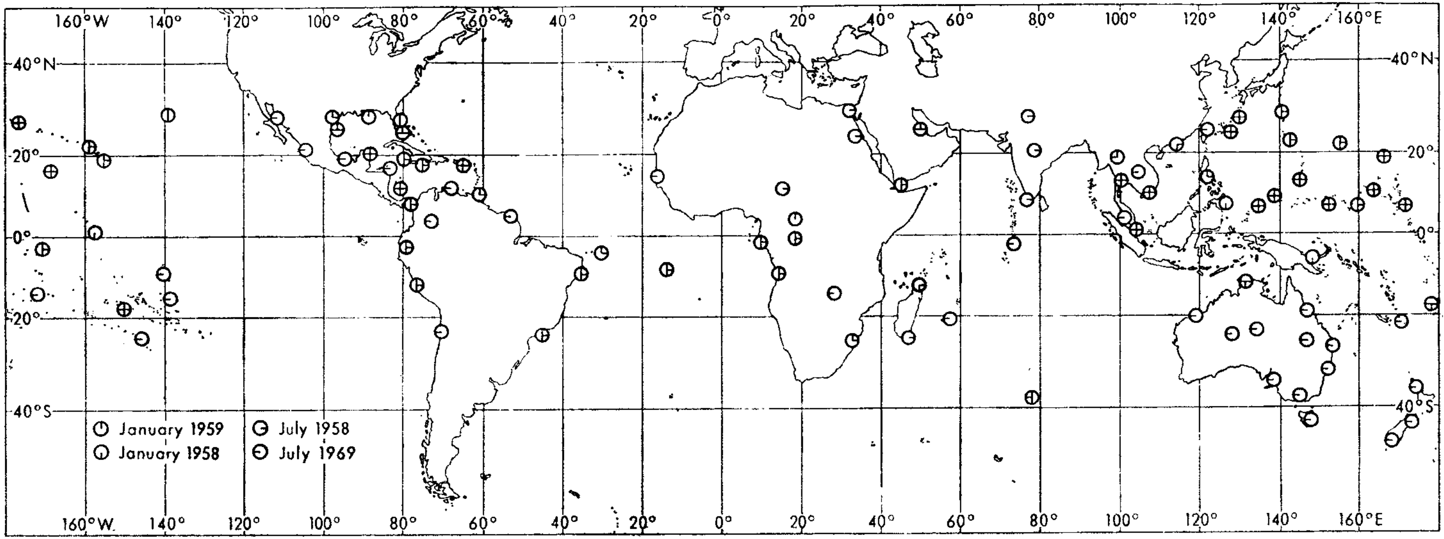

FIGURE 2—STATIONS FOR WHICH DATA WERE USED IN THE PREPARATION OF THE 30-mb MONTHLY MEAN WIND CHARTS

and its relative importance can be judged by the fact that a more detailed analysis has shown that it accounts for about 70 per cent of the total variance at 30 mb and 65 per cent at 50 mb, whilst the annual variation accounts for only 4 per cent and 6 per cent of the total variance at the same two levels.[1]

The stations for which monthly mean winds were used in constructing the charts are indicated in Figure 2. Only those stations between 30°N and 50°S are shown because north of 30°N there are many more reporting stations over some parts of the hemisphere and only those required to position the isopleths were used. The available data suggest that, in low latitudes, the predominantly easterly and westerly wind régimes — when they are established — are organized in definite latitude zones but clearly there are large areas over which observations are non-existent, and the analysis in these areas relies largely on what happens at comparable latitudes where observations are more adequate.

The easterly phase of the QBO. Figure 3 shows the monthly mean wind pattern for January 1959 (two months after an easterly maximum of the QBO). The strong (greater than 50 kt) easterlies are continuous in a belt extending from about 5°N to nearly 20°S. To the south of this, in the summer hemisphere, the winds are light easterly. To the north of the equator, in the winter hemisphere, the easterlies extend to 25°N or beyond — especially over the Pacific in the region of the Aleutian stratospheric high. Farther north the winds are generally westerly.

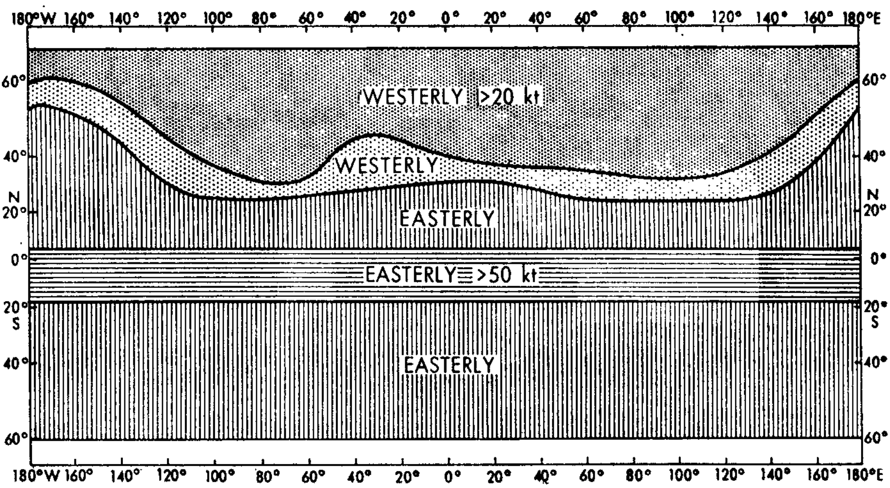

FIGURE 3—30-mb MONTHLY MEAN WINDS, JANUARY 1959

In July 1958 (four months before an easterly maximum of the QBO) the monthly mean winds show a belt of strong (greater than 50 kt) easterlies from near the equator to about 20°N (see Figure 4). To the north of this (in the summer hemisphere) the winds are light easterly. South of the equator (in the winter hemisphere) the easterlies extend to about 35°S and then change to the westerlies typical of winter.

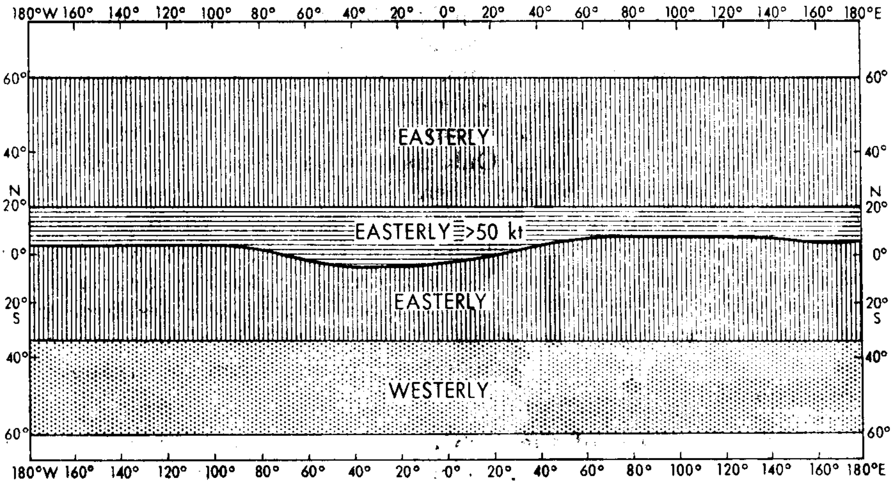

FIGURE 4—30-mb MONTHLY MEAN WINDS, JULY 1958

From these two diagrams it is clear that when the phase of the QBO is easterly and the easterlies are strong, there is a broad band of strong easterlies with its axis not at the equator but displaced into the summer hemisphere. There can be little doubt that these easterlies are continuous around the equator on the monthly mean chart.

The chart for an individual day, 29 July 1965 (Figure 5), shows that, in spite of the considerable areas with no observations, there is little doubt that easterly winds with a speed of about 50 kt do encircle the earth in the equatorial belt. (July 1965 was four months before an easterly maximum of the QBO.)

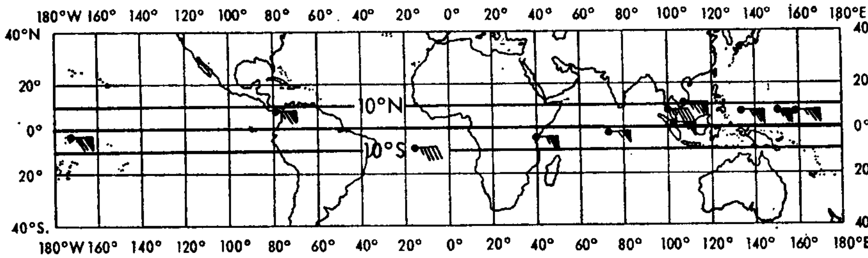

FIGURE 5—30-mb WIND ON 29 JULY 1965

International symbols are used for plotting the winds.

The westerly phase of the QBO. Figures 6 and 7 show the monthly mean 30-mb winds for January 1958 (four months after a westerly maximum of the QBO) and July 1969 (two months after a westerly maximum). In January 1958 there is a narrow belt of westerlies with speeds greater than 20 kt situated very close to the equator and these are embedded in a broader band of westerlies which extends to about 10°S. Farther south, in the summer hemisphere, there are strong easterlies (greater than 20 kt) between about 12°S and 37°S. North of the equator, in the winter hemisphere, the westerly component decreases and easterly winds appear over quite considerable areas. In higher latitudes the typical winter stratospheric westerlies are established.

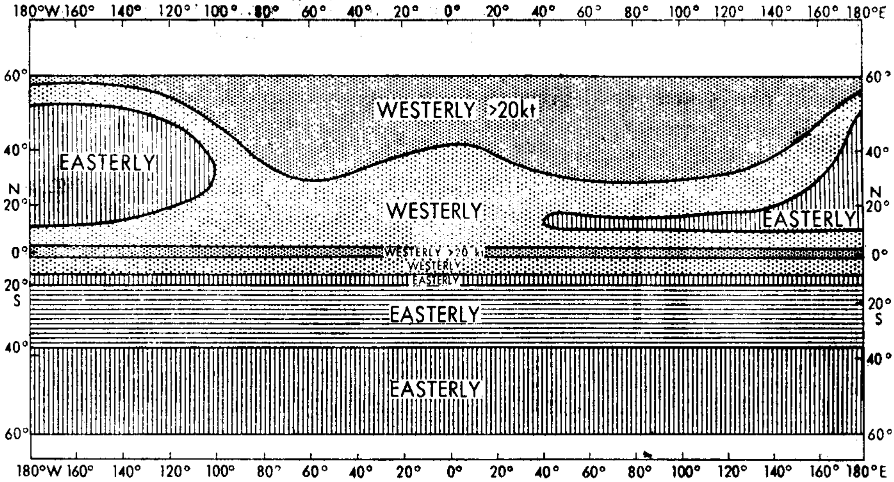

FIGURE 6—30-mb MONTHLY MEAN WINDS, JANUARY 1958

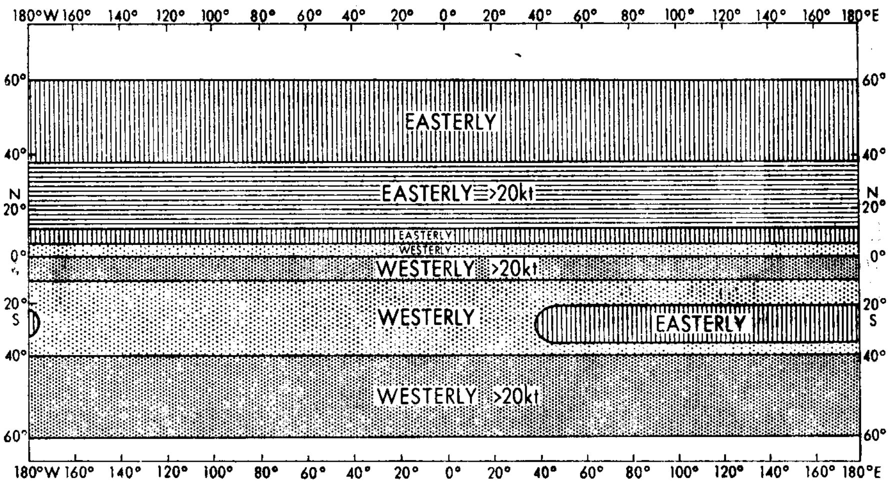

FIGURE 7—30-mb MONTHLY MEAN WINDS, JULY 1969

In July 1969 there is a narrow (about 10 degrees) band of westerly winds with speeds greater than 20 kt from the equator to 10°S. These westerlies extend to about 5°N, at which latitude a change-over to easterly takes place. Farther north, in the summer hemisphere, there are stronger easterlies between about 12°N and 37°N. In higher latitudes there are the light easterlies typical of summer. To the south of the equator, in the winter hemisphere, the westerly component decreases — with easterlies appearing in some areas between about 20°S and 35°S. South of this minimum westerly the zonal component increases again to the stronger westerly régime typical of the higher-latitude winter.

The 50-mb (20·5 km) monthly mean wind diagram for July 1969 in Figure 8 shows a pattern very similar to that at 30 mb for the same month and, in particular, it indicates quite clearly the existence of actual easterly winds in places near 20 degrees in the winter hemisphere when the QBO is westerly at the equator.

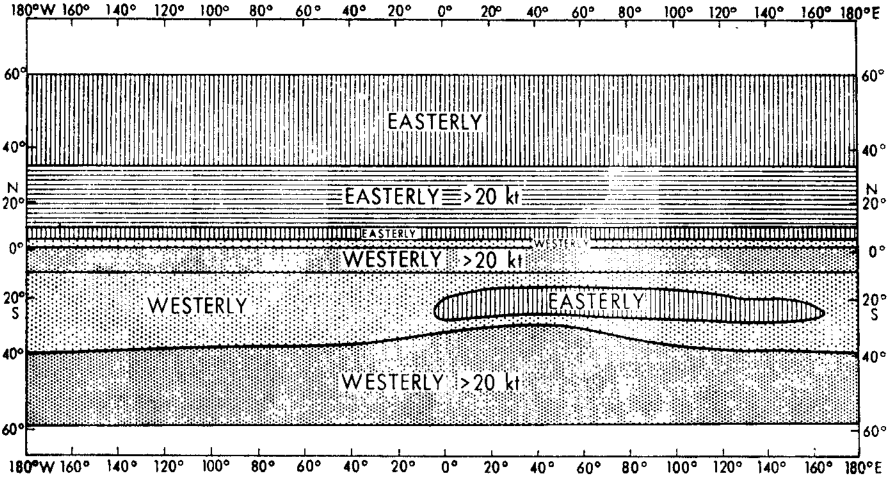

FIGURE 8—50-mb MONTHLY MEAN WINDS, JULY 1969

Figure 9 is a cross-section of monthly mean zonal wind components near 80°W for July 1969. This shows that the monthly mean winds were westerly in the equatorial stratosphere from below 100 mb (16·5 km) up to above 10 mb (30 km). The westerlies were strongest at 25–15 mb (25–27 km) and they extend to about 6° or 7°N of the equator. To the south of the equator the westerly zonal component decreases to less than 10 kt near 20°S.

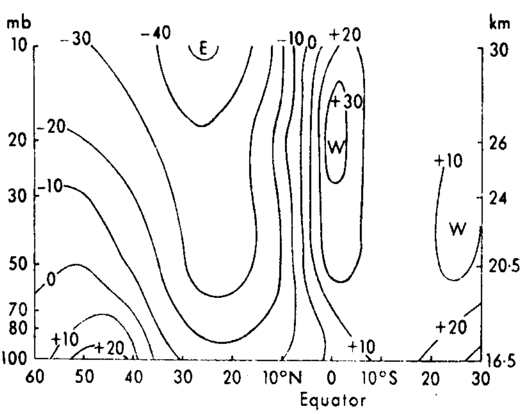

FIGURE 9—MONTHLY MEAN ZONAL WIND COMPONENT CROSS-SECTION NEAR 80°W, JULY 1969

Components towards the east are positive.

Figures 6, 7 and 8 certainly suggest that the belts of stronger westerlies are continuous around the equator on the monthly mean wind charts but it is of interest to know if these westerlies do, in fact, encircle the earth on any particular day. The 30-mb winds between 10°N and 10°S on 18 January 1967 are shown in Figure 10 and, in spite of the large areas for which no data exist, one is bound to say that it appears very much as if the wind is westerly about 30 kt all the way around the equator. (January 1967 was four months after a westerly maximum of the QBO.)

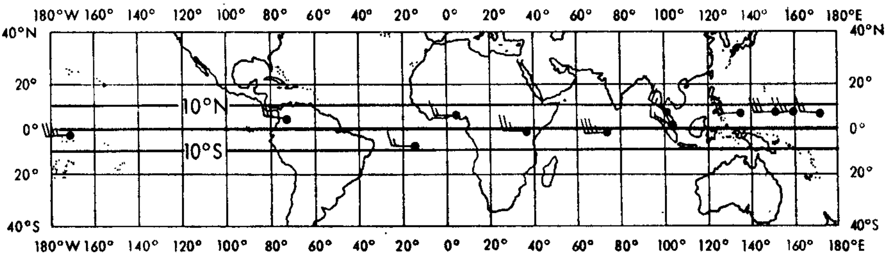

FIGURE 10—30-mb WINDS ON 18 JANUARY 1967
International symbols are used for plotting the winds.

Further discussion. The data presented in this note suggest that on both the monthly and the daily time-scales the wind régimes associated with the QBO are such that easterly or westerly winds can encircle the equator. Any general circulation model, if it is to describe winds in the equatorial stratosphere, must cater for quite rapid changes from westerly to easterly or vice versa in both the vertical and the horizontal (i.e. with increasing latitude) and also for the westerly and easterly régimes being continuous around the equator.

It is of interest to note that further evidence of the continuity of the low-latitude easterly and westerly régimes is provided by the balloon flights, at heights of 20–24 km, launched from Ascension Island (07° 58′S 14° 24′W) in connection with feasibility studies concerning the first Global Atmospheric Research Programme (GARP) global experiment.[2] One such flight was launched on 11 June 1970 and the balloon remained in the latitude band approximately 15°S to the equator whilst orbiting the earth six times during its 105-day flight. This flight took place during a strong easterly phase of the QBO. Another flight was launched from Ascension Island on 22 August 1969 and flew for 111 days during which time the QBO changed phase from westerly to easterly. This balloon remained in the latitude band 13°S–3°N and completed one and a half orbits in the westerly winds before reversing its direction of travel in the easterly circulation. These flights were launched at 8°S but, as is suggested in the progress report on the development of this work,[2] three launching sites are needed (one located close to the equator, one at 5°–10°N and one at 5°–10°S) in order to provide a more complete description of the behaviour of tropical stratospheric winds.

It is apparent that in preparing a descriptive note of this nature the lack of adequate stratospheric wind data imposes a severe restriction on the analysis which it is possible to undertake and also on the confidence which can be placed in the analysis. Although an effort was made to ensure that months and days were used which provided the maximum data coverage there are considerable areas for which no observed winds were available. Nevertheless, it is felt that these diagrams do provide a little more descriptive material regarding the behaviour of the QBO and how it fits into the global circulation patterns. The charts presented here deal only with particular Januarys and Julys — it may well be that similar charts for other months over a longer period could provide much more useful information and materially add to an understanding of the role of the QBO. Such charts might provide synoptic evidence in support of the suggestion that the phase of the QBO has a bearing on the time of the spring wind reversal in the high-latitude stratosphere.[3] In addition, there appears to be a correlation between the time of this spring reversal in the stratosphere and the index of the weather of the following summer over some parts of the northern hemisphere. A better understanding of the part played by the QBO in the interaction between the high- and low-latitude stratospheres, combined with a study of stratospheric/tropospheric relationships, might lead to a suggested mechanism for forecasting developments for a season ahead.

The time is approaching when it will be possible to prepare stratospheric charts with more confidence in some low-latitude areas. The implementation of the World Weather Watch Global Observing System combined with the plans being made for the improvement in data coverage for the World Meteorological Organization's Atlantic Tropical Experiment of the Global Atmospheric Research Programme (GATE) will certainly result in a far more adequate network of radiosonde and radiowind stations in some tropical areas. In spite of this improved coverage over a wide area, there will still be regions of the tropics over which the network of stations reporting stratospheric winds will probably remain as it is at present and in these areas detailed analysis will remain difficult and uncertain.

REFERENCES

1. EBDON, R. A.; Periodic fluctuations in equatorial stratospheric temperatures and winds. *Met Mag, London,* **100**, 1971, pp. 84–90.
2. FRYKMAN, R. W., LALLY, V. E. and LICHFIELD, E. W.; Progress report on the development of a balloon carrier vehicle for tropical soundings. COSPAR Working Group 6 Report to JOC, Annex D, January, 1971. Unpublished copy available in the Meteorological Office Library, Bracknell.
3. EBDON, R. A.; Spring and autumn reversals of stratospheric winds over Scotland. *Met Mag, London,* **101**, 1972, pp. 65–77.

551.507.362.1:551.508.822:681.2.08

TEMPERATURE CORRECTIONS FOR THE SKUA ROCKETSONDE TEMPERATURE SENSOR

By B. D. MASON and J. ACRES

Summary. The temperature profile of the stratosphere and lower mesosphere is investigated by means of a parachute-borne tungsten-wire sensor carried to heights above 70 km by a SKUA rocket. The temperature recorded by the sensor is not the true air temperature because the sensor is subjected to various forms of heat transfer during its descent. This paper describes tests which have recently been conducted in a low-density wind-tunnel and a vacuum chamber to determine the corrections to be applied. The wind-tunnel tests were performed over a range of speeds corresponding to the normal fall-speed of the SKUA rocketsonde at pressures equivalent to heights between 35 km and 61 km whilst the vacuum-chamber experiments enabled the corrections for infra-red and solar radiation to be obtained. From the results presented it is concluded that for rocket soundings during the hours of darkness the only major correction to be applied is caused by dynamic heating.

Introduction. The temperature sensor used in the SKUA meteorological rocketsonde (Almond[1]) is constructed from spiralized tungsten-wire of diameter 13·5 μm, with a total wire length of 772 cm and a total resistance of approximately 3100 ohms at 0°C. The wire is supported on polytetrafluorethylene (PTFE) monofilaments stretched across an 8·9-cm diameter ring of resin-bonded fabric.

During its descent from heights above 70 km the sensor is subjected to various forms of heat transfer. A theoretical analysis of the different factors that contribute to the heat flow has been made by Hyson,[2] who concluded that during night flights, in the absence of solar radiation, the only major source of error in the indicated temperature was caused by dynamic heating.

In order to determine the various temperature corrections to be applied, experiments had been conducted during 1963, before the first rocket soundings, in the low-density wind-tunnel of the National Physical Laboratory (Clark[3]), but most of the measurements were taken at wind speeds in excess of the fall-speed of the sonde at the appropriate pressures. Further wind-tunnel experiments have been performed recently over a larger range of pressures and at more representative wind speeds. In addition, measurements of the rate of energy transfer by convection were made and tests were conducted in a laboratory vacuum chamber to determine the radiation characteristics of the sensor.

Wind-tunnel experiments. For the purpose of the wind-tunnel experiments one sensor was mounted on a rotatable base, as used by Clark,[3] and placed in the working chamber of the tunnel with a second identical sensor mounted in the stagnation chamber, the pressures in the two chambers being measured by a Pace gauge and a precision oil-gauge respectively. In addition, a McLeod gauge was used as a standard to calibrate the recording gauges before each run, when the pressure in the two chambers was equal; a further comparison was made at the end of each run. When any appreciable drift of the gauges occurred the readings were not accepted, but this was infrequent.

The normal fall-speed of the sonde and parachute decreases from about 150 m s^{-1} at 62 km to 65 m s^{-1} at 50 km and 31 m s^{-1} at 40 km and it is in the region above 50 km that the temperature sensor experiences the greatest effect from dynamic heating. Thus the tests were conducted over a range of airspeeds to include the above descent rates at the appropriate pressure levels. Most of the investigations were carried out at pressures of 80, 160, 320, 500 and 1000 μmHg, corresponding to approximate heights of 61, 56, 50, 47 and 42 km, with a small number of tests at 1500, 2000 and 3000 μmHg; the pressure equivalents in millibars are given in Table I. At the higher pressures the limitations of the wind-tunnel pumps prevented speeds other than about 50 m s^{-1} from being obtained.

The simplified energy balance equation of the sensor is

$$E + Du^2 = k\,(T_i - T)$$

where E is the energy supplied to the sensor; D is a dynamic heating coefficient and is probably a function of u and T and pressure, p, of the working chamber; and $k = k_c + k_r$ where k_c is the coefficient of convective heat transfer and k_r is a radiation coefficient. The observed stagnation and working pressures enable values of the airspeed, u, and the ambient temperature, T, of the working chamber to be calculated; T_i, the indicated air temperature,

TABLE I—HEAT-FLOW AND ASSOCIATED PARAMETERS OF THE SENSOR DURING DESCENT

p	p	$\rho \times 10^3$*	H(U.S.)*	u	$u^2 \times 10^{-4}$	$k \times 10^3$	$D/k \times 10^4$	Du^2/k	ΔT_r	ΔT_s	C/k
μmHg	mb	kg m^{-3}	km	m s^{-1}		J s^{-1}K^{-1}	K m^{-2} s^{-2}	degrees Kelvin			s
80	0·11	0·15	61	128	1·64	3·5	6·9	11·3	1·6	18·6	0·9
160	0·21	0·29	56	97	0·94	6	6·7	6·3	1·0	10·9	0·5
320	0·43	0·62	50·5	68	0·46	10	5·5	2·5	0·6	6·5	0·3
500	0·67	0·97	47	54	0·29	15	6·9	2·0	0·3	4·3	0·2
1000	1·33	2·06	42	37	0·14	25	9·7	1·4	0·2	2·6	0·1
1500	2·00	3·04	39·5	30	0·09	28	10·4	0·9	0·1	2·3	0·1
2000	2·67	4·17	37·5	25	0·06	34	10·7	0·6	0·1	1·9	0·1
3000	4·00	6·85	35	21	0·04	41	12·6	0·5	0·1	1·6	0·1

* Density, ρ, and height, *H*, values are based on the U.S. Standard Atmosphere 1966 for 60°N January (cold).

is measured directly. Figure 1 shows the values of $\Delta T = T_i - T$ plotted against u^2 for $p = 160$ µmHg and $E = 0$, and indicates a linear relationship, the gradient of which is D/k, the dynamic heating factor; Clark's[3] results from 1963 and Hyson's[2] theoretical curve for a cylinder in free molecular flow are also shown. Values of D/k for the various pressures and the dynamic heating correction Du^2/k, for normal sonde fall-speeds and heights based on the U.S. Standard Atmosphere 1966, are given in Table I. The effect of yaw was studied by repeating some runs with the sensor inclined at various angles to the airstream but this only confirmed the findings of Clark, that there is virtually no change in indicated temperature for angles of yaw up to 45°.

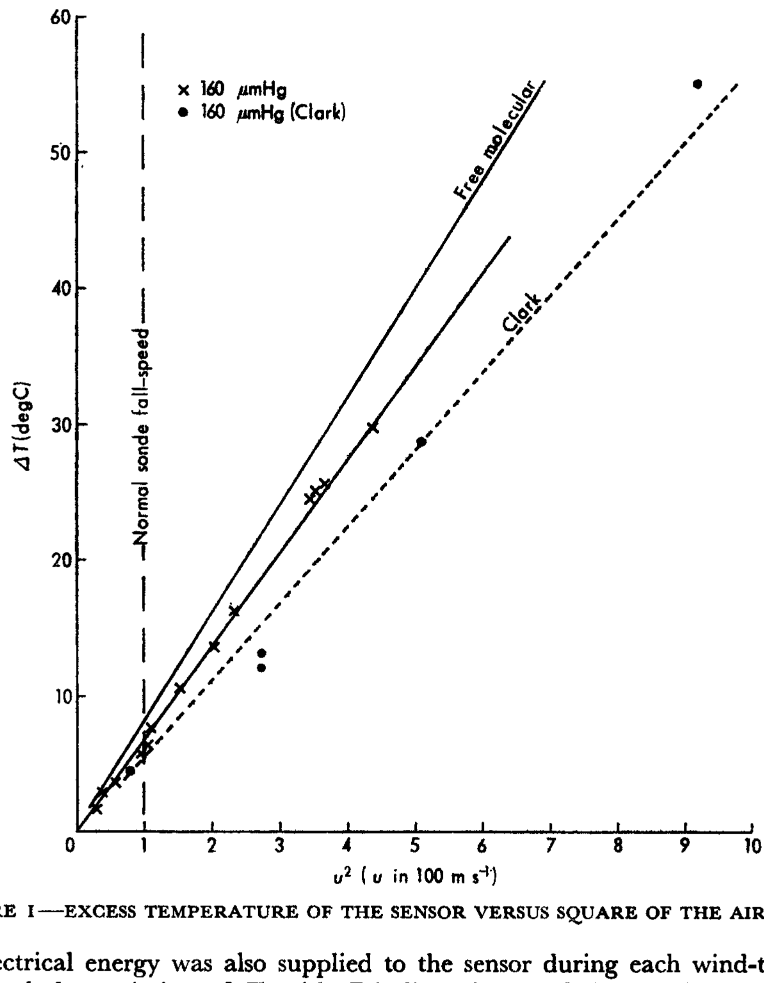

FIGURE 1—EXCESS TEMPERATURE OF THE SENSOR VERSUS SQUARE OF THE AIRSPEED

Electrical energy was also supplied to the sensor during each wind-tunnel test and the variation of T_i with E indicated a good linear relationship in almost all cases; examples are shown in Figure 2. At the lower pressures of 80 and 160 µmHg, where it was possible to obtain a large range of airspeeds, the value of $k = dE/dT_i$ varied only slightly with airspeed, but at higher pressures the value of k was more variable. Estimated values of k for normal sonde fall-speeds are given in Table I.

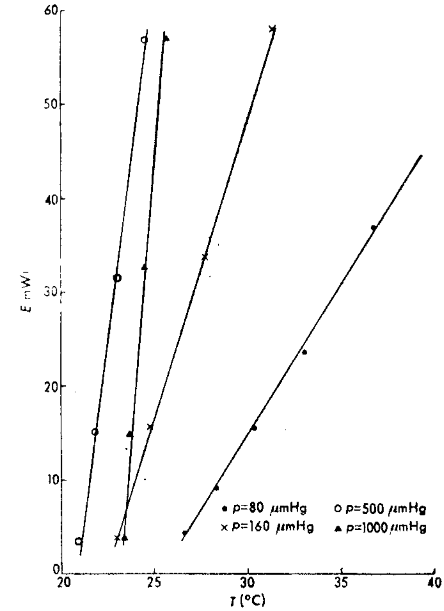

FIGURE 2—RELATIONSHIP BETWEEN ENERGY SUPPLIED TO THE SENSOR AND THE INDICATED TEMPERATURE

The tests were conducted over a period of three weeks and were not carried out in a systematic order.

Vacuum-chamber experiments. Experiments were conducted on the sensor in a vacuum chamber at a pressure of 0·3 μmHg. An electric current was passed through the sensor and the power absorbed varied linearly with the excess of temperature of the sensor over the temperature of the chamber walls. The power absorbed by four different elements, when there was an excess temperature of 30 degK, varied by ± 20 per cent from the mean value of $9{\cdot}4 \times 10^{-3}$ joule s^{-1} but for a given supply of power there was no variation of the temperature for a reasonable change of pressure at this low pressure. It is therefore concluded that energy transfer by convection was negligibly small and that all the electrical energy is dissipated by infra-red radiation and conduction at a rate of $3{\cdot}1 \times 10^{-4}$ joule s^{-1} K^{-1}.

Conduction will occur along the monofilaments from the outer ring of the tungsten wire to the support frame, a distance of about 1 cm. For a thermal conductivity of $\lambda = 2{\cdot}5 \times 10^{-3}$ joule s^{-1} cm^{-2} K^{-1} cm^{-1} the conduction is at the rate of 6×10^{-5} joule s^{-1} K^{-1}. Similarly although the wire is almost isothermal, some conduction will occur at the two ends of the wire where it is connected to the terminal electrodes. For a distance of 1 cm at each end of the wire and $\lambda = 1{\cdot}70$ joule s^{-1} cm^{-2} K^{-1} cm^{-1} the rate of conduction is $4{\cdot}8 \times 10^{-6}$ joule s^{-1} K^{-1}. Thus the rate at which energy is dissipated by conduction is small compared with the total rate of energy dissipation. If the mean value of $9{\cdot}4 \times 10^{-3}$ joule s^{-1} is adopted as the energy dissipated when the temperature of the wire is 30 degK above the chamber wall temperature of 295 K, and equate this with $\varepsilon A_\varepsilon \sigma(325^4 - 295^4)$, where σ is the Stefan-Boltzmann constant, the value of the effective emission constant of the sensor $\varepsilon A_\varepsilon = 0{\cdot}46$, where ε is the emissivity and A_ε the effective radiating area of the sensor. It is difficult to obtain an accurate value of A_ε because some parts of the radiating surface will be shadowed by others and there will be some emission from the PTFE monofilaments, but a good estimate would be $A_\varepsilon = 3$ cm² from which we deduce $\varepsilon = 0{\cdot}15$. However, it is the value of $\varepsilon A_\varepsilon$ which is important since it represents the effective emission constant of the complete sensor.

The sensor was next exposed to short-wave radiation from a quartz-iodine lamp through the window of the chamber and the radiation flux was measured by substituting a solarimeter for the sensor. It was found that for a radiation flux of $18{\cdot}6 \times 10^{-3}$ joule $s^{-1}cm^{-2}$ the excess temperature was 28·7 degK giving a value of $\alpha A_\alpha = 0{\cdot}48$ where α is the absorption coefficient and A_α the effective absorption area of the sensor. When the plane of the element is normal to the radiation the effective absorption area of the sensor is about 0·67 cm², from which $\alpha = 0{\cdot}72$.

Radiation corrections. If we use the values of $\varepsilon A_\varepsilon$ and αA_α obtained above and assume that the sensor is in long-wave radiation equilibrium with the atmosphere below, but emits freely upwards, values of the infra-red radiation correction, ΔT_r, to be added can be obtained. The rate of emission of infra-red radiation is $\frac{1}{2}\varepsilon A_\varepsilon \sigma T_i^4$ where T_i is the indicated air temperature at a given level. Values of $\Delta T_r = \frac{1}{2}\varepsilon A_\varepsilon \sigma T_i^4/k$ given in Table I are based on temperatures from the U.S. Standard Atmosphere. The radiation correction, ΔT_s, due to incident solar radiation on the sensor is $0{\cdot}48S/k$, where S is the radiation flux in joule $s^{-1}cm^{-2}$. If albedo effects are neglected and a value of $S = 136 \times 10^{-3}$ joule $s^{-1}cm^{-2}$ is used, the corrections are as shown in Table I.

Time constant. The time constant of the sensor is C/k where C is the thermal capacity of the sensor and has a value of about 3×10^{-3} joule K^{-1}. From the values shown in Table I it can be seen that the sonde would fall about 115 m in 0·9 s at a height of 61 km. The lag of the sensor is thus quite small and can be neglected.

Conclusion. It is evident from Table I that the greatest single correction to be applied during daylight soundings is that caused by solar radiation. The amount of heating caused by solar radiation incident on a sensor will vary according to the angle of insolation, the albedo and the effective area of the sensor receiving solar radiation at a given time; this is particularly difficult to estimate because on its descent the parachute oscillates causing the angle of incidence to vary continually. Shading will also occur from the parachute. Corrections to be applied due to solar radiation are therefore difficult to determine and for this reason the British Meteorological Office only conducts rocket soundings during the hours of darkness, when the only major correction to be applied is that caused by dynamic heating.

Acknowledgement. The authors would like to thank the staff of the National Physical Laboratory Aerodynamics Division for providing the facilities of their low-density wind-tunnel.

REFERENCES

1. ALMOND, R.; Techniques of temperature and wind sounding with the SKUA meteorological rocket. *Met Mag, London*, **94**, 1965, pp. 327–331.
2. HYSON, P.; The tungsten wire temperature sensor. *J Appl Met, Lancaster, Pa*, **7**, 1968, pp. 684–690.
3. CLARK, D. D.; A meteorological rocket sonde. *J Scient Instrum, London*, **42**, 1965, pp. 733–736.

REVIEWS

Forecast for Overlord — June 6, 1944, by J. M. Stagg, C.B., O.B.E. 238 mm × 160 mm, pp. 128, *illus.* Ian Allan Ltd, Shepperton, Surrey. 1971. Price: £2·60.

This is a most valuable and absorbing book. Its value springs from its full and dispassionate account, given by the man who was at the centre, of a particularly critical aspect of the invasion of Europe which took place on 6 June 1944 and was known by the code name Overlord. Operation Overlord was on such an enormous scale and of such vital consequence it will always have its place among the few decisive events in all history. A powerful group of nations had decided to stake almost everything, if not everything, upon the success of this operation. The outcome contained only two possibilities: either success which might take a long time to complete and consolidate, or rapid utterly calamitous failure.

But, except for one aspect, success was virtually assured by the weight of resources available and by the flexibility with which they could be deployed. The exception was the weather, the one thing no one could control, the one thing that could certainly bring disaster to what was the most completely planned military operation of all time. Apart from general readiness, there were numerous factors such as moon and tides to be taken into account and, subject to the weather, the most favourable combination of all these factors occurred in the first week of June 1944. An alternative period, but less favourable in several particulars, was the third week of that month. As it happened, the weather conditions in and around the English Channel during the early days of June, so far from illustrating the calm of summer, were stormy and overcast. As for the outlook, the meteorological situation was of such complexity and difficulty that the views of the best experts were bound to be divided. As D-day approached the task of Group Captain James Stagg as Chief Meteorological Officer to General Eisenhower, the Supreme Allied Commander, could not have been more worrying in regard to both the scientific judgements he had to make and the extreme importance of the advice he had to give. After the event, but not at the time, it is gratifying to note that the circumstances of great events are often so fashioned as to exact greatness from the principal characters — and in this particular great event let there be no doubt that Stagg was a principal.

The book is absorbing because it deals comprehensively with one of the important ingredients of a major historical occasion. Stagg was appointed to the Supreme Commander's staff in November 1943 and all his e were geared to the production of the D-day forecast some seven months later. Team-work had to be developed because many meteorologists, British and American and others, were involved with the various naval, army and air forces taking part in Overlord. These meteorologists each had their special problems, according to the role assigned to the military formation they were serving. There were also the Central Forecasting Office of the Meteorological Office at Dunstable, that of the Admiralty in London and that of the United States Army Air Force at the Widewing Headquarters in Teddington, Middlesex. Facilities were therefore provided for telephone conferences as frequently as necessary with all these centres simultaneously, each participant having his own charts in front of him and able to give his own views to all the others and to listen to the views they expressed. Stagg had to distil all these opinions, together with his own, into a forecast for the Supreme Commander. The procedure was tested at regular intervals, sometimes in connection with exercises, and one notes with interest the author's comment that in the whole series of conferences unanimity on a complete forecast was never achieved.

A special reason for welcoming this book is that in other published histories of the 1939–45 war the weather aspects of D-day are seldom presented adequately. In some cases it is clear that these aspects were not understood, in others attempts are made to dramatize individuals whereas the weather itself contained all the drama that anyone could wish for. Stagg's account is no less fascinating for the non-meteorologist than for the meteorologist. In it we see weather forecasting in its wide operational context and can perceive the responsibilities and anxieties of commanders as well as advisers. The decision to postpone D-day from 5 to 6 June because of the weather conditions is fully described with the aid of synoptic charts and it is seen that 6 June was the one day in the month of June when Overlord could have been launched.

A feature of the book is the generous acknowledgement which Stagg makes to the other meteorologists who participated with him, either in the telephone conferences or in other ways, in framing the weather forecasts for the operation. He insists that what he did was the culmination of team effort and, as we read on, the familiar names of some of the great forecasters pass before us. However, let us not conspire with the author in submerging his own contribution. James Stagg was the central figure in this significant element of a most momentous event. He carried the main weight of responsibility and the forecast, which did not represent the majority view, was highly accurate in a situation of the utmost difficulty.

P. J. MEADE

Standard dictionary of meteorological sciences — English–French/French–English, by G.-J. Proulx. 254 mm × 190 mm, pp. xxix + 307. McGill-Queen's University Press, 70 Great Russell Street, London WC1, 1971. Price: £9·50.

This beautifully produced but rather expensive dictionary, aimed not only at the meteorologist but at users in other disciplines, contains too many expressions. It would be more useful if confined to purely meteorological and associated hydrological/oceanographical terms and idiomatic expressions; as it is there is a superabundance of adjectival expressions that are obvious and are not required.

Due acknowledgements and references are given in the preface to the *Meteorological glossary* (London, HMSO, 1963) and to the *International cloud atlas* and *International meteorological vocabulary* of the World Meteorological Organization as well as to the American Meteorological Society's *Glossary of meteorology*. In addition a selected English-language and French bibliography is given. No reference is made, presumably because of timing, to G.-O. Villeneuve's *Glossaire météorologique* published earlier in 1971 by the Quebec Meteorological Service and to which this dictionary is complementary.

The French preface amplifies the various sections into which meteorology is divided and draws attention to other disciplines involved.

It is, however, excellent for the names of local weather phenomena, particularly winds, and the author has been very industrious here. Included are the caver — a Hebridean breeze, the doister or dyster — a gale off the sea, the haar, and so on throughout the world, to the vent d'autun of southern France, and the youg — a warm Mediterranean wind. I had hoped to find 'pied de vent' but unfortunately no, in fact these phenomena, being mostly the same in English and French, are more suited to a glossary.

Also it is very useful to have the English/French, French/English titles and abbreviations of the various meteorological and allied organizations under the one cover.

In general it is certainly a dictionary that every meteorological library will be expected to have on its shelves.

H. H. de CARLE

Kuwait: urban and medical ecology, by Geoffrey E. Ffrench and Allan G. Hill. 303 mm × 215 mm, pp. xiii + 124, *illus.*, Springer-Verlag, 1 Berlin 33, Heidelberger Platz 3, Berlin-West, 1971. Price: DM 58.

Described as a geomedical study this account of the State of Kuwait gives emphasis to sociological and economic developments, and contains a wealth of detail about health and disease, but only devotes some three pages to the climate. However, the statistics given, based mainly on the observations at the Government station of Shuwaikh (29°20′N 47°57′E) for the period 1956–69, but also including temperature and rainfall graphs for three other climatological stations as well as for the International Airport for the period 1956–69, adequately portray the essential features of sporadic winter rainfall, very hot dry summers and an extreme overall range of temperature (−3°C to +49°C for the 10-year period). Monthly wind roses for the Airport (period?) show clearly the north-westerly wind (shamal) which predominates at all times of the year. No mention is made of the earlier observations made by the India Meteorological Department and published in *Tables of temperature, relative humidity and precipitation for the world, Part V* (London, Meteorological Office, 1958) which gave an annual average rainfall of 129·5 mm at Kuwait City compared with the 1956–69 average of 102·4 mm at Shuwaikh. In a desert region rainfall is of course notoriously variable, but the excavation on the island of Failaka of a well-established bronze-age settlement — old perhaps when Babylon was new — as well as the remains of the flourishing 4th century B.C. Greek colony of Ikaros, suggests that over the past 3000 years the climate of Kuwait has become progressively less hospitable.

F. E. DINSDALE

NOTES AND NEWS

Retirement of Mr L. Jacobs

Mr Lewis Jacobs joined the Office as a Technical Officer in 1936. For the next 20 years he was engaged in forecasting or in the organization of forecasting services. He first served at Royal Air Force stations at home and then spent 3 years lecturing and forecasting for the General Reconnaissance School in Canada during the war, returning to England to become Senior Meteorological Officer with Airborne Forces in 1944. In 1945 he was awarded the United States Medal of Freedom with Bronze Palm for his services to the 1st Allied Airborne Army. He was mobilized as a wing commander in 1945 and later served in the Azores, returning, on his release from the RAFVR in 1947, to become one of the senior forecasters at the Central Forecasting Office at Dunstable. In 1950 Mr Jacobs became Senior Meteorological Officer at Gloucester. During 1956/57 Mr Jacobs represented the Director-General on a small committee responsible for planning the new headquarters building at Bracknell.

In 1957 Mr Jacobs was promoted to Assistant Director in charge of observatories and micrometeorology, remaining in this post for 12 years. During this period he was an active member of national and international committees on geomagnetism, atmospheric electricity and solar and terrestrial radiation and wrote several scientific papers on these subjects. The *Observatories' Year Book* had been discontinued at the outbreak of the war in 1939 and from 1957 onwards Mr Jacobs undertook the mammoth task of editing and publishing the back numbers of this annual, bringing it up to date with the volume for 1967 when responsibility for seismology and geomagnetism was transferred to the Institute of Geological Science, Natural Environment Research Council.

Since 1970 Mr Jacobs has been Assistant Director in charge of climatological services. Here his persistence and flair for organization have resulted in arrangements for the analysis by prison labour of autographic climatological records; by this means it is hoped to work through a very large backlog of useful records which would otherwise remain untouched.

Mr Jacobs has had wide interests and responsibilities in the Meteorological Office; as well as the activities mentioned above he prepared several climatological memoranda one of which, prepared during the war, helped the planning for the layout of runways at London /Heathrow Airport.

Mr Jacobs retired on 14 February 1972, and his colleagues will not be surprised that he has now turned his zeal and energies to teaching mathematics in a Grammar School near his home. We wish Mr Jacobs and his wife many happy years of retirement.

J. K. BANNON

LETTER TO THE EDITOR

Lightning strikes

We were interested to see Mr Pilsbury's account in the *Meteorological Magazine* for December 1971, pp. 373–375, of the lightning strike on the tree near the Meteorological Office. Of particular interest to us was the sizzling noise reported by Mrs Gaines. At Tarrant Rushton, Dorset, in 1953, we saw lightning strike a low building and a small tree about 150 yards from the office window through which we were looking. There was a noticeable sizzling which we heard immediately before the strike. It seemed to come from the air through which the lightning passed and not from the objects struck.

Meteorological Office, Bracknell

S. G. CORNFORD K. BRYANT

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WESTERLY-TYPE RAINFALL AND ATMOSPHERIC MEAN-SEA-LEVEL PRESSURE OVER ENGLAND AND WALES

By E. N. LAWRENCE

Summary. For days with a 'straight' westerly type (that is, not the anticyclonic-westerly or cyclonic-westerly types) of atmospheric circulation over the British Isles region, the long-term monthly and annual averages of the daily rainfall amount over England and Wales (combined) for 5-mb ranges of MSL pressure and the corresponding frequencies of these ranges were calculated for the period 1950–69 (20 years). The results were harmonically analysed for each range of pressure.

The results show that both the average daily rainfall amount and the amplitude of its annual variation increase with decreasing pressure; but with very low pressure there is a tendency for the daily rainfall amount to level off or even decrease. The date of the annual maximum daily rainfall amount varied from late November or earlier for well below average pressure, to December for higher pressure.

The frequency of days with 'straight' westerly-type circulation and the amplitude of its annual variation are largest when MSL pressure is about average. For low pressure the maximum frequency occurs mainly in winter, while with higher pressure the maximum frequency occurs mainly in summer and autumn.

The results are discussed in relation to sea temperature and land–sea orientation.

Introduction. An earlier project, to obtain synoptic-type daily rainfall averages over England and Wales,[1] showed that indirect estimates of total rainfall for individual months, based on these averages and on the register of daily synoptic types for the British Isles region,[2] fell short of the actual rainfall, or the so-called direct estimate of rainfall, for months which were extremely wet or extremely dry. The cause of these errors was attributed mainly to the loss of variance resulting from the use of averages for synoptic types with large frequencies, notably the 'straight' westerly type (that is, not the anticyclonic-westerly or cyclonic-westerly types[2]) of atmospheric circulation. To overcome this weakness in the procedure, as far as the 'straight' westerly type is concerned, days of this type were sub-classified according to atmospheric pressure at MSL.

The present work consists of the calculation of daily rainfall averages over England and Wales (combined) for varying ranges of pressure and the average frequencies of these ranges, for each calendar month and for the year for days of 'straight' westerly-type circulation.

Method. To ascertain objectively the daily pressure over England and Wales on 'straight' westerly-type days during the period of 20 years from 1950 to 1969, the pressure (to the nearest millibar) was read from the midday chart of the *Daily Weather Report** for the central point of 53°N 02°W.

For these days, the direct estimates of daily areal rainfall amounts for England and Wales[1] were processed to obtain for each calendar month the average daily rainfall amount for 5-mb ranges of pressure (e.g. 990–994, 995–999, 1000–1004 mb) and the corresponding average frequencies of the ranges (in days per month).

To eliminate irregularities arising from small samples, the average daily rainfall amount and average frequency, for each range of pressure separately, were adjusted by the use of a 1:2:1 weighting for each month together with its two adjacent months. The weightings were applied to rainfall totals, making due allowance for varying frequency. The resulting frequencies were slightly further adjusted, proportionally, to ensure that the total frequency for each month, for all values of surface pressure, remained the same as the initial frequencies given for the 'straight' westerly type.[1] The resulting values of the average daily rainfall amount and the average frequency, for each month separately, were then further adjusted by the use of a 1:2:1 weighting between consecutive five-millibar pressure categories. As before, the weightings were applied to rainfall totals, making allowance for varying frequency. This inter-pressure category weighting procedure was then repeated.

This repeated procedure of inter-pressure category weighting leads to two extra pressure categories at each extreme of pressure in each month. Such ranges of pressure did not actually occur within the 20-year period, either in the month indicated or in either of the two adjacent months. These 'theoretical' categories were eliminated by grouping the three pressure categories at each extreme of pressure, for each month separately. Results are shown in Table I.

Annual variation.

Daily rainfall amount. For days with a 'straight' westerly-type circulation, the average daily rainfall amount in each calendar month and for each of four alternate 5-mb ranges of pressure are shown in Figure 1, which shows also the first harmonic curves. The 'theoretical' categories, previously mentioned, are included in the plotted points of Figure 1 and also in the harmonic analysis whenever such categories occur. This procedure provides values in the pressure range of 990–994 mb in the summer months.

The harmonic coefficients, for various ranges of pressure, are given in Table II, using the notation :

$$R \text{ or } F = a_0 + \sum_{k=1}^{k=5} \left(a_k \cos \frac{2\pi k}{12} t + b_k \sin \frac{2\pi k}{12} t \right),$$

where $t = 0, 1, 2$, etc. refer to January, February, March, etc. and R millimetres per day is the average daily rainfall amount for a given range of pressure and F days per month is the average frequency of the given range, for days of 'straight' westerly-type circulation. It can be seen from Table II that the

* London, Meterological Office. *Daily Weather Report.*

TABLE I—AVERAGES OF RAINFALL OVER ENGLAND AND WALES FOR GIVEN RANGES OF MSL PRESSURE AND FREQUENCIES OF THESE RANGES IN THE PERIOD 1950–69 FOR 'STRAIGHT' WESTERLY-TYPE CIRCULATION

		Pressure range (mb)											
		975–979	980–984	985–989	990–994	995–999	1000–1004	1005–1009	1010–1014	1015–1019	1020–1024	1025–1029	1030–1034
Jan.	*R*	4·4	4·8	4·8	4·9	5·1	5·0	4·5	3·9	3·3	2·8	2·1	1·2
	F	0·03	0·08	0·16	0·29	0·48	0·70	0·83	0·93	0·97	0·79	0·45	0·21
	RF	0·13	0·38	0·77	1·42	2·45	3·50	3·73	3·63	3·20	2·21	0·95	0·25
Feb.	*R*		4·1	3·8	3·8	4·2	4·3	3·9	3·2	2·5	2·0	1·5	0·8
	F		0·07	0·11	0·20	0·35	0·50	0·60	0·68	0·73	0·64	0·38	0·19
	RF		0·29	0·42	0·76	1·47	2·15	2·34	2·18	1·83	1·28	0·57	0·15
Mar.	*R*		3·8	3·5	3·8	4·1	4·0	3·4	2·6	2·1	1·6	1·2	0·6
	F		0·04	0·07	0·16	0·33	0·53	0·71	0·83	0·82	0·62	0·32	0·15
	RF		0·15	0·25	0·61	1·35	2·12	2·41	2·16	1·72	0·99	0·38	0·09
Apr.	*R*				3·6	3·8	3·5	2·9	2·4	2·1	2·0	1·7	1·1
	F				0·11	0·20	0·41	0·68	0·92	0·91	0·62	0·28	0·10
	RF				0·40	0·76	1·43	1·97	2·21	1·91	1·24	0·48	0·11
May	*R*				2·6	3·0	2·9	2·6	2·2	2·0	1·8	1·7	
	F				0·04	0·11	0·31	0·65	1·00	1·09	0·77	0·42	
	RF				0·10	0·33	0·90	1·69	2·20	2·18	1·39	0·71	
June	*R*					2·2	2·4	2·4	2·2	2·0	1·7	1·4	
	F					0·10	0·27	0·68	1·17	1·34	0·96	0·47	
	RF					0·22	0·65	1·63	2·57	2·68	1·63	0·66	
July	*R*					3·1	2·9	2·7	2·5	2·2	1·9	1·4	
	F					0·10	0·31	0·81	1·36	1·49	1·02	0·47	
	RF					0·31	0·90	2·19	3·40	3·28	1·94	0·66	
Aug.	*R*					4·5	4·1	3·6	3·1	2·7	2·2	1·6	
	F					0·16	0·43	0·94	1·40	1·39	0·88	0·41	
	RF					0·72	1·76	3·38	4·34	3·75	1·94	0·66	
Sept.	*R*					4·8	4·3	3·9	3·4	3·0	2·4	1·8	
	F					0·30	0·58	1·06	1·42	1·35	0·85	0·42	
	RF					1·44	2·49	4·13	4·83	4·05	2·04	0·76	
Oct.	*R*			8·9	6·1	5·1	4·5	3·9	3·5	3·0	2·5	1·8	
	F			0·04	0·12	0·35	0·70	1·09	1·36	1·28	0·85	0·47	
	RF			0·36	0·73	1·79	3·15	4·25	4·76	3·84	2·13	0·85	
Nov.	*R*	5·6	7·8	7·4	6·6	5·9	5·3	4·5	3·7	3·2	2·6	2·0	
	F	0·02	0·04	0·10	0·23	0·48	0·80	1·05	1·16	1·06	0·74	0·47	
	RF	0·11	0·31	0·74	1·52	2·83	4·24	4·73	4·29	3·39	1·92	0·94	
Dec.	*R*	4·7	6·1	6·1	6·0	5·9	5·5	4·9	4·1	3·5	2·9	2·2	1·3
	F	0·03	0·07	0·17	0·32	0·59	0·88	1·06	1·13	1·06	0·78	0·41	0·16
	RF	0·14	0·43	1·04	1·92	3·48	4·84	5·19	4·63	3·71	2·26	0·90	0·21
Year	*R*	4·75	5·20	5·51	5·07	4·83	4·38	3·70	3·08	2·63	2·20	1·71	1·00
	F	0·08	0·30	0·65	1·47	3·55	6·42	10·16	13·36	13·49	9·52	4·97	0·81
	RF	0·4	1·6	3·6	7·5	17·1	28·1	37·6	41·2	35·5	21·0	8·5	0·8

R = monthly or annual rainfall averages in mm/day
F = average frequencies of the pressure ranges in days/month or days/year
RF = product of *R* and *F* in mm.

TABLE II—HARMONIC COEFFICIENTS OF (a) THE ANNUAL VARIATION OF WESTERLY-TYPE RAINFALL AMOUNT AND (b) FREQUENCY OF WESTERLY TYPE FOR DIFFERENT RANGES OF MSL PRESSURE OVER ENGLAND AND WALES, 1950–69

Pressure range mb	Harmonic coefficients										
	a_0	a_1	b_1	a_2	b_2	a_3	b_3	a_4	b_4	a_5	b_5
(a) Rainfall amount, *R*					millimetres/day						
990– 994	+4·363	+0·965	−1·535	−0·424	+0·006	−0·176	−0·388	+0·107	+0·104	+0·020	−0·047
995– 999	+4·309	+1·002	−1·039	−0·200	+0·069	−0·083	−0·423	−0·028	+0·091	+0·050	−0·030
1000–1004	+4·060	+0·988	−0·791	−0·032	+0·077	−0·013	−0·311	−0·091	+0·045	+0·040	−0·012
1005–1009	+3·594	+0·808	−0·710	+0·093	+0·062	+0·053	−0·193	−0·073	+0·003	+0·012	+0·000
1010–1014	+3·075	+0·576	−0·663	+0·130	+0·012	+0·117	−0·131	−0·006	−0·013	+0·004	+0·010
1015–1019	+2·622	+0·414	−0·573	+0·106	−0·053	+0·151	−0·126	+0·047	−0·010	+0·009	+0·017
1020–1024	+2·205	+0·295	−0·436	+0·045	−0·107	+0·153	−0·137	+0·062	+0·008	+0·007	+0·024
1025–1029	+1·761	+0·169	−0·286	−0·035	−0·153	+0·144	−0·130	+0·052	+0·041	−0·002	+0·033
(b) Frequency, *F*					days/month						
990– 994	+0·128	+0·141	−0·031	+0·025	−0·022	−0·005	−0·015	−0·004	−0·011	+0·001	−0·005
995– 999	+0·285	+0·211	−0·088	+0·001	−0·031	−0·010	−0·026	−0·007	−0·022	+0·002	−0·010
1000–1004	+0·536	+0·197	−0·171	−0·029	−0·030	−0·009	−0·043	−0·005	−0·033	+0·002	−0·015
1005–1009	+0·847	+0·015	−0·237	−0·037	−0·018	−0·005	−0·053	+0·007	−0·038	+0·001	−0·019
1010–1014	+1·114	−0·217	−0·238	+0·000	−0·020	−0·002	−0·041	+0·028	−0·044	+0·001	−0·021
1015–1019	+1·124	−0·268	−0·164	+0·062	−0·037	+0·003	−0·002	+0·039	−0·044	+0·001	−0·019
1020–1024	+0·794	−0·121	−0·072	+0·080	−0·038	+0·007	+0·027	+0·027	−0·027	+0·001	−0·014
1025–1029	+0·364	+0·018	−0·018	+0·047	−0·017	+0·008	+0·021	+0·011	−0·008	+0·001	−0·008

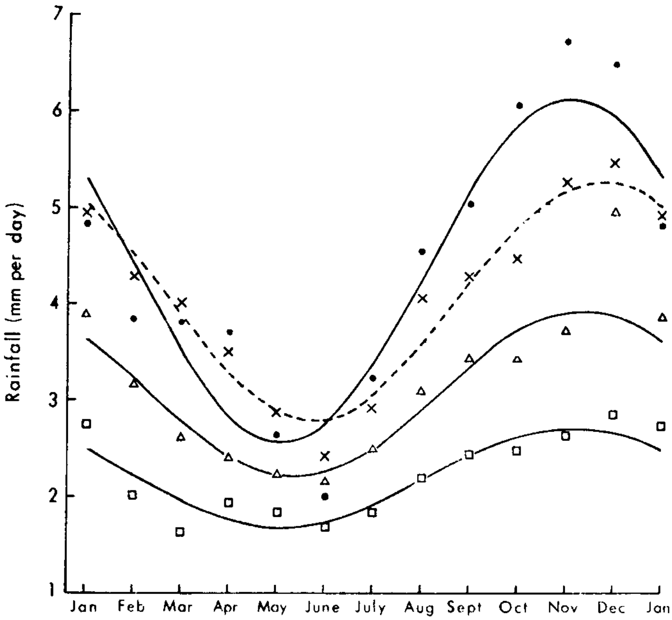

FIGURE 1—ANNUAL VARIATION OF THE AVERAGE DAILY WESTERLY-TYPE RAINFALL AMOUNT OVER ENGLAND AND WALES FOR DIFFERENT RANGES OF PRESSURE AT MSL AND THE FIRST HARMONIC CURVES, DURING THE PERIOD 1950–69

● ——— ● 990–994 mb X- - - - -X 1000–1004 mb

△ ——— △ 1010–1014 mb □ ——— □ 1020–1024 mb

first harmonic coefficients are the most important and that the second and third harmonics add significant contributions; the remaining harmonics can be regarded as 'noise'.

The first harmonic coefficients (Table II) were used to calculate, for each 5-mb range of pressure, the amplitude of the annual variation of average daily rainfall amount (Figure 2), and the first three harmonic coefficients

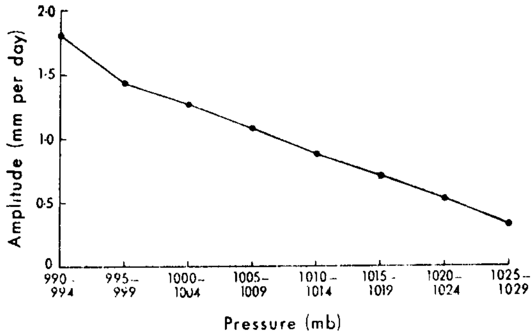

FIGURE 2—AMPLITUDE OF THE ANNUAL VARIATION OF THE AVERAGE DAILY WESTERLY-TYPE RAINFALL AMOUNT OVER ENGLAND AND WALES FOR DIFFERENT RANGES OF PRESSURE AT MSL, BASED ON FIRST HARMONICS, DURING THE PERIOD 1950–69

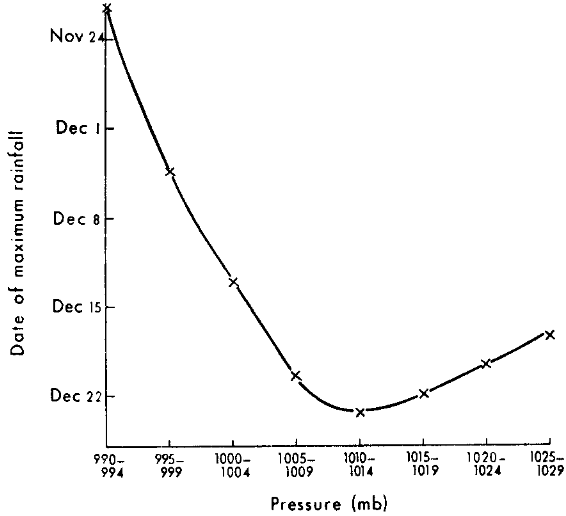

FIGURE 3—DATE OF THE ANNUAL MAXIMUM AVERAGE DAILY WESTERLY-TYPE RAINFALL AMOUNT OVER ENGLAND AND WALES FOR DIFFERENT RANGES OF PRESSURE AT MSL, BASED ON THE FIRST THREE HARMONICS, DURING THE PERIOD 1950–69

(Table II) were used to calculate the date of the annual maximum average daily rainfall amount (Figure 3) for the 'straight' westerly type. For each range of pressure in Figure 3 the estimated date of the maximum value of R was obtained from the formula :

$$R = a_0 + \sum_{k=1}^{k=3} \left\{ a_k \cos(30kt)^\circ + b_k \sin(30kt)^\circ \right\},$$

where t varies from 8·5 (beginning of October) to 0·5 (end of January) (the period which includes the maximum value of R), and where the values of a_0, a_k and b_k are obtained from Table II.

Frequency of westerly-type circulation. For days of 'straight' westerly-type circulation, the average frequency in each calendar month and for each of four ranges of pressure are shown in Figure 4, which shows also the first harmonic curves. The so-called 'theoretical' categories, previously discussed, were included in the plotted points and also in the harmonic analysis whenever such categories occurred.

The harmonic coefficients, for various ranges of pressure, are given in Table II, using the notation previously described.

The first harmonic coefficients were used to calculate, for each range of pressure, (a) the amplitude of the annual variation of average frequency (Figure 5) and (b) the date of the annual maximum average frequency (Figure 6) — for the westerly type. The equation of the first harmonic curve of the amplitudes of Figure 5 is :

$$F = 0{\cdot}209 + 0{\cdot}11 \sin(45p - 62)^\circ ,$$

where p = 0, 1, 2, etc. give F for 990–994, 995–999, 1000–1004 mb, etc.

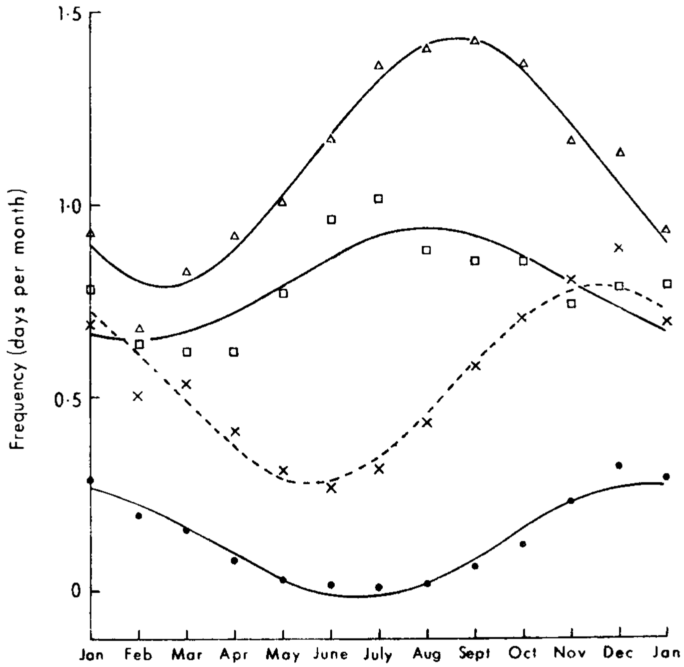

FIGURE 4—ANNUAL VARIATION OF THE AVERAGE FREQUENCY OF DAYS WITH WESTERLY-TYPE CIRCULATION OVER THE BRITISH ISLES REGION FOR DIFFERENT RANGES OF PRESSURE AT MSL AND THE FIRST HARMONIC CURVES, DURING THE PERIOD 1950–69

● ——— ●	990–994 mb	X- - - - -X	1000–1004 mb
△ ——— △	1010–1014 mb	□ ——— □	1020–1024 mb

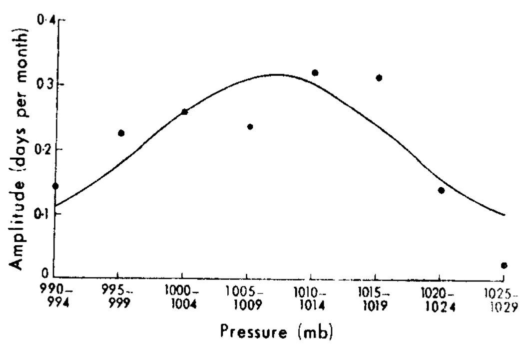

FIGURE 5—AMPLITUDE OF THE ANNUAL VARIATION OF THE AVERAGE FREQUENCY OF DAYS WITH WESTERLY-TYPE CIRCULATION OVER THE BRITISH ISLES REGION FOR DIFFERENT RANGES OF PRESSURE AT MSL, BASED ON FIRST HARMONICS, AND THE FIRST HARMONIC CURVE OF THESE AMPLITUDES, DURING THE PERIOD 1950–69

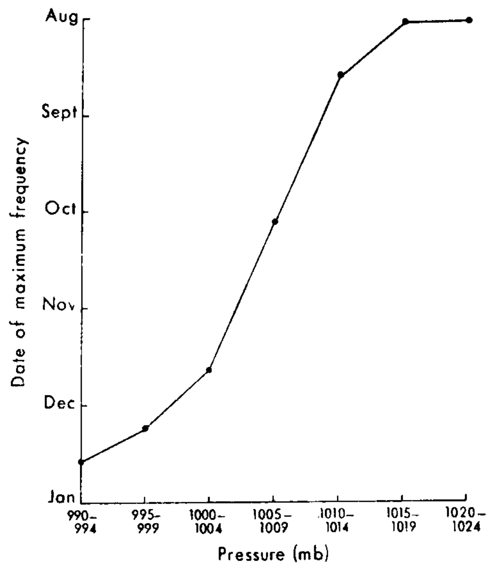

FIGURE 6—DATE OF THE ANNUAL MAXIMUM AVERAGE FREQUENCY OF DAYS WITH WESTERLY-TYPE CIRCULATION OVER THE BRITISH ISLES REGION FOR DIFFERENT RANGES OF PRESSURE AT MSL, BASED ON FIRST HARMONICS, DURING THE PERIOD 1950–69

In Figure 6, the point corresponding to the range of pressure, 1025–1029 mb is not plotted because the annual variation of frequency for this pressure range is small and shows no clear single annual maximum, as indicated by the non-dominant first harmonic coefficients of Table II. In Figure 6, the annual 'peak' dates of mid-January, mid-December, etc. correspond to phase angles of 90°, 120°, etc. in the first harmonic curves based on Table II data.

Discussion. Table I and Figures 1 and 2 show the expected result that for 'straight' westerly-type circulation over the British Isles the average daily rainfall amount and the amplitude of its annual variation both increase with decreasing pressure; the annual mean and the amplitude decrease almost linearly with pressure from 995 to 1029 mb (Table I and Figure 2); in this range of pressure, the ratio of the amplitude to the mean also decreases steadily, from 0·33 to 0·19; but with very low pressure, there is a tendency for the daily rainfall amount to level off or even decrease. This latter result may be caused by a greater *cyclonic* curvature over the North Atlantic when pressure is lower, and hence by an influx of drier air masses; also, because very low pressures may indicate that the depression 'associated' with the westerlies is at or near its maximum depth, a large part of England and Wales may be well away from active fronts and have drier and colder air aloft, associated with the 'cold pool' stage of cyclonic development. A decrease of rainfall with very low pressure may result also from a decrease of orographic rainfall associated with decreased gradients.

The date of the annual maximum rainfall amount changed from late November (or earlier) to late December as the pressure increased from 990–994 mb (or below) to 1010–1014 mb, but with further increase of pressure to 1025–1029 mb, there was a tendency for the date of daily maximum rainfall amount to become slightly earlier again, that is, to change to about mid-December (Figure 3). A possible explanation of these results is that the various pressure ranges are associated with different isobaric curvatures over the North Atlantic and so with different air-mass sources namely :

(1) 990–994 mb from the region between Iceland and Greenland (cyclonic curvature),
(2) 1000+ mb from the Davis Straits region (slight cyclonic curvature) or the Newfoundland region (small mean curvature), and possibly also
(3) 1015–1024 mb from the south-west of the North Atlantic, south and east of Newfoundland (slight anticyclonic curvature).

The annual variation of British rainfall could thus depend on the annual variation of meteorological factors, notably sea surface temperature, in these regions.

The association of anomalous sea surface temperature gradients with greater cyclonic development or other anomalous meteorological factors is alleged or suggested by a number of authors.[6,7,8] In particular, a maximum daily rainfall amount in November, with pressure of 990–994 mb may be associated with a November maximum in the sea surface temperature gradient in region (1). In this region unpublished sea-temperature data[3] for ocean weather station (OWS) A (62° 00′N, 33° 00′W) for the period 1951 to 1960 together with published data[4] for OWS C (52° 45′N, 35° 30′W) for the same period show a November maximum in the north–south gradient of sea surface temperature, though published data for OWS A[5] together with data for OWS C[4] show only that the north–south gradient was greater in November than in December.

The area of maximum sea surface temperature gradient may well move south to region (2) by December and thus lead to a December maximum in British rainfall for air masses originating in this region. Certainly monthly averages of sea surface temperature, as evidenced by OWS B (56° 30′N, 50° 00′W),[4] show a decrease through the autumn and winter, presumably associated with an increasing tongue of cold surface water of the Labrador current.

The tendency for the date of maximum rainfall to become earlier again (moving from late December to mid-December) for pressures in the range of 1015–1024 mb may well be due to an association of such pressure values with air masses originating partly in region (3). In this region, data[4] for OWS C and OWS D show a maximum sea surface temperature gradient in November.

According to this sea-temperature hypothesis as the explanation of the annual variation in the date of the daily maximum rainfall amount (Figure 3), the results in general suggest that the area of cyclogenesis relevant to British rainfall may include all these regions and so extend well beyond the region to the south of Newfoundland.[8]

An alternative explanation of the small annual pressure-dependent shift in the date of the maximum average daily rainfall amount with the 'straight' westerly-type circulation is based on the pattern of annual variation in *overland* thermal convection. Rainfall resulting from such convection may be greater when there is (a) more direct polar air, that is, more cyclonic curvature over the North Atlantic, presumed to be associated with lower pressure or (b) smaller pressure gradients overland, associated with high and low extremes of pressure. Since both synoptic situations (a) and (b) are in general more likely to produce thermal convection rainfall at times of the year when insolation is greater, a shift of the annual rainfall maximum from December to November or earlier could occur with the more extreme values of pressure or at least with the lower extremes.

The importance of the annual variation of both overland thermal convection and sea temperature in explaining the annual variation of synoptic-type average daily rainfall amount is suggested by the results of an earlier investigation.[1]

Table II and Figures 4 and 5 show the expected result — that the frequency of days with 'straight' westerly-type circulation and the amplitude of its annual variation are largest when pressure is about average. Figure 6 shows that the annual maximum frequency with low pressure occurs mainly in winter, while the maximum frequency with higher pressure occurs mainly in summer and autumn, presumably reflecting the seasonal displacement of the Azores anticyclone.

Concluding remarks. The 'straight' westerly-type circulation over the British Isles has a frequency and daily rainfall amount which change systematically with atmospheric MSL pressure. These results reflect the significance of the calculated rainfall and frequency averages.

REFERENCES

1. LAWRENCE, E. N.; Synoptic-type rainfall averages over England and Wales. *Met Mag, London*, **100**, 1971, pp. 333–339.
2. LAMB, H. H.; British Isles weather types and a register of the daily sequence of circulation patterns, 1861–1971. *Geophys Mem, London*, **16**, No. 116 (in press).
3. London, Meteorological Office. Monthly mean sea temperatures at ocean weather ships, 1951–60. (Unpublished, copy available in the Meteorological Office Library, Bracknell.)
4. World Meteorological Organization. Climatological normals (CLINO) for climat and climat ship stations for the period 1931–1960. WMO No. 117, Geneva, 1962.
5. PFLUGBEIL, C.; Zur Klimatologie des Nordatlantischen Ozeans, I. *Einzelveröff, Seewett-Amt, Hamburg*, Nr 38, 1963.
6. VINOGRADOV, N. D.; The relation between the types of atmospheric circulation and the temperature of the surface water in the northern part of the Atlantic Ocean. *Probl Arkt Antarkt, Leningrad*, **25**, 1967, pp. 44–53 (translation available).
7. KRYNDIN, A. N.; The role of the North Atlantic in the formation of spring-summer air temperature anomalies in the European USSR. *Gidromet Nauchno-issled Cent SSSR, Trudy, Leningrad*, **23**, 1968, pp. 31–45 (translation available).
8. RATCLIFFE, R. A. S. and MURRAY, R.; New lag associations between North Atlantic sea temperature and European pressure applied to long-range weather forecasting. *Q J R Met Soc, London*, **96**, 1970, pp. 226–246.

551.515.13:551.582.2(564.3):551.589.1

EXTREME WEATHER CONDITIONS OVER CYPRUS DURING APRIL 1971

By R. BOAST and J. B. McGINNIGLE

Summary. The island of Cyprus experienced extreme weather conditions during April 1971. The statistics are presented and the synoptic situations which were the cause of the extreme weather are identified and examined in detail. Broad-scale synoptic features are considered and compared with relevant statistics.

Introduction. The island of Cyprus lies at the eastern end of the Mediterranean Sea at about latitude 35°N. The month of April is within the 'transition' period during which winter conditions give way to the hot, dry summer. Statistically, April is shown to be a pleasant month, with day-time temperatures rising to the low twenties (°C). Average rainfall is 15–20 millimetres in most low-lying areas[1] with 'wet days' ($\geqslant$1 mm/24 hours) likely to occur only three times during the month.

By the middle of April 1971, it was apparent that the island was experiencing an exceptionally wet month. Examination of records for Nicosia, in the centre of the island, and Akrotiri on the south coast (Figure 1), revealed that the previous maximum rainfall totals for the month had already been exceeded. By the end of the month, more new records had been set. New extreme figures for the greatest rainfall in a day and for the number of wet days in a month had been recorded at both Nicosia and Akrotiri. Nicosia had also recorded its lowest April sunshine duration and the maximum wind gust previously recorded had been equalled.

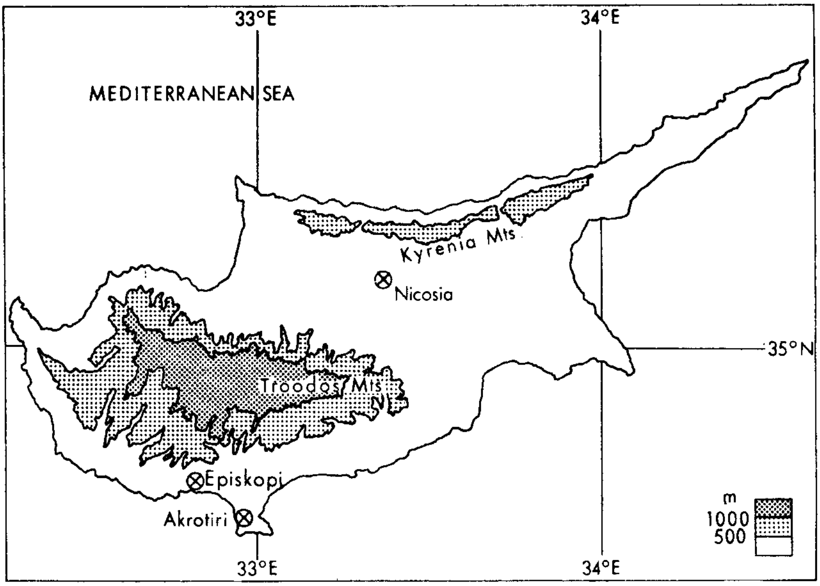

FIGURE 1—MAP OF CYPRUS

Further examination of the statistics for the month showed that although both Nicosia and Akrotiri had experienced a record number of wet days, the record rainfall totals were mainly due to several days on which large amounts of rainfall were recorded. Nicosia recorded 91 per cent of its rainfall for the month during the 24-hour periods (06–06 GMT) of the 3rd, 12th, 16th, and 23rd, while Akrotiri recorded 95 per cent of its total on the 3rd, 12th, 14th, and 15th.

Statistics. Table I shows previous means and extremes of temperature, rainfall, surface wind and sunshine for April, at Nicosia and Akrotiri, together with the values recorded during April 1971. Dates and years of previous extremes have been omitted except where new records were set during April 1971. No sunshine records are available for Akrotiri.

Table II shows the rainfall distribution for April 1971 at Nicosia and Akrotiri. Rainfall is measured each day at 06 and 18 GMT (08 and 20 local

TABLE I—COMPARISON OF MEANS AND PREVIOUS EXTREMES WITH APRIL 1971 VALUES

	NICOSIA Means and previous extremes for April	NICOSIA April 1971	AKROTIRI Means and previous extremes for April	AKROTIRI April 1971
Temperature (°C)				
Mean maximum	23·1(1)	21·0	21·3(3)	20·8
Mean minimum	10·1(1)	9·1	13·1(3)	12·2
Highest maximum	39·5(2)	30·5	33·0(4)	27·8
Lowest maximum	12·8(2)	13·1	14·7(4)	16·4
Highest minimum	21·9(2)	15·0	21·4(4)	19·7
Lowest minimum	2·8(2)	5·2	5·2(4)	7·3
Rainfall (mm)				
Mean monthly total	17·3(1)		14·5(3)	
Highest monthly total	47·3(2) 1957	105·4*	39·5(4) 1965	78·5*
Lowest monthly total	2·0(2) 1959		1·5(4) 1964	
Highest daily total	31·7(2) 1968	39·4*	14·1(4) 1969	31·3*
Mean No. wet days†	3 (1)		3 (3)	
Highest No. wet days†	8 (2) 1948	9 *	7 (4) 1965	8 *
Wind (kt)				
Highest hourly wind	41 (2)	26	32 (4)	24
Highest gust	56 (2) 1964	56 *	55 (4)	39
Sunshine (hours)				
Mean monthly total	281·0	221·9	—	—
Highest daily mean	11·30	—	—	—
Lowest daily mean	8·06	7·40*	—	—

Figures in brackets give period covered: (1) 1943–68, (2) 1945–70, (3) 1957–66 and (4) 1957–70. * New extreme values. † Wet day > 1·0 mm/24 hours (06–06 GMT).

TABLE II—NICOSIA/AKROTIRI RAINFALL DISTRIBUTION FOR 06–18, 18–06 AND 06–06 GMT FOR APRIL 1971

Date	NICOSIA 06–18	NICOSIA 18–06	NICOSIA 06–06	AKROTIRI 06–18	AKROTIRI 18–06	AKROTIRI 06–06
		millimetres			*millimetres*	
3	13·7	4·6	18·3	31·2	0·1	31·3*
7	0·0	0·0	0·0	Trace	0·0	Trace
11	0·0	2·4	2·4	0·0	0·6	0·6
12	13·8	25·6	39·4*	6·6	9·5	16·1
13	2·3	0·0	2·3	0·1	Trace	0·1
14	0·2	0·9	1·1	3·2	9·5	12·7
15	1·0	Trace	1·0	8·8	6·1	14·9
16	15·1	0·0	15·1	0·9	1·6	2·5
17	0·1	0·0	0·1	0·1	0·2	0·3
18	0·1	0·0	0·1	0·0	0·0	0·0
21	Trace	0·0	Trace	0·0	0·0	0·0
22	3·0	0·0	3·0	0·0	0·0	0·0
23	22·6	0·0	22·6	0·0	0·0	0·0
26	0·0	0·0	0·0	Trace	0·0	Trace

* New records for the month.
Trace = <0·1 mm.

time). The daily total shown for each day is that measured between 06 GMT on that day and 06 GMT on the following day. The daily totals are also shown in histogram form in Figure 2. In order that the combined Nicosia and Akrotiri rainfall can be studied, Figure 2 uses a common abcissa with the Akrotiri histogram columns inverted. Thus it can be seen that the combined rainfall amounts on the 3rd and the 12th were similar but the distribution at the two stations was reversed on these dates. Reasons for this time/space distribution will be discussed in the later sections of this paper.

Table II and Figure 2 show that the rainfall for the month fell during four distinct periods covering the 3rd, the 11–13th, the 14–17th and the 22–23rd. The first three periods affected both stations but the fourth affected only Nicosia.

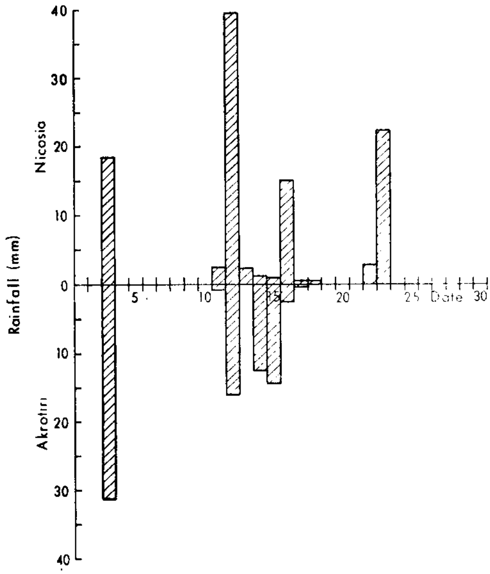

FIGURE 2—DAILY RAINFALL DISTRIBUTION FOR NICOSIA AND AKROTIRI FOR APRIL 1971

Synoptic analysis.

Central and eastern Mediterranean. An examination of the April 1971 chart series for this area showed that Cyprus had been affected by four surface depressions during the month. The periods during which these depressions were adjacent to Cyprus were coincident with those already identified from the rainfall statistics.

These four depressions have been examined in detail in the four subsections below. In each case, surface and 300-mb continuities are presented and composite surface/1000–500-mb thickness/300-mb contour charts, for both developing and developed stage, are reproduced.

(a) *Depression 1 (1–4 April 1971).* This 'Saharan depression'[2] was first identified at 00 GMT on 1 April when it was centred over western Libya. It moved east along the North African coast, with only diurnal changes in its central pressure, until 12 GMT on the 2nd (Figure 3). During the next 12 hours, an upper trough moving from the north-west (Figure 3) produced a tightening south-westerly thermal gradient over the depression, causing it to develop and move north-east (Figure 4). It passed over Cyprus on the 3rd as a fully developed frontal depression (Figure 5).

Continuous rain began at Akrotiri during the late morning (3rd) and was heavy at times. The extensive rain area of the depression

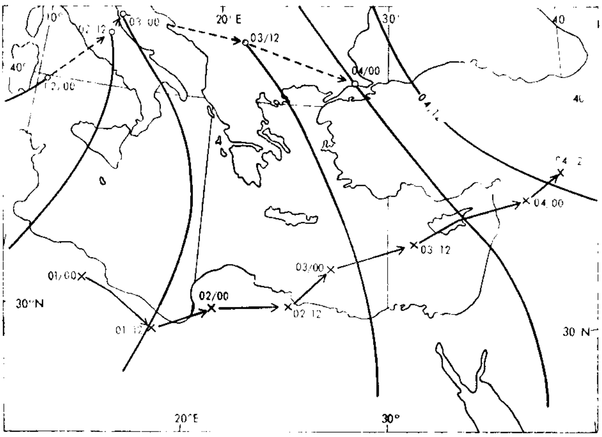

FIGURE 3—MOVEMENT OF SURFACE CENTRE AND 300-mb CENTRE AND TROUGH FROM 00 GMT ON 1 APRIL UNTIL 12 GMT ON 4 APRIL 1971

o - - - o Track of 300-mb centre ———— 300-mb trough
x —— x Track of surface centre
Times are shown in the form: date/time (GMT)

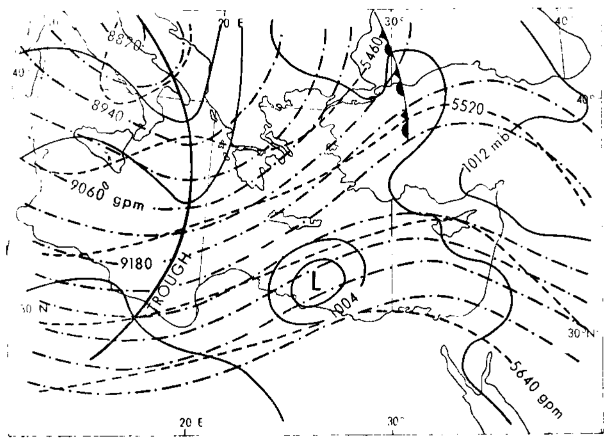

FIGURE 4—SURFACE AND UPPER AIR PATTERNS FOR 00 GMT ON 3 APRIL 1971

——— Surface isobars — · — 300-mb contours
– – – 1000–500-mb thickness lines

combined with Akrotiri's position on an exposed coast, resulted in a new maximum daily rainfall being recorded. At Nicosia, precipitation began during the early afternoon but ceased for a time as the centre of the depression passed almost overhead between 17 and 18 GMT. During the onset of the north-westerly surface winds west of the centre, a gust of 56 knots (1 kt ≈ 0·5 m/s) was recorded, equalling the previous record for April.

After crossing Cyprus, the depression continued to move north-east towards Syria. Once over the land, it quickly lost its momentum and became slow moving over the Syrian/Turkish border by 12 GMT on the 4th.

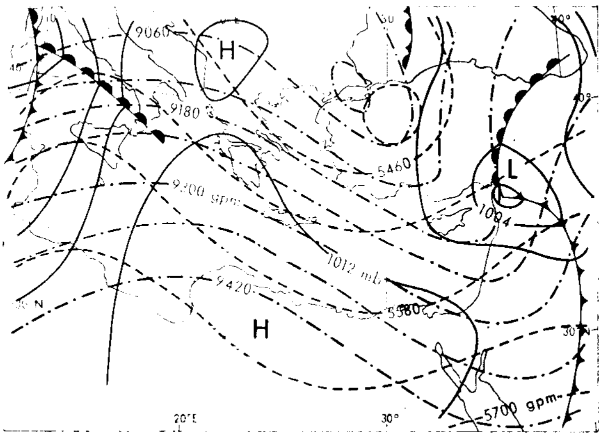

FIGURE 5—SURFACE AND UPPER AIR PATTERNS FOR 00 GMT ON 4 APRIL 1971

——— Surface isobars —·— 300-mb contours
– – – 1000–500-mb thickness lines

(b) *Depression 2 (10–14 April 1971).* This was another 'Saharan depression' situation, though more complex than the previous one. At 00 GMT on 10 April, two depressions were identified, one over Libya and the other over Saudi Arabia. At the same time the 300-mb contour chart showed a slow-moving low centre over Sicily, with weak troughs extending south from the centre. During the next 24 hours, the situation changed rapidly.

The weak 300-mb trough intensified and moved quickly east increasing the thermal gradient over the Libyan depression and causing it to move quickly north-east (Figure 6). At the same time, the Saudi Arabian depression moved west under the influence of a

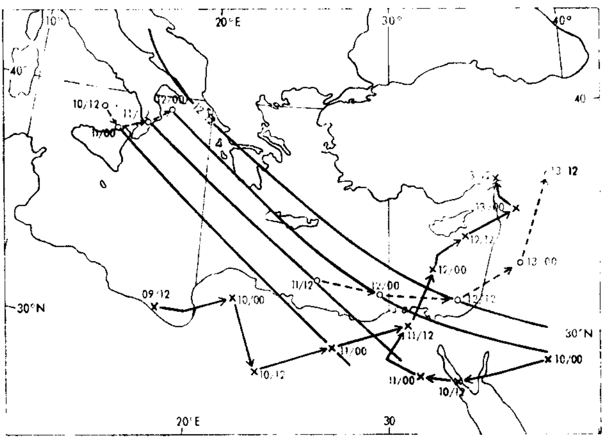

FIGURE 6—MOVEMENT OF SURFACE CENTRES AND 300-mb CENTRES AND TROUGH FROM 12 GMT ON 9 APRIL UNTIL 12 GMT ON 13 APRIL 1971

o – – – o Track of 300-mb centres ——— 300-mb trough
x —— x Track of surface centres
Times are shown in the form: date/time (GMT)

light easterly thermal gradient on the north side of a weak cold pool over Saudi Arabia. The two depressions subsequently combined to become one feature (Figure 7) in an area of thermal diffluence on the cold side of the westerly jet which extended across the Sahara to Saudi Arabia. The combined depression deepened and then moved north-east as a south-westerly thermal flow was established over its centre. The depression passed close to Cyprus on the 12th (Figure 8).

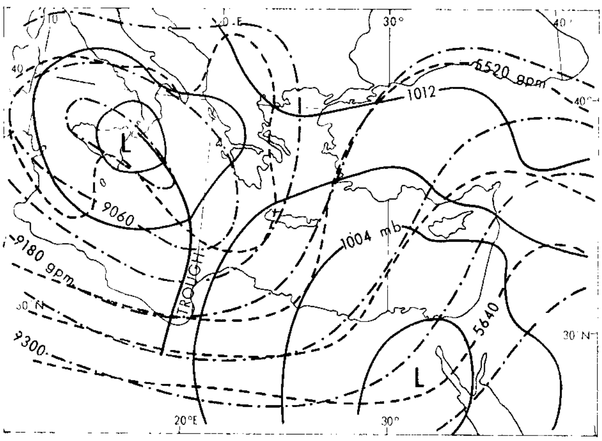

FIGURE 7—SURFACE AND UPPER AIR PATTERNS FOR 00 GMT ON 11 APRIL 1971

——— Surface isobars —·— 300-mb contours
– – – 1000–500-mb thickness lines

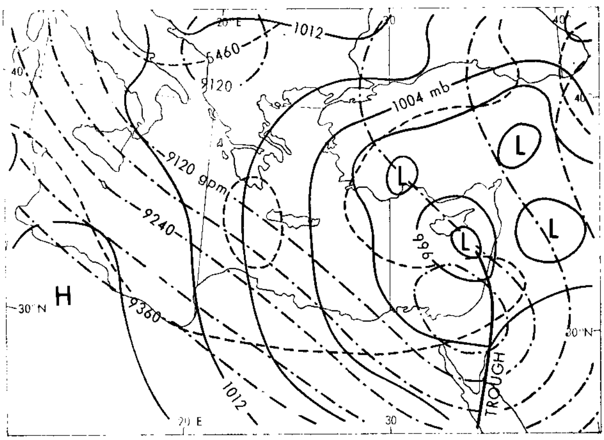

FIGURE 8—SURFACE AND UPPER AIR PATTERNS FOR 12 GMT ON 12 APRIL 1971

——— Surface isobars —·— 300-mb contours
– – – 1000–500-mb thickness lines

On this occasion it was Nicosia, being exposed to the east and south-east, which recorded a new maximum daily rainfall total. Akrotiri experienced a marked decrease in precipitation close to the centre of the depression.

This depression lost its momentum after crossing the Syrian coast and became slow moving over approximately the same area as the first one.

(c) *Depression 3 (14–17 April 1971).* At 00 GMT on 14 April, a slack upper circulation, residual from the previous depression system, was slow moving over the eastern Mediterranean and a trough at 300 mb was lying north-east–south-west over southern Italy. At the surface, a northerly airstream over Turkey was causing a marked lee trough over the Cyprus area. A shallow depression was identified, on the axis of this trough, centred over south-west Turkey. A cold front lying north-east–south-west over the Black Sea was moving south with very cold polar continental air behind it. During the 14th the cold front continued its southward movement (Figure 9) until its central portion became slow moving close to the centre of the lee depression (Figure 10). The 300-mb trough moved steadily east and a

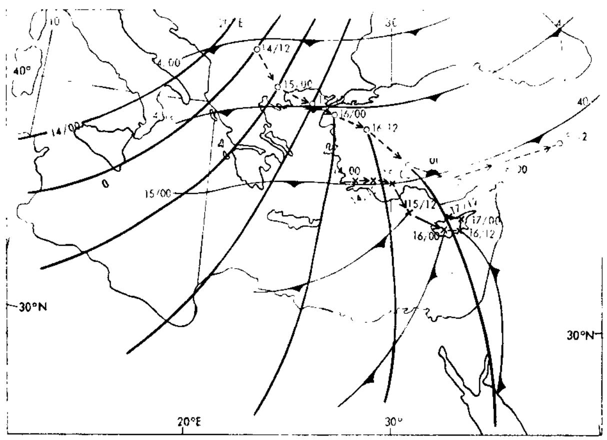

FIGURE 9—MOVEMENT OF SURFACE CENTRE AND FRONT AND 300-mb CENTRE AND TROUGH FROM 00 GMT ON 14 APRIL UNTIL 12 GMT ON 18 APRIL 1971

o – – – o Track of 300-mb centre ——— 300-mb trough
x —— x Track of surface centre
Times are shown in the form: date/time (GMT)

circulation developed on its axis over northern Greece (Figure 9). This situation caused shower activity over Cyprus but significant rainfall was confined to exposed coastal districts. During the 15th the western part of the cold front moved south-east and, as the very cold air was fed around the surface depression, it began to develop. The slow moving part of the front became unidentifiable over Turkey and the cold front was reanalysed to extend from the depression centre, which by this time was moving south-east towards Cyprus. As before, shower activity over the island was mainly confined to exposed coastal areas.

During the 16th the continued eastward movement of the 300-mb trough produced a backing in the thermal gradient over the depression (Figure 11), causing it to cease its eastward movement and begin to

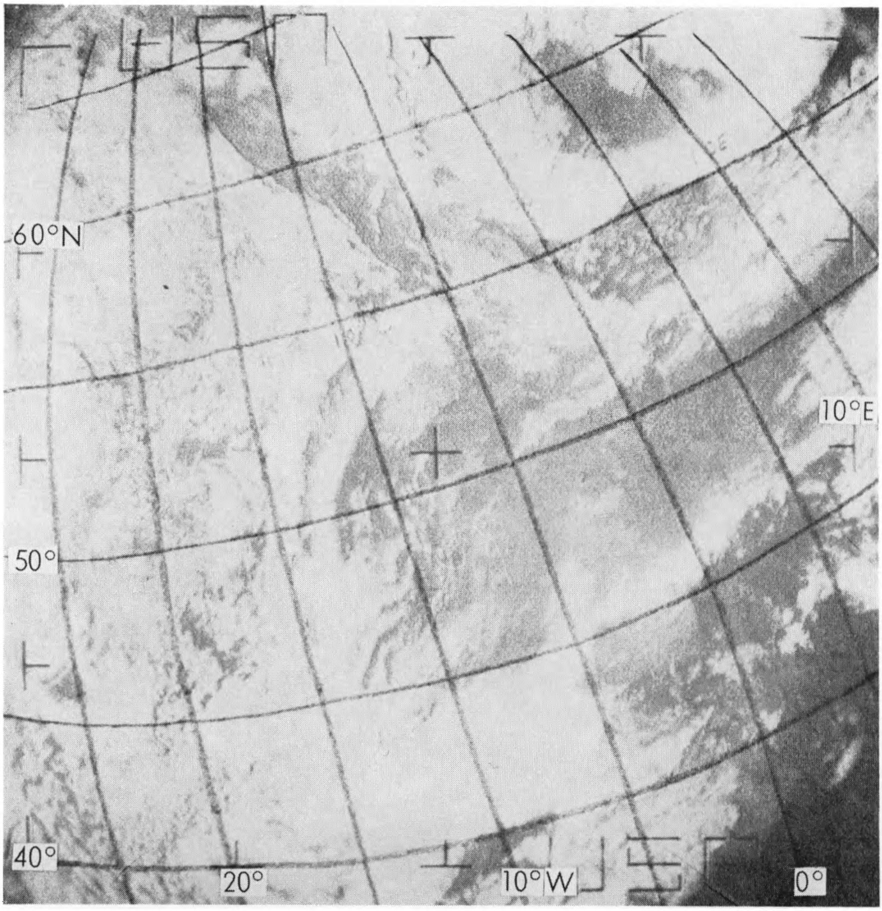

PLATE I—ESSA 8 SATELLITE PICTURE FOR 1117 GMT ON 17 JULY 1971

See page 153.

Photograph by D. R. Hindley

PLATE II—YORKSHIRE COAST SHOWING CONVECTION CLOUD DEVELOPING INLAND ON 17 JULY 1971

See page 155.

Photograph by D. R. Hindley

PLATE III—YORKSHIRE COAST SHOWING CLEAR CORRIDOR BETWEEN CONVECTION CLOUD FORMING INLAND AND THAT FORMING OUT TO SEA, 17 JULY 1971

See page 155.

Photograph by D. R. Hindley

PLATE IV—CONVECTION CLOUD DEVELOPING OUT TO SEA OFF THE YORKSHIRE COAST ON 17 JULY 1971

See page 155.

To face page 145

Photograph by Mrs J. V. Hurst

PLATE V—EROSION OF VEGETATION BY WIND AND SALT ON THE COAST SOUTH OF TRIPOLI, LEBANON, APRIL 1966

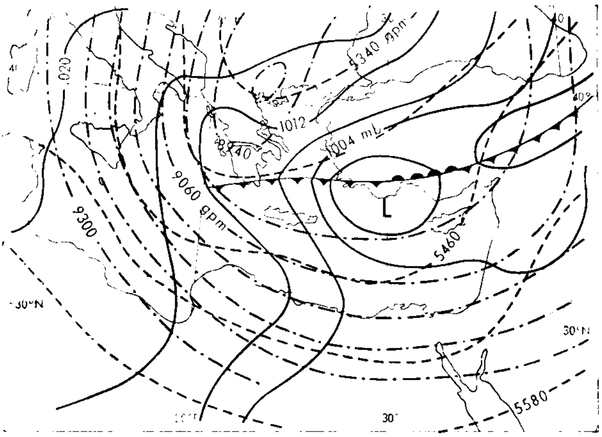

FIGURE 10—SURFACE AND UPPER AIR PATTERNS FOR 00 GMT ON 15 APRIL 1971

——— Surface isobars —·— 300-mb contours
– – – 1000–500-mb thickness lines

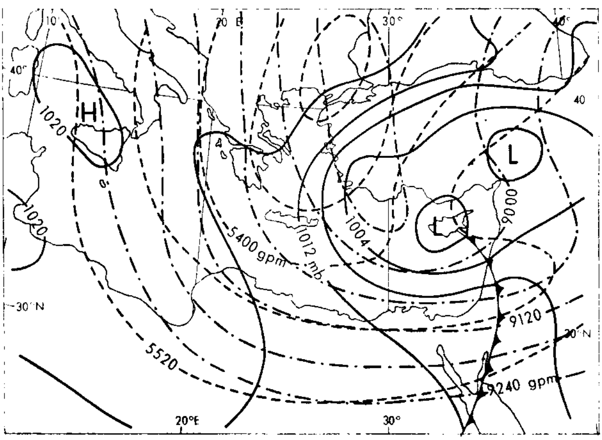

FIGURE 11—SURFACE AND UPPER AIR PATTERNS FOR 12 GMT ON 16 APRIL 1971

——— Surface isobars —·— 300-mb contours
– – – 1000–500-mb thickness lines

move north. With the depression centred over Cyprus and the upper trough approaching from the west, shower activity was more general during the 16th, with widespread thunderstorms. During the 17th the upper trough relaxed as its associated centre filled and the surface depression lost its identity. Isolated showers continued to affect Cyprus until the 18th.

(d) *Depression 4 (20–24 April 1971)*. This was another case of the lee trough over the Cyprus area becoming more intense. During the 20th a low centre at 300 mb moved south-east over the western Black Sea while its associated trough moved south-east over western Turkey (Figure 12). At 12 GMT on the 21st a shallow surface depression was identified, lying below the upper trough. During the next 24 hours this depression moved south-east with the upper trough (Figure 12).

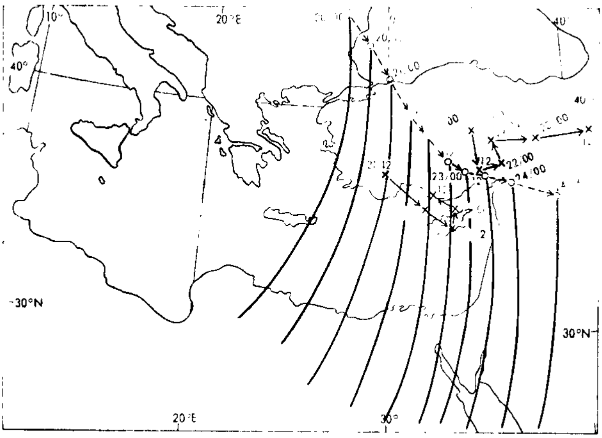

FIGURE 12—MOVEMENT OF SURFACE CENTRES AND 300-mb CENTRE AND TROUGH FROM 00 GMT ON 20 APRIL UNTIL 12 GMT ON 24 APRIL 1971

o - - - o Track of 300-mb centre ——— 300-mb trough
x —— x Tracks of surface centres
Times are shown in the form: date/time (GMT)

Although the depression did not develop greatly (Figure 13), day-time heating was sufficient to set off scattered thunderstorms over central Cyprus during the 22nd. No vigorous convection was observed over the sea. During the 23rd the depression became slow moving over Cyprus as the upper centre began to fill (Figure 14). Again, day-time heating set off thunderstorms and Nicosia recorded 22·6 mm of rain in 1·6 hours during one of them.

By 12 GMT on the 24th the upper centre had moved away east and no circulation was identifiable over the Cyprus area.

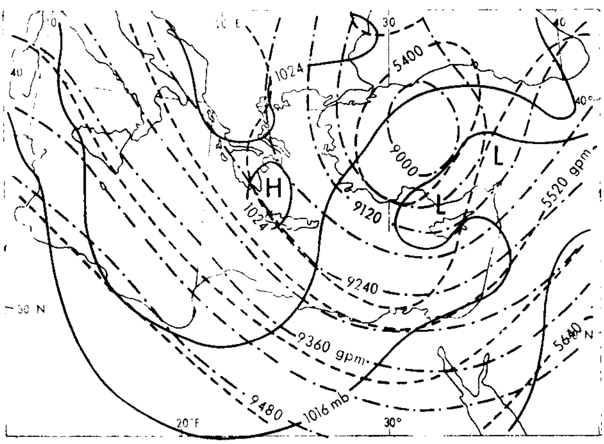

FIGURE 13—SURFACE AND UPPER AIR PATTERNS FOR 00 GMT ON 22 APRIL 1971

——— Surface isobars —·— 300-mb contours
- - - 1000–500-mb thickness lines

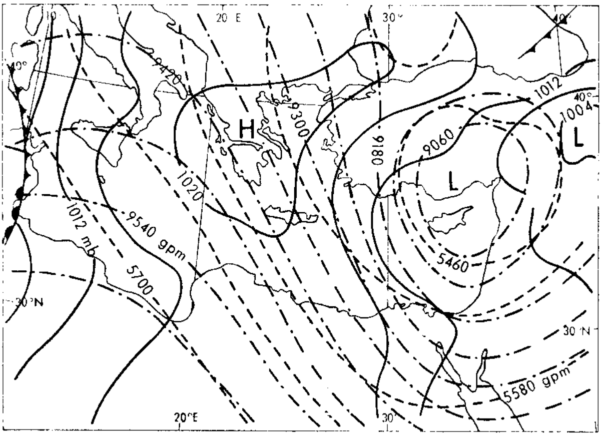

FIGURE 14—SURFACE AND UPPER AIR PATTERNS FOR 12 GMT ON 23 APRIL 1971

——— Surface isobars —·— 300-mb contours
– – – 1000–500-mb thickness lines

The previous sections have described the four depressions which were responsible for the severe weather conditions over Cyprus during April 1971. The first two were developments of 'Saharan depressions', whose origins were over the Sahara desert south of the Atlas Mountains. The first of these was a classic case as defined.[2] The second, though clearly still a 'Saharan depression' development, was more complex as a result of the amalgamation of the original Atlas low with a depression which originated over Saudi Arabia. The combined total rainfall at Nicosia and Akrotiri was similar in each of these cases but the spatial distributions varied because of the difference in the depression tracks. The first depression had a relatively long sea track, precipitation was mainly from layer cloud and no thunderstorms were observed. The second depression had a shorter sea track but was accompanied by thunderstorms which intensified the associated rainfall.

The other two depressions were both 'Cyprus depressions'[3] which formed near Cyprus. Both were formed when lee troughs (south of the Anatolian plateau (Turkey)) were intensified by the introduction of cold continental air into their circulations. Rainfall from depressions formed in this way is usually much more marked in the autumn than in the spring because of the higher sea temperatures which produce widespread convection. The cold air associated with the first of the 'Cyprus depressions' was, however, sufficiently cold to cause widespread convection. The second depression was less marked than the first and no significant convection occurred over the sea, but day-time heating was sufficient to produce thunderstorms over inland areas.

Broader-scale considerations. A broad-scale appreciation of synoptic movement and development for the whole month was carried out. The area considered was from the eastern Atlantic to central Russia and from Scandinavia to the Tropic of Cancer (information in south permitting).

Three distinct synoptic régimes for the month were identified.

(a) *1 to 10 April.* This period was notable for a predominantly meridional flow over the eastern Atlantic with a zonal flow over the Mediterranean and little significant movement or development over Europe. The cold airflow to north-west Africa was interrupted three times during the period as the northern part of the mid-Atlantic ridge system moved east and became cut off. The first two occasions resulted only in a 24-hour interruption of the cold airflow. The third cut-off, which occurred on the 10th, resulted from a major extension of the mid-Atlantic ridge. After this cut-off had occurred, the original ridge quickly collapsed as a zonal upper flow became established between 30° and 40°N. An anticyclone developed over the United Kingdom with a consequent cold air feed to Europe on its eastern side.

(b) *11 to 22 April.* Throughout this period, a quasi-stationary trough/ridge/trough pattern persisted from the eastern Atlantic to eastern Europe. This situation caused progressively colder air to be fed to the eastern Mediterranean region during the 11th to the 17th, after which the cold air supply was cut off until the 21st when it was re-established.

(c) *23 to 30 April.* The trough/ridge/trough pattern quickly became more mobile and flattened. A split zonal flow over the Atlantic and a broad zonal flow over Europe became established and persisted until the end of the month.

The broad-scale synoptic pattern identified during the first period (1st to 10th) was favourable for the formation of 'Saharan depressions' and their subsequent movement to the Cyprus area. The almost continuous supply of cold air to the area south of the Atlas Mountains provided ideal conditions for the formation of 'Saharan depressions' and the zonal upper flow over the Mediterranean provided the mobility necessary for them to reach the Cyprus area.

The synoptic situation during the second period (11th to 22nd) was favourable for the formation of 'Cyprus depressions' as it provided a good supply of cold air to the eastern Mediterranean.

During the period 23rd to 30th, mobility over central Europe confined all significant weather well to the north of Cyprus.

Comparison with synoptic statistics.

300-mb winds. The average 300-mb wind chart for April[4] indicates that the flow is zonal over the eastern Atlantic/Europe/North Africa area, with the stronger winds over Egypt and the Red Sea. The 22 days during which meridional patterns were persistent over the eastern Atlantic and Europe indicate that April 1971 was significantly different from the average.

Vector mean winds and standard vector deviations for Malta and Episkopi (Cyprus) were calculated in order to compare April 1971 with the average values over the central and eastern Mediterranean area. The comparison is shown in Table III.

TABLE III—COMPARISON OF AVERAGE 300-mb WINDS* WITH THOSE OF APRIL 1971

	Malta	Episkopi (Cyprus)
Monthly average wind (degrees/kt)	270/37	270/33
Standard vector deviation (kt)	38	37
April 1971		
Vector mean wind (degrees/kt)	275/49	285/37
Standard vector deviation (kt)	32	33

* 1947–50 inclusive.

It can be seen that both Malta and Episkopi had significantly stronger 300-mb vector mean winds during April 1971, with the direction in each case veered from the average. The standard vector deviations are smaller in each case, showing a smaller-than-average spread of individual vectors.

This comparison clearly reflects how the meridional blocking patterns which were a feature of northern latitudes for most of the month, concentrated greater-than-normal mobility along the central and eastern Mediterranean Sea.

Depressions. The frequency and tracks of depressions which have affected the Cyprus area have been compiled[6] and these are shown in Figure 15 in respect of 'Saharan depressions'. The statistics are for a period March–May inclusive and from these it can be inferred that the number of 'Saharan depressions' which affected Cyprus during April 1971 was by no means unusual.

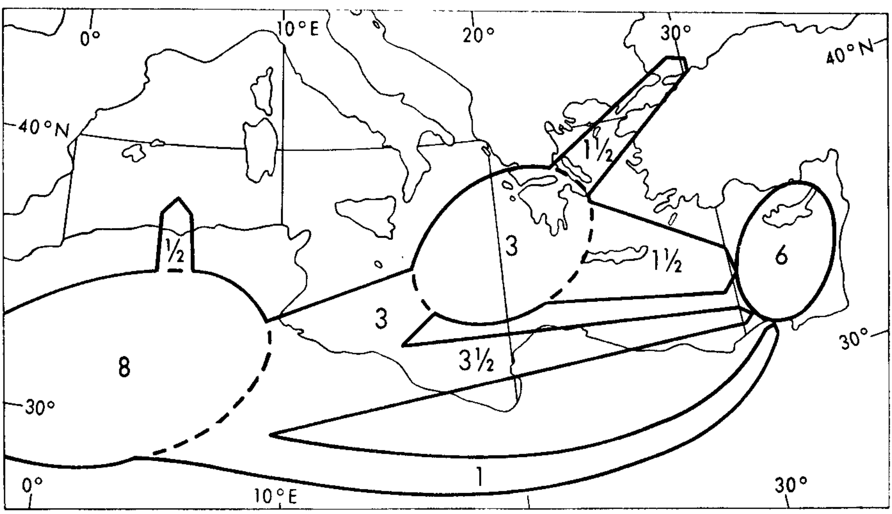

FIGURE 15—AVERAGE TRACKS AND AVERAGE FREQUENCIES OF OCCURRENCE OF 'SAHARAN DEPRESSIONS' FOR THE PERIOD MARCH TO MAY INCLUSIVE

From the statistics,[5] it has been stated that, during the same period (March–May), an average of only one depression forms over the Cyprus area. The two occasions identified and discussed in this paper therefore give a frequency higher than average.

The number of depressions which originate in the western Mediterranean and subsequently enter the Cyprus area is given as $5\frac{1}{2}$ during the three-month period. No such depressions affected Cyprus during April 1971.

In comparison with these depression statistics, the frequency of 'Saharan depressions' was normal, the frequency of 'Cyprus depressions' was higher than average while no depressions originating in the western Mediterranean affected the area. The total of four depressions during April 1971 would appear to be an approximate average for the month, although the origin distribution is unusual.

Concluding remarks. It is therefore concluded that the extreme weather conditions experienced over Cyprus during April 1971 were due to :

(a) The occurrence of two persistent broad-scale synoptic régimes of a meridional type, which are sympathetic to the development and movement of two significant weather-producing Cyprus situations, the developed 'Saharan depression' and the developed 'Cyprus depression'.

(b) The strong development patterns which produced these situations and the effects, on a smaller scale, of track and associated air-mass character.

REFERENCES

1. Nicosia, Government of Cyprus, Meteorological Office. The rainfall of Cyprus. *Tech Note* No. 2, Nicosia, 1959.
2–5. London, Meteorological Office. Weather in the Mediterranean, Volume I. London, HMSO, 1962, pp: 40; 43; 127; 33 and 35.
6. London, Meteorological Office. Weather in the Mediterranean, Volume II, London, HMSO, 1964, pp. 354, 356.

551.515.8

THE TROWAL, AN IMPORTANT FEATURE OF FRONTAL ANALYSIS

By R. M. MORRIS

One of the best-known modifications of the original Bjerknes frontal model was developed by Canadian meteorologists during the post-war years. The three-front model[1] was conceived to take account of upper air data which revealed a more complex structure than was envisaged by Bjerknes. A fundamental feature of the three-front model was a recognition of the trowal; the trowal is located on synoptic maps as a surface trough beneath a thermal ridge. The trowal is essentially an upper frontal zone but it is also associated with a discontinuity in weather elements observed from the ground. Usually the passage of a trowal marks a change from typical pre-frontal continuous precipitation to a more showery type with well-broken cloud. In other words the trowal appears to exhibit the characteristics of both a warm and cold front together but there is not necessarily any significant change of temperature at the surface. Since the trowal is associated with a relatively strong thermal wind aloft, it is also identified as a discontinuity in the thermal advection field. Such a discontinuity has dynamical significance, particularly in regard to the diagnosis of vertical motion.

In a recent paper[2] it was shown how a qualitative estimate of vertical motion could be assessed from synoptic charts by making use of the omega equation. The relevant equation (1*a*) in that paper is restated as follows :

$$\omega \approx -\frac{\partial}{\partial p}(\mathbf{V}.\nabla Q) - \nabla^2(\mathbf{V}.\nabla h_{TT}). \qquad \ldots (1)$$

Thus ascending air (ω negative) occurs in association with relatively strong positive (cyclonic) vorticity advection aloft and/or a maximum of warm-air advection in the layer. If the equation is applied to the 1000–500-mb layer the mean vertical velocity in the layer depends upon the difference between the vorticity advection at 500 mb and at 1000 mb and the advection of the thickness by a mean wind in the layer.

The purpose of this note is to illustrate the diagnosis of a trowal that was present on the synoptic chart at 00 GMT on 20 March 1970. As in the previous case,[2] use is made of computer-analysed charts and comparisons are made between the objectively derived vertical-motion field and subjective assessments based upon equation (1).

Figure 1 depicts the 1000–500-mb thickness and superimposed 1000-mb contour-height flow. The essential features are clearly evident; there is a well-marked thermal ridge beneath which there is an equally prominent trough in the 1000-mb flow. Figure 2 depicts the 500-mb contour flow with superimposed isopleths of thickness advection ($\mathbf{V}.\nabla h_{TT}$) calculated from Figure 1. The 500-mb flow consists of a rather ill-defined ridge-axis lying approximately north–south across the British Isles and a south-westerly stream to the west within which there appears to be a very low-amplitude undulation.

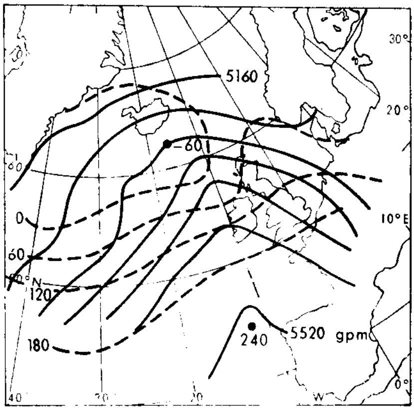

FIGURE 1—1000–500-mb THICKNESS AND SUPERIMPOSED 1000-mb CONTOUR-HEIGHT FLOW AT 00 GMT ON 20 MARCH 1970

——— 1000–500-mb thickness   — · — 1000-mb contours

It is instructive to assess the balance of terms in equation (1) on each side of the trowal axis. East of the trowal there is cyclonic vorticity advection at 1000 mb beneath cyclonic vorticity advection at 500 mb (region just upwind of the ridge axis) north of 55 degrees latitude. South of 55° the 1000-mb flow curvature is weak whilst the 500-mb flow curvature is roughly constant in the ill-defined ridge. Thus the magnitude of the vorticity advection term (equation (1)) is probably weak in the whole region because it depends upon the relative magnitude of two like terms in the north and because only small amounts of vorticity advection are present in the south. The thickness advection field shows a pronounced maximum of warm-air advection extending

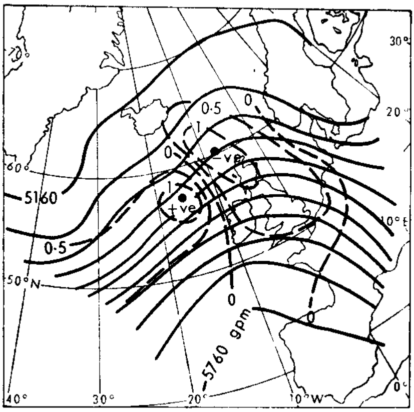

FIGURE 2—500-mb CONTOURS WITH SUPERIMPOSED ISOPLETHS OF THICKNESS ADVECTION AT 00 GMT ON 20 MARCH 1970

——— 500-mb contours — — — — Isopleths of thickness advection

from south-east Iceland across Scotland. It appears that on the basis of equation (1) there will be ascending motion in the region between south-east Iceland and central Britain, due largely to the thermal advection term. West of the trowal the curvature at both 1000 mb and 500 mb is small so that the vorticity advection term is probably very small too. On the other hand, the thermal advection field contains a prominent maximum of cold air advection. On the basis of equation (1) there will be descending air north-west of Ireland associated with the thermal advection field.

Figure 3 depicts the distribution of mean vertical velocity in the 1000–600-mb layer, as produced by the computer. The similarity between the pattern of vertical velocity and thickness advection distribution is very clear.

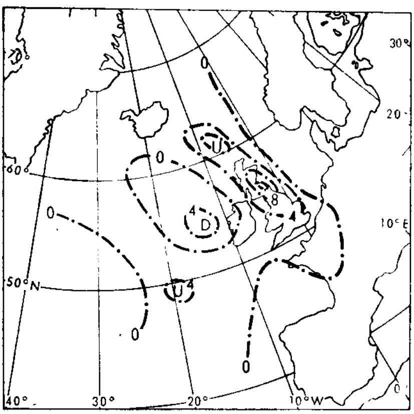

FIGURE 3—DISTRIBUTION OF MEAN VERTICAL VELOCITY IN THE 1000–600-mb LAYER, AS PRODUCED BY THE COMPUTER, 00 GMT ON 20 MARCH 1970

— · — Mean vertical velocity at intervals of 4 mb/h
U = up D = down

Ascending air coincides with the maximum of warm-air advection and descending air almost coincides with the maximum of cold-air advection. Furthermore, the isopleth of zero vertical velocity is closely identified with the isopleth of zero thickness advection.

The recognition of trowals supplements the more familiar frontal concepts. Trowals occur sufficiently frequently to deserve a separate classification, although they do not occur as frequently as other frontal features. The essential point to note is that each frontal feature has a distinctive thermal and dynamical structure. Thus the cold and warm fronts are associated with a zone of strong thermal wind and cold- and warm-air advection fields respectively. The trowal is associated with a strong thermal ridge and both warm- and cold-air advection fields. On the other hand, the occlusion is a composite system in which the upper frontal trough is usually displaced horizontally from the position of the surface trough.

Finally it must be remembered that the emphasis on upper fronts in no way reduces the importance of low-level air-mass analysis which is often concerned with shallow layers not closely related to the flow structure aloft. These surface fronts have important secondary effects, e.g. low cloud, surface convection, ice factor, etc., but they are not identified with deep vertical-motion fields except in association with upper fronts.

REFERENCES

1. GALLOWAY, J. L.; The three front model: its philosophy, nature, construction and use. *Weather, London*, **13**, 1958, pp. 3–10.
2. MORRIS, R. M.; A case study of the spectacular developments and movement of a February storm. *Met Mag, London*, **100**, 1971, pp. 14–27.

551.553.11

SEA-BREEZE FRONT NEAR THE SOUTH COAST OF ENGLAND

By K. ROWLES

A satellite photograph taken by ESSA 8 on 17 July 1971 at 1117 GMT is reproduced in Plate I. It shows a prominent belt of convective cloud along the south coast, extending from Cornwall to Kent.

The synoptic situation at 09 GMT (Figure 1) shows an area of high pressure to the west of the British Isles with an associated ridge extending eastwards across Wales and the southern half of England. This maintained light winds between north and east along the south coast. A sea-breeze had set in along the south coast by 11 GMT, at which time air temperatures inland had risen to 18°C. Five-day mean (15–19 July 1971) sea surface isotherms, which have been superimposed on the 12 GMT chart (Figure 2), show that the sea surface temperature was between 15°C and 16°C. Land temperatures were therefore some 2 degC to 3 degC higher than those over the sea at the time of the onset of the sea-breeze. A streamline analysis of the surface wind flow shown on the same chart reveals a zone of convergence parallel to the coast, and some 10 to 20 miles inland.

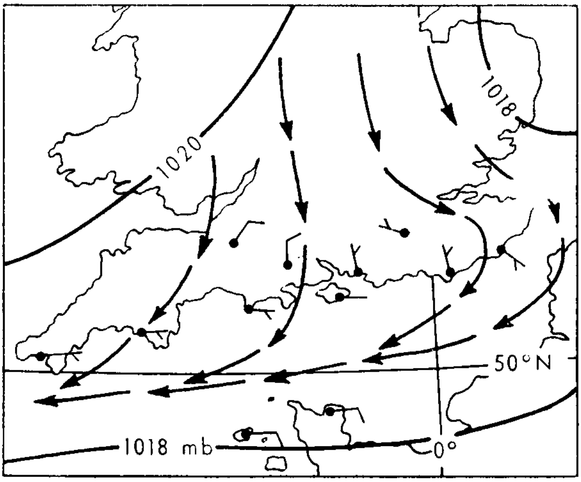

FIGURE 1—SYNOPTIC SITUATION AT 09 GMT ON 17 JULY 1971
Arrows denote streamlines.

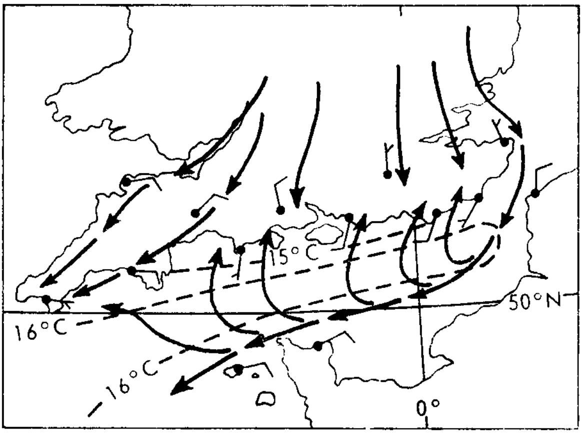

FIGURE 2—SEA SURFACE ISOTHERMS AT 12 GMT ON 17 JULY 1971
Arrows denote streamlines.

By 15 GMT there was a small pressure trough lying from Bournemouth to the Thames Valley; this was about the time of maximum development of the sea-breeze circulation. As the land surface cooled during the evening so the trough filled and disappeared, and by 21 GMT the circulation was reversed, with a light north-easterly flow re-established along the south coast.

The 12 GMT Crawley radiosonde ascent indicated a shallow layer of instability from the surface to an inversion based at 800 mb (6500 ft). This allowed shallow cumulus to form with a general base at 6000 to 7000 ft (2 km) and isolated tops to 8000 ft. Cloud bases of between 4000 and 5000 ft were indicated for air inland. Along the sea-breeze front, however, where there was an influx of moister air from the Channel, bases were as low as 2000 to 3000 ft.

The satellite picture was useful in confirming the continuity of the front along the south coast and the existence of individual convection cells.

551.526.6:551.558.1

THE IMPORTANCE OF LOW SEA SURFACE TEMPERATURES IN INHIBITING CONVECTION ALONG THE NORTH SEA COAST IN SUMMER

By D. R. HINDLEY

Summary. An example is given of the way in which convection cloud is prevented by the relatively low sea surface temperatures occurring in a belt off the coast of north-east England. It is suggested that this should be taken into account in forecasting for the coastal belt.

There have been a number of occasions in the past, during summer, when with unstable north-north-westerly flow along the east coast of England, the coastal belt has been free of showers and has enjoyed long hours of sunshine.

There was such an occasion on 17 July 1971, when a cool showery day was expected. The national and area forecasts included 'showers being moderate or perhaps heavy at times near the east coast'. In the event, convection was markedly damped down along the coastal belt.

The nature of the air mass along the east coast is shown by the Shanwell 00 GMT ascent (Figure 1). With an air-mass dew-point of 7°C, a temperature of 13·5°C was required (over land or sea) to initiate formation of convection cloud. By 12 GMT air temperatures had reached 16 to 19°C in inland areas. Along the coastal strip of sea off north-east England they were 11 to 12°C. Further east over the North Sea, they were 13 to 15°C.

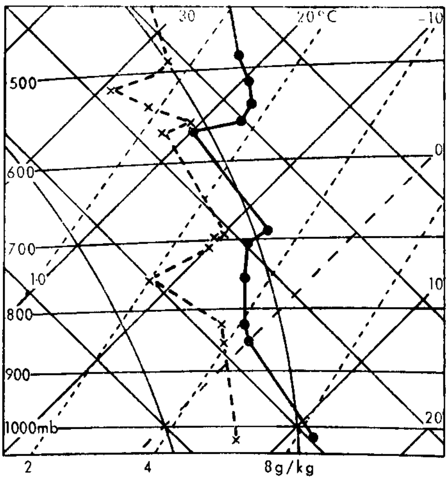

FIGURE 1—SHANWELL ASCENT FOR 00 GMT ON 17 JULY 1971

——— Temperature - Dew-point

The author was in a position to photograph the cloud formations near the east coast, and Plates II to IV were taken near Scarborough at about 12 GMT.

Plate II, looking north-north-west along the coast shows convection cloud developing a few miles inland. Plate III, looking due north, shows a clear corridor between the convection cloud inland and the convection cloud forming over the sea some miles out from the coast. Plate IV, facing north-east to east shows the cloud out to sea.

The explanation lies in the distribution of temperature along and off the coast. Figure 2 gives the five-day mean sea surface temperatures over the North Sea. The sea surface temperature distribution is a persistent feature. It is cool relative to the day-time temperatures normally reached inland at this time of year. It is also cooler than the sea surface over the shallower waters further east towards the Dogger Bank.

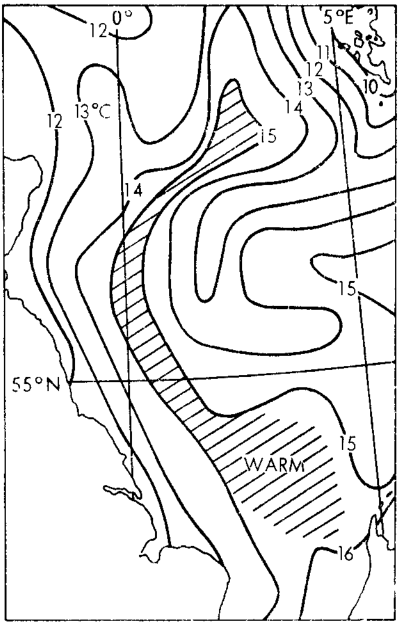

FIGURE 2—FIVE-DAY MEAN SEA SURFACE TEMPERATURES OVER THE NORTH SEA

It is clear that this is an instance of the coastal strip being free of cloud because of the cool coastal waters. These were effective in preventing the convection temperature being reached. Long sunshine hours were experienced at the coastal stations, varying between 10·3 hours at Scarborough and 14·1 hours at Kilnsea. From the increasingly important tourist industry point of view, the sunshine amount is of great significance. Provided the wind speed is not too strong, sunshine may be more important than temperature.

It is considered that rather more optimistic forecasts could be made for the coastal belt in the type of case illustrated in this note. It is suggested that a forecast of little or no cloud, and consequently 'dry and sunny', could be made for the coastal belt when the following criteria are satisfied :

(a) No major troughs or fronts are expected during the forecast period.
(b) Dew-points in the air mass are at least 3 degC below the sea surface temperatures (hence fog or low stratus are not in prospect).
(c) The geostrophic wind direction is along the coastline, i.e. 330–350 degrees. The geostrophic wind speed does not exceed 25 kt (stronger winds bring an excessive chill factor).
(d) The expected maximum air temperature along the coastal strip is less than the convection temperature shown by the 00 GMT Shanwell ascent.

NOTES AND NEWS

Retirement of Mr K. H. Smith

Mr K. H. Smith who, since 1968, has been the Assistant Director responsible for publications and training, retired from the Meteorological Office on 17 April 1972. After graduating in physics at London University followed by a spell as a schoolmaster, he joined the Office in 1938 and was assigned to forecasting duties, first at the flying-boat base at Calshot and then at Uxbridge which was the headquarters of No. 11 (RAF) Group and which became the main Air Traffic Control Centre in the United Kingdom.

In 1948 'KH', as he was widely known, was posted as an instructor to the Meteorological Office Training School. For the remainder of his career he was to be concerned with staff, either in their training or in their administration. From time to time postings appear to be haphazard, not least to the victim, but occasionally a flash of lightning illuminates the scene and certainly Mr Smith's transfer to the Training School in 1948 was quickly recognized as one of the best postings the Office has ever made. In 1952 he became Head of the Training School and two years later became Head of Met.O.10, the personnel branch, a post which he occupied for 14 years and left on promotion to Assistant Director when training once again became his principal responsibility. In these latter years one of his major projects, now successfully concluded, was the transfer of the Training School from Stanmore to Shinfield Park and its transformation into a residential college with more extensive and more varied training programmes.

For the past 24 years all members of the staff must have had personal dealings with KH not once but several times. As an individual, therefore, he was one of the best known in the Office and indeed we should widen the circle and bring into the reckoning the hundreds of overseas meteorologists who have taken our training courses. All of us will remember him as in every sense a guide, philosopher and friend. He had a wide and deep knowledge of his subject, an unusual degree of balanced judgement and whenever necessary he could stand back and take a detached view. No-one came to him in vain for advice and invariably the advice was seen to be helpfully inspired.

KH was admired in many ways but above all he will be remembered for that divine gift of humour which was so lavishly bestowed upon him. Samuel Johnson said that the gaiety of nations passed away with David Garrick. In the Meteorological Office we are somewhat more restrained in our praise but there can be no doubt KH's humour eased many a difficult situation and added to the harmony of his colleagues. We wish him and Mrs Smith a long and happy retirement.

P. J. M.

OBITUARY

It is with regret that we have to record the death of Mr C. C. Chapman (Scientific Officer) on 2 January 1972.

REVIEW

Weather and animal diseases, WMO Technical Note No. 113, by L. P. Smith. 275 mm × 213 mm, pp. iv + 49, *illus.*, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1970. Price: Sw.Fr. 10.

This publication was prepared at the request of the WMO Commission for Agricultural Meteorology, to review recent progress in applying standard meteorological data to forecasting the incidence and intensity of animal diseases, and to survey the techniques involved. The request reflects the considerable advances being made in this field and the interest which has been generated in the last 10 years, and this bulletin fills a very real gap in the literature.

The effect of climate on disease is widely recognized as a general phenomenon, but the detailed examination of the quantitative relationship between weather and specific diseases is at present restricted to a relatively small number of conditions for which sufficient data are available, and consideration is restricted to these. In the first section they are grouped as wind-borne diseases (particularly foot-and-mouth disease and fowl-pest), environmental and nutritional stress conditions, parasitic and fungal diseases and fertility problems. In each case the weather factors thought to influence the condition are briefly discussed and the correlation examined to identify those characteristics on which a positive forecast could be based. It is surprising to find that insufficient data are available on hypomagnesaemia to permit its inclusion in this section.

In the second part of the review the technical details of forecasting methods for specific diseases which are in use or in development in the United Kingdom are described, including work which has not been published elsewhere. While the first section will be of general interest to many workers in veterinary science and agriculture, this second section summarizes a great deal of information in a clear and concise form, and will be of great value to serious students of the subject. Particular attention is paid to foot-and-mouth disease, which has attracted considerable attention because of the disastrous epidemic of 1967–68.

The bibliography lists over a hundred references, but of necessity this is only a selection of the relevant published work, which is widely scattered through the biological, veterinary and meteorological literature. However, it provides a sound basis for further reading and as such is extremely useful. The review copy contains an annoying printing error in that 17 of its 50 pages are not numbered, and the author shows a rather carefree attitude to singular and plural nouns as, for instance, in 'advances has emanated' and 'snowfalls is very efficient'. Generally, though, errors are few and this is a very readable and informative introduction to a subject which is only now beginning to receive the attention it deserves.

R. J. THOMAS

LETTER TO THE EDITOR

551.507.362.2:551.521.12(548.82):551.576.3

The effect of cloud on solar radiation receipt at the tropical ocean surface

I was interested to read Mr D. E. Parker's paper in the August 1971 issue.*

Mr Parker's results could be used to calculate total solar radiation received at the ocean surface during one day (or a few days), but if any investigator wishes to do this, I think that in the tropics it would be simpler to work directly with daily totals and mean daily cloud amounts. In the tropics on a large majority of days the cloud is predominantly convective, and from a limited investigation which I made some years ago using Dar-es-Salaam data, it appears that there is a good linear correlation between daily totals (Q) and mean cloud amount $\bar{C}$ (excluding the few days with large amounts of As or Ns) provided $\bar{C} > 2$ oktas. For values of $\bar{C} < 2$ oktas, Q is virtually constant.

As an example, I attach a scatter diagram (Figure 1) relating daily totals of solar radiation to mean amount of cloud (low plus medium) for the hours 08–17 EAST at Dar-es-Salaam during May 1964. The 26 points marked x are occasions when the cloud was predominantly of convective origin, the 5 points marked o are occasions when large amounts of As were reported, with

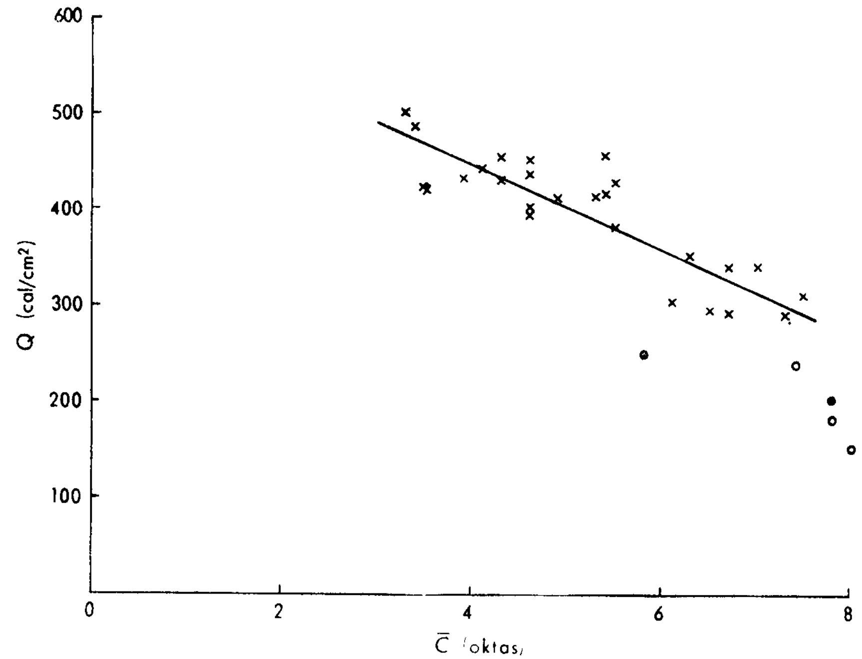

FIGURE 1—SCATTER DIAGRAM RELATING DAILY TOTALS OF SOLAR RADIATION TO MEAN CLOUD AMOUNT FOR 08–17 EAST AT DAR-ES-SALAAM DURING MAY 1964

* *Met Mag, London*, **100**, 1971, pp. 232–240.

variable amounts of low cloud. The straight line $Q = 628 - 44{\cdot}6\ \overline{C}$ gives a good fit to the x points ($r = 0{\cdot}77$) for values of $\overline{C}$ between 3 and 7·5 oktas. The occasions with thick medium cloud need separate treatment.

Regional Meteorological Training Centre,
East African Community, Nairobi

F. E. LUMB

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CONTENTS

NOTICES

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A CLIMATOLOGY OF THE POTENTIAL VERTICAL EXTENT OF GIANT CUMULONIMBUS IN SOME SELECTED AREAS

By W. T. ROACH and B. F. JAMES

Summary. This paper consists of two interrelated parts :

(a) Based on earlier evidence that simple 'parcel' theory using the tephigram was a good indicator of the maximum height likely to be reached by cumulonimbus clouds on a given day, a climatology of parcel heights is presented for some areas (United States, India, Singapore, the Mediterranean) where possible future supersonic transport routes are likely to encounter giant cumulonimbus.

(b) Recently available statistical radar data on storm-top heights are reviewed and shown to be quantitatively consistent with (a) above. They are also used to suggest a simple quantitative model which can be used to forecast (on the bench) on any given day in any part of the world the vertical distribution of storm-top heights from parcel theory.

Introduction. It has been recognized for some time that the vertical extent of cumulonimbus cloud is an important consideration in the design and operation of supersonic transport (SST). Until about five years ago reliable observations of the heights and distributions of cumulonimbus tops were still virtually non-existent in most areas of potential interest. However, the use of radar and photogrammetric methods has significantly increased knowledge in some areas, particularly in the United States.

The available sources were discussed by Roach[1,2] whose main finding was that where reliable observations of the vertical extent of cumulonimbus could be related to the local atmospheric structure (using radiosonde data), the 'parcel' theory using the tephigram (Figure 1) worked quite well (and much better than tropopause height) as an indicator (Figure 2) of the maximum height which storms would be likely to reach on a given day.

More specifically, there was some evidence to suggest that organized storms (also referred to as severe storms, wind-shear storms, or frontal storms) reached or exceeded the 'maximum' parcel height, Z_p, more frequently than less organized storms (air-mass or heat thunderstorms). This difference was attributed to a greater efficiency of conversion of the energy of potential instability (the 'positive area' energy) into kinetic energy of vertical motion in the organized storms than in the disorganized storms (e.g. Browning and Ludlam[3]; Ludlam[4]; Roach[2]).

From the operational viewpoint, it appeared that an aircraft flying at Z_p would be above the visual tops of most storms (although not clear of their associated turbulence) whatever their type, and that the spacing of storm tops reaching Z_p would be at about 300-km intervals along fully developed severe storm belts (squall lines).

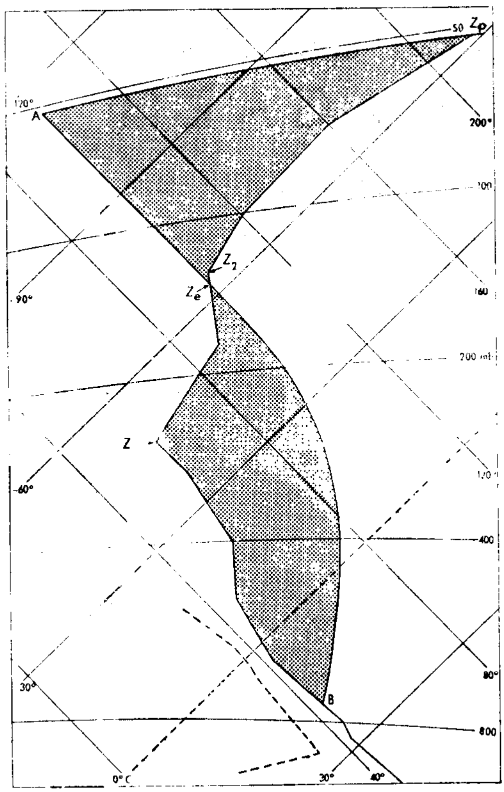


FIGURE 1—TEPHIGRAM SHOWING AN ASCENT OF GREAT POTENTIAL INSTABILITY

——— Temperature - - - Dew-point

Curve AZ_eB is the parcel ascent curve for a wet-bulb potential temperature (28°C) representative of the lowest 100 mb.

Z_1 and Z_2 are tropopauses.

Z_e is the 'equilibrium' parcel height at which the parcel temperature equals the environment temperature.

Z_p is the 'maximum' parcel height for which the positive (stippled) area (below Z_e) is equal to the negative (stippled) area between Z_e and Z_p.

This work suggested that it might be worth while compiling a climatological survey of Z_p based on conventional radiosonde ascents for areas subject to giant thunderstorms and most likely to lie on future SST routes. It is emphasized that such a survey would do no more than indicate the *potential* vertical extent of convective activity in the areas considered. Z_p does not by itself determine the extent and distribution of convective activity on any given day, although it might be reasonable to expect there to be an overall statistical relationship between Z_p and the distribution of convective activity reaching SST levels in a given (large) area.

While the climatological survey of Z_p was in progress, comprehensive radar studies of the vertical extent of convective cloud in the United States (Grantham and Kantor[5]; Kantor and Grantham[6]) became available, and these in fact show a good correlation with the Z_p data. Thus, it was thought worth while to construct a model which gives a reasonable quantitative account

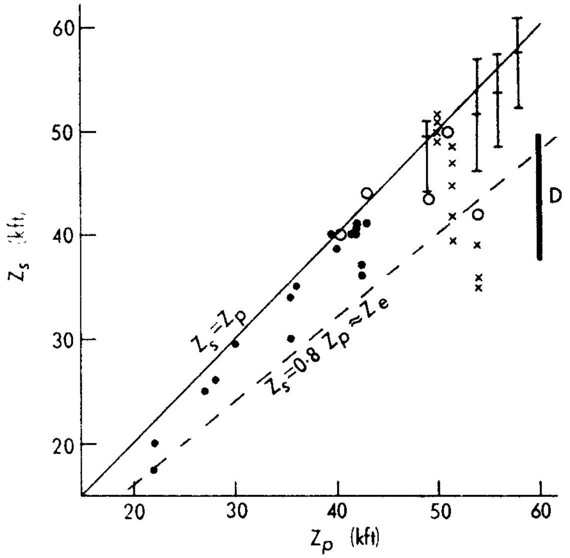


FIGURE 2—CORRELATION OF STORM-TOP HEIGHTS, Z_s, WITH PARCEL HEIGHT, Z_p

● Observations by RAF pilots over U.K.
○ Observations mainly of severe storms, by Ludlam (unpublished note)
× Radar observations from Miami, Florida

Thin vertical lines represent summary of observations of storm tops made from U–2 aircraft flying at 65 000 ft; the upper horizontal tick is maximum Z_s, the middle horizontal tick is mean Z_s plus standard deviation, and the lower horizontal tick is mean Z_s.
The thick vertical line, D, indicates the mean plus and minus the standard deviation of 300 storm-top heights reported by Deshpande[13] in the monsoon period. Since individual values of Z_p were not available because the time and place of observation was not reported, the value of Z_p here is a representative mean value for the monsoon period.

of this correlation. Rather limited radar data from India[7,8,9] and Singapore (Moore, unpublished) also exist.

The presentation and discussion of the climatology of Z_p and its relationship with available radar observations of storm tops thus form the main topics of this paper.

Climatology of Z_p.

General comment. The computation of Z_p (Figure 1) for a given day depends upon :

(a) The temperature profile of the atmosphere above about 3000 ft.*
(b) The choice of a wet-bulb potential temperature (θ_w) representative of the lowest 3000 ft of atmosphere as far as possible at the time of maximum diurnal heating.

The resultant value of Z_p is rather sensitive to the choice of θ_w, its sensitivity varying with the type of ascent. In an atmosphere with a well-defined tropopause and a potentially unstable troposphere (characteristic of unstable conditions in subtropical and temperate latitudes in spring and early summer), the positive and negative areas are likely to be large and Z_p well defined. In such an atmosphere a change of 1 degC in θ_w will result in a change of about 5000 ft in Z_p. However, in an atmosphere with a high tropopause and a troposphere with a lapse rate close to saturated adiabatic (typical of

* 1000 ft ≈ 305 m.

tropical atmospheres), the computation of Z_p is less reliable and consequently of less value. Positive areas tend to be thinner and more elongated than those associated with severe storms so that a change of 1 degC in θ_w might change Z_p by up to 15 000 ft, and in such conditions the tropopause height is probably no worse an indicator of the potential vertical extent of convective activity than Z_p.

Areas selected. The stations for which Z_p was computed were :

United States	Charleston Great Falls Lake Charles Oklahoma City Peoria St Cloud Tampa Topeka	For the months April–October in the years 1959–63 (all inclusive) Ascents at 00 GMT (about 18 local time)
India	Allahabad Bangalore Calcutta Gauhati Jodhpur Nagpur New Delhi	For the months March–November in the period 1961–66 Ascents at 12 GMT (about 18 local time)
Mediterranean	Malta Cyprus	May–November 1960–67 Ascents at 12 GMT (about 13 local time)
Far East	Singapore	All months for the period 1959–66 Ascents at 00 GMT (07 local time)

This sample is limited, but nevertheless has involved the examination of some 20 000 radio soundings for potential instability. Although this was carried out by computer, all the original data had to be punched on tape.

The details of the method are described in Appendix I, and the location of the stations used in the United States and India are shown in Figures 3 and 4.

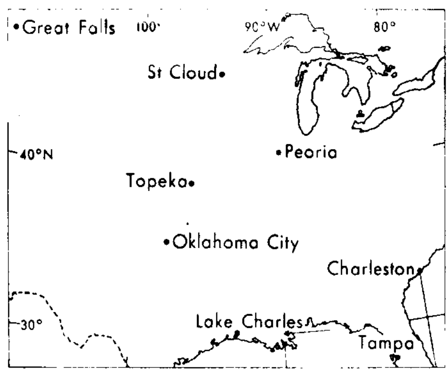


FIGURE 3—MAP OF UNITED STATES SHOWING STATIONS FOR WHICH Z_p WAS EVALUATED

Results. The results are summarized in Figure 5. The histograms show the percentage of days in each month over the period analysed (5–8 years) for which Z_p reached or exceeded the fixed levels 50, 55, 60 and 65 thousand feet (kft).

Another way of representing the results is to plot the frequencies in Figure 5 on probability paper. This has been done for some stations (Figure 6). The

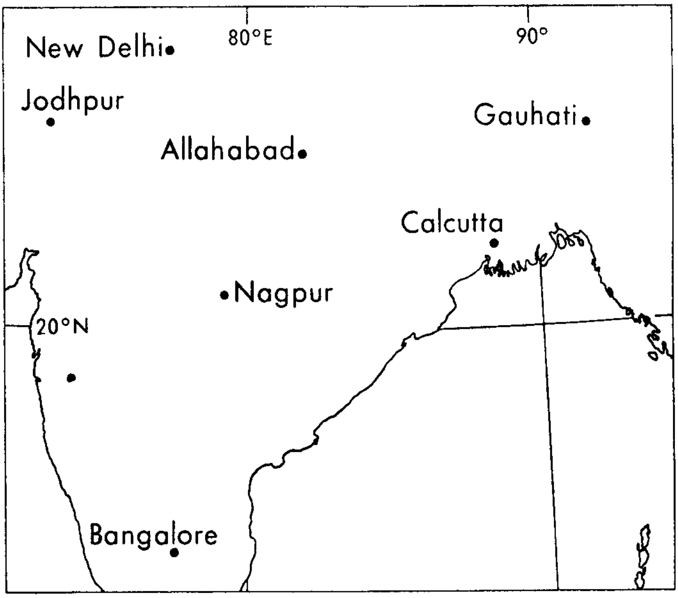


FIGURE 4—MAP OF INDIA SHOWING STATIONS FOR WHICH Z_p WAS EVALUATED

data for an individual month and station are based on only two or three points so that the slopes of lines joining these points cannot by themselves be considered significant. However, taken as a whole, the slopes of these lines do appear to be very consistent and in fact the standard deviation of the slopes about a mean value is about 20 per cent. These slopes can therefore be considered to represent tails of a normal (Gaussian) distribution with a mean Z_p during the summer of 45–50 kft and a standard deviation of $5{\cdot}8 \pm 1{\cdot}2$ kft.

Similar remarks appear to be true for Singapore, which exhibits a mean Z_p varying from about 40 kft in January and February to about 50 kft in May and June.

The Indian results, on the other hand, show a distinct curve which implies either a platykurtic or skew distribution depending upon where the curve lies with respect to the 50 per cent probability line. However, the slope of the curve is similar to the other results at high values of Z_p, but steepens towards lower (and more frequent) values of Z_p.

The general levels of Z_p in India are higher (by about 5000 ft) than in Oklahoma, and are probably the highest in the world, occasionally exceeding 70 kft. This is mainly a reflection of the higher values of θ_w (25–30°C) prevalent in India from May to September than in the United States where θ_w is typically in the range 20–25°C.

There is a marked year-to-year variation in the frequency with which Z_p exceeds given altitudes at a given station in a given month (Table I). At first sight, the variability looks quite large, but in fact is equivalent to a variation in mean Z_p over a range of 5000 ft at most. For example, in the year of minimum Z_p at Oklahoma (1961) the figure for 50 kft (17 per cent was the same as the figure for 55 kft in the year of maximum Z_p (1962).

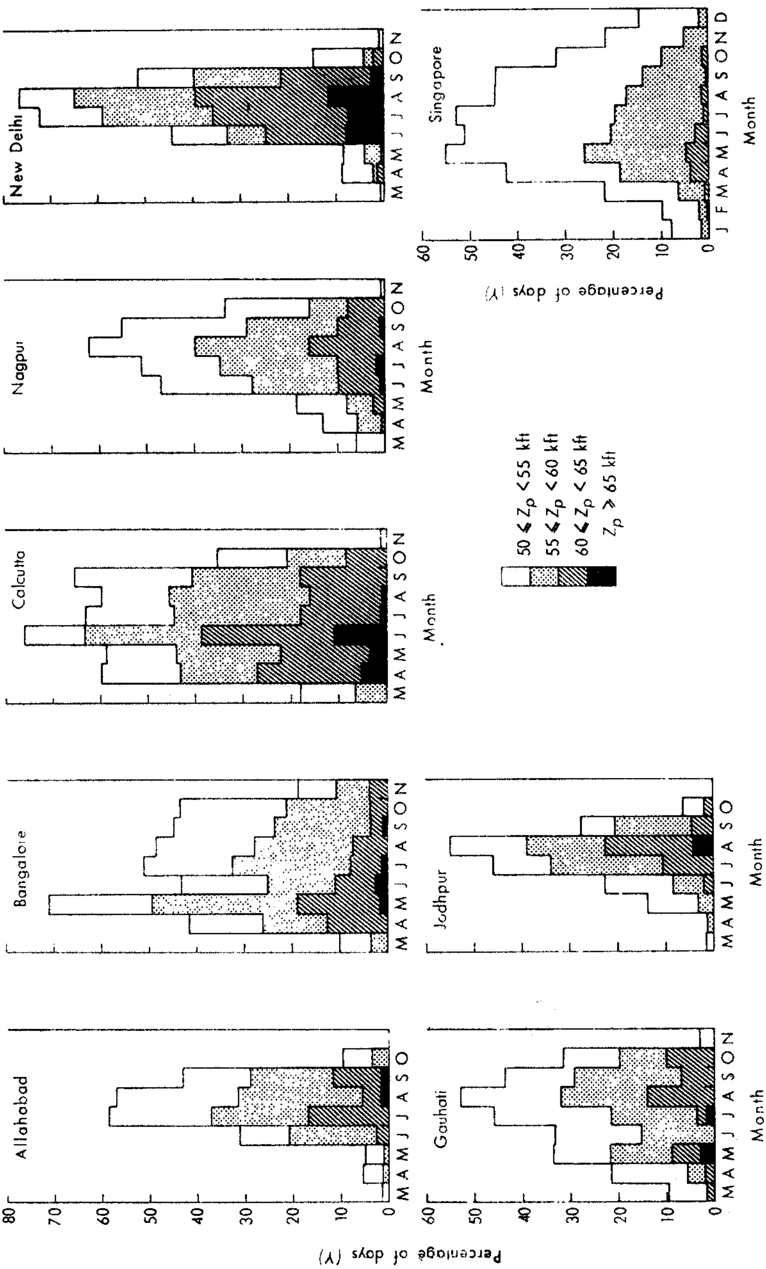
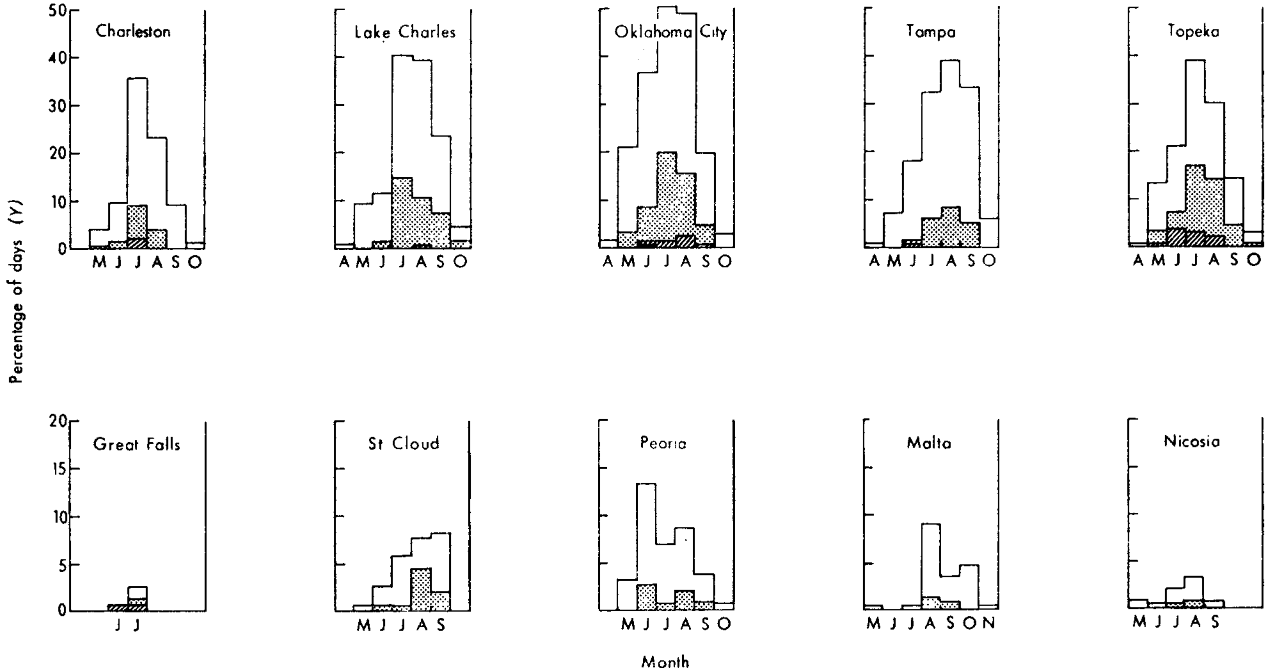


FIGURE 5 (a) Indian stations 1961–66 and Singapore 1959–66



(b) United States stations 1959–63 and Mediterranean stations 1960–67

FIGURE 5—SUMMARY CHART OF PERCENTAGE DAYS (Y) ON WHICH Z_p EXCEEDED $h = 50, 55, 60$ OR 65 kft AT THE STATIONS SELECTED

Sample sizes for each month were about 80–100 per cent of the maximum possible for the United States stations, Singapore, Malta and Nicosia, but only about 30–60 per cent for the Indian stations.

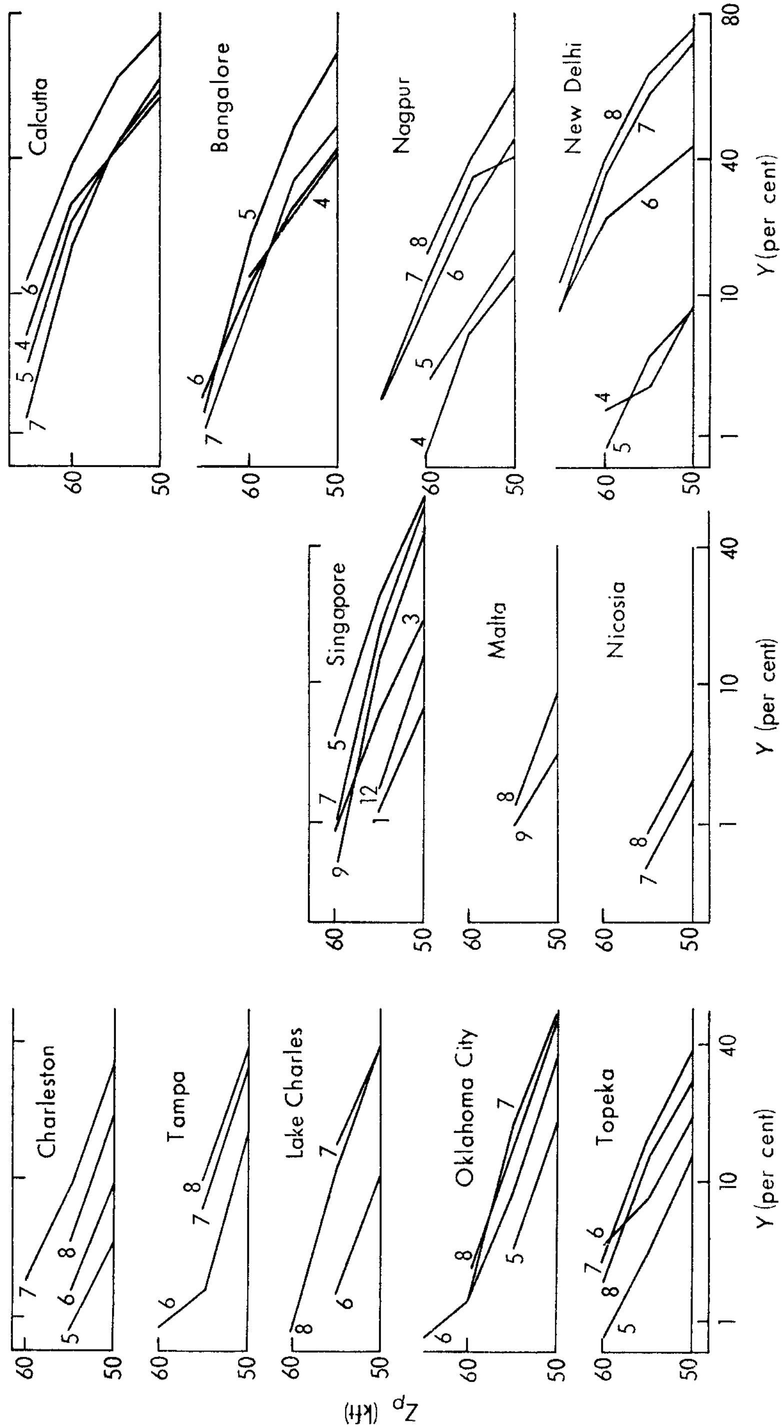


FIGURE 6—SOME OF THE DATA PRESENTED IN FIGURE 5 PLOTTED ON PROBABILITY PAPER

Months identified by 1 = Jan. 3 = Mar. 4 = Apr., etc.

TABLE I—SAMPLES OF ANNUAL STATISTICS OF Z_p FOR OKLAHOMA CITY (JUNE) AND CALCUTTA (MAY)

Oklahoma City : June	Lower limit of Z_p (kft)			
Year	50	55	60	65
		percentage		
1959	28	14	3	3
1960	40	0	0	0
1961	17	3	0	0
1962	52	17	3	0
1963	45	7	0	0
Mean	36	8	1·2	0·6
Calcutta : May				
1961	(60)	(60)	(20)	(0)
1962	(89)	(67)	(50)	(25)
1963	64	38	9	0
1964	52	35	26	0
1965	64	52	38	9
1966	47	39	12	0
Mean	59	44	22	3·3

Brackets denote percentages based on less than 10 observations. Means are of annual figures weighted by the total number of observations in each year.

This allows some confidence in stating that the comparison of Z_p data for the years 1959–63 with radar data for the period 1962–67 (discussed later, pages 171 - 174) is unlikely to produce conclusions significantly different from those obtained by making a comparison over identical periods.

As regards the Mediterranean, the general level of Z_p is much lower than in other areas investigated and is highest in August, rather before the main autumn thunderstorm season.

The number of thunderstorm days is tabulated elsewhere (e.g. WMO[10]) but for reference here, it can be stated that this amounts to a maximum of about 10 days per month in summer in the plains States of the U.S.A. and rather more (15–20) around the coasts of the southern States. In India, the maximum is 10–15 in June in coastal areas decreasing to about 5–10 well inland (e.g. New Delhi) in the same month. At Singapore, it varies between 10 and 20 throughout the year (maximum in spring, minimum in winter), while in the Mediterranean, it is only about 1 during the months (July and August) of maximum Z_p increasing to about 5 in the autumn.

The relationship between Z_p and 'positive area' energy. It is reasonable to expect that large values of Z_p will in general be associated with large values of positive area energy E. However, this relationship must be a diffuse one since the value of Z_p associated with a given E will be sensitive to the shape of the positive area, which varies considerably from situation to situation.

The positive areas were evaluated as part of the computational programme and expressed as an equivalent velocity, W_{max}, defined by

$$E = \tfrac{1}{2}(W_{max})^2,$$

where W_{max} would be the maximum vertical velocity attained by an air parcel moving up a saturated adiabatic without mixing with its surroundings.

The results are summarized in Figure 7 in the form of histograms showing the spread of W_{max} for various ranges of Z_p for the United States, Singapore and India. The median values of W_{max} (M_w) are shown as vertical lines.

The following features are apparent :

(a) All the histograms show well-defined peaks with a spread corresponding

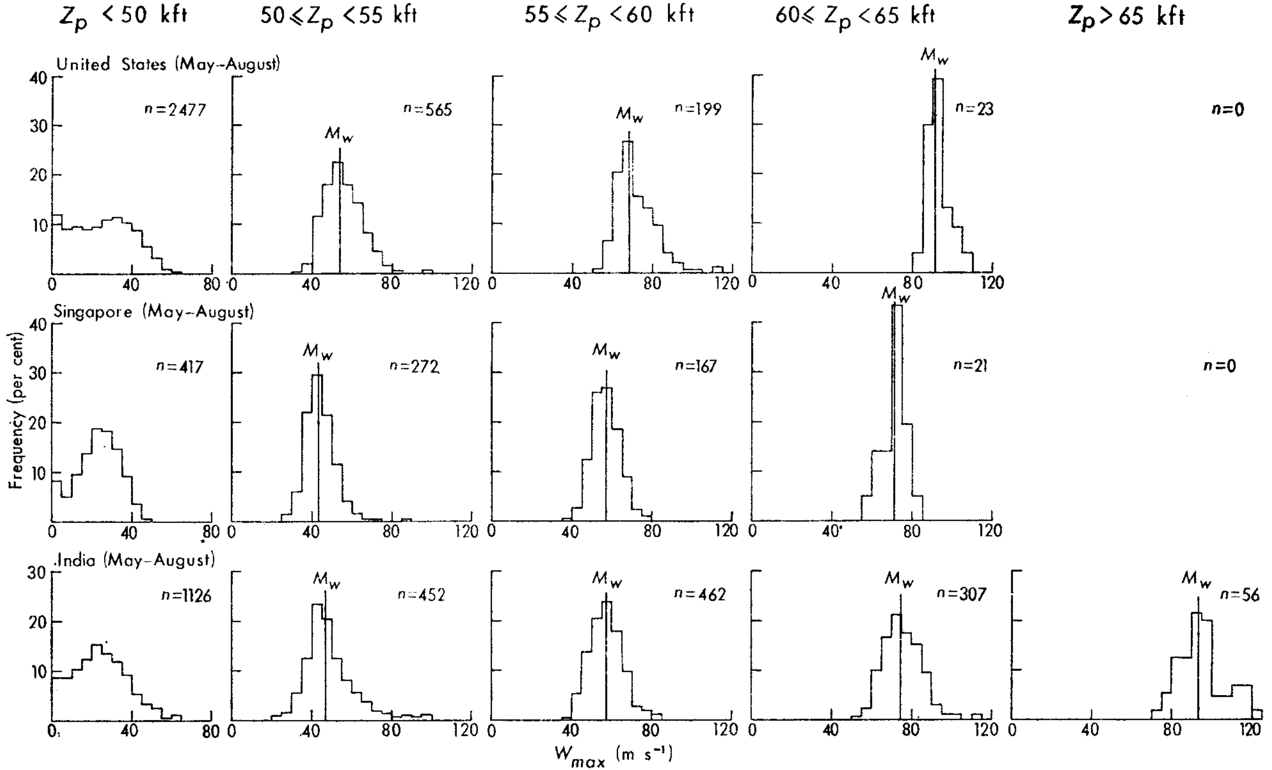


FIGURE 7—HISTOGRAMS OF 'POSITIVE AREA' ENERGY EXPRESSED AS EQUIVALENT MAXIMUM VERTICAL VELOCITY FOR THE UNITED STATES, SINGAPORE AND INDIA

In each case, the results averaged over the period May–August are presented. The vertical line, M_w, denotes the median of the histogram (except for the category $Z_p < 50$ kft).

to a standard deviation of about 10–15 m/s with some tendency for the standard deviation to decrease with increasing Z_p in the United States and Singapore data, but not in the Indian data.

(b) The value of M_w corresponding to a given range of Z_p is 10–15 m/s higher for the United States than for either Singapore or India. The difference of 2–3 m/s between Singapore and India is not significant.

(c) Extreme values of W_{max} obtained approach 120 m/s in the United States, 140 m/s in India, but only 80 m/s in Singapore. A similar conclusion has been reported by Lee and McPherson.[14]

(d) The W_{max} distribution for $Z_p \leqslant 50$ kft suggests that large vertical velocities may be found in storms whose summits are less than 50 kft.

There is also a marked seasonal decrease in the United States of M_w by 10–15 m/s from May to August (not shown). In May, M_w for a given Z_p is 20–25 m/s higher than the corresponding value of M_w for Singapore. There is no marked seasonal trend in either the Singapore or Indian data.

The high values of M_w for the United States (particularly in May), would appear to reflect the greater instabilities which occur there in association with frontal (or severe) thunderstorms. In these conditions, temperature differences between the parcel ascent curve and the environment curve at a given level may exceed 10 degC in mid-troposphere mainly because of the development of deep layers containing a dry adiabatic lapse rate above the moist surface layers. On the other hand, in air-mass storms growing in a fairly homogeneous environment, the parcel–environment temperature difference is more usually in the range 2–5 degC. This statement is particularly true in tropical latitudes where the environment lapse is often near saturated adiabatic throughout most of the troposphere. The contrast between temperate and tropical latitudes is further accentuated by the relatively low tropopause of temperate latitudes which also tends to limit the height which a storm of given energy can attain.

The marked seasonal decrease in M_w observed in the United States is probably associated with a progressive change of the predominant storm type from frontal to air mass accompanied by a rising tropopause.

Comparison of radar echo with Z_p climatology.

United States of America. Of the radar studies made in U.S.A., the work of Grantham and Kantor[5,6] was chosen for comparison with the Z_p climatology outlined above. The basic data used by them consisted of a record of the maximum echo height observed at each hourly observation (in practice, within a few minutes around each hour) within a radius of 100 miles ($\approx$160 km) of each of 31 stations in the United States operating a WSR-57 radar over a period of six years. The figures tabulated were percentage frequencies of occasions in each month (of the period January 1962–December 1967) when the hourly maximum echo top was observed to exceed 50, 55, 60, 65 and 70 kft.

The various sources of error which can arise in echo height determination have been generally realized for about a decade (e.g. Jordan[11]) and the observations from the network were corrected for the effects of earth curvature, atmospheric refraction and beam width. The frequency of very high echoes per unit area was found to remain sensibly constant with range from the radar, which is reasonable evidence of the coherence and reliability of the data.

There is some evidence (e.g. Saunders and Ronne[12]) that the difference between echo-top height and visual cloud-top height of a given storm is about 2000 ft, which is considered too small to be of significance here.

Five stations and two years (1962–63) chosen by Grantham and Kantor were common to the stations and years for which Z_p was evaluated. Thus the comparison was based on these stations (Charleston, Lake Charles, Oklahoma City, Tampa, Kansas City*), but the whole period of the radar data (1962–67) was compared with the whole period for which Z_p was evaluated (1959–63).

It was decided, in the first instance, to plot for a given month and station the percentage of days, Y_j, when Z_p exceeded a given height, h_j, against the percentage of occasions, X_j, when the maximum echo height exceeded h_j during the period 13–21 hours local time. This time was chosen because Z_p was based on the 00 GMT (18 local time) ascent which was not far removed from the time of maximum diurnal heating and was at about the time of maximum convective activity.

The results for all five stations are shown in Figure 8. It was found convenient to plot Y_j against X_j on logarithmic scales to accommodate the wide range of values occurring for different values of h_j. There is a significant correlation between Y_j and X_j for $h_j \geqslant 50$ kft and $h_j \geqslant 55$ kft, but not for $h_j \geqslant 60$ kft. However, the observations for the United States taken *in toto* all appear to cluster about the line $Y = 3X$, although there are large variations in individual cases. This is equivalent to the statement that if Z_p exceeds h_j on the day in a given month, storm heights in excess of h_j will be observed on radar within 100 miles of the station for about 10 per cent of the period 13–21 hours summed over that month.

The scatter of points about the line $Y = 3X$ in Figure 8 is by no means random for individual stations. Values of $(Y/X)_j$ are plotted against month for individual stations in Figure 9. A distinct seasonal trend is apparent at most stations. $(Y/X)_j$ shows a marked increase in spring and summer at all stations (except Lake Charles) followed by a tendency to level out (Oklahoma City, Kansas City) or to decrease (Lake Charles, Charleston) in the autumn.

An increasing value of $(Y/X)_j$ implies a decrease in the number of storms reaching Z_p. This may depend partly on the efficiency with which potential instability is converted into kinetic energy of vertical motion, and partly on the total number of storms. For instance the percentage frequency of occasions on which no echo is visible varies considerably with season and station (Table II based on Grantham and Kantor[5,6]).

TABLE II—PERCENTAGE FREQUENCY OF OCCASIONS WHEN NO ECHO IS VISIBLE ON RADAR BETWEEN 13 AND 21 HOURS

	April	July	October
Charleston	57	16	61
Lake Charles	57	32	65
Oklahoma City	75	50	79
Tampa	67	2	49
Kansas City	51	47	73

A significant fraction of the echo period is due to frontal precipitation which tends to produce a distribution of echo heights which is platykurtic

* In fact, Topeka was used in the Z_p study, but as Topeka is only 60 miles from Kansas City, it was taken to be in the same location as Kansas City from a climatological viewpoint.

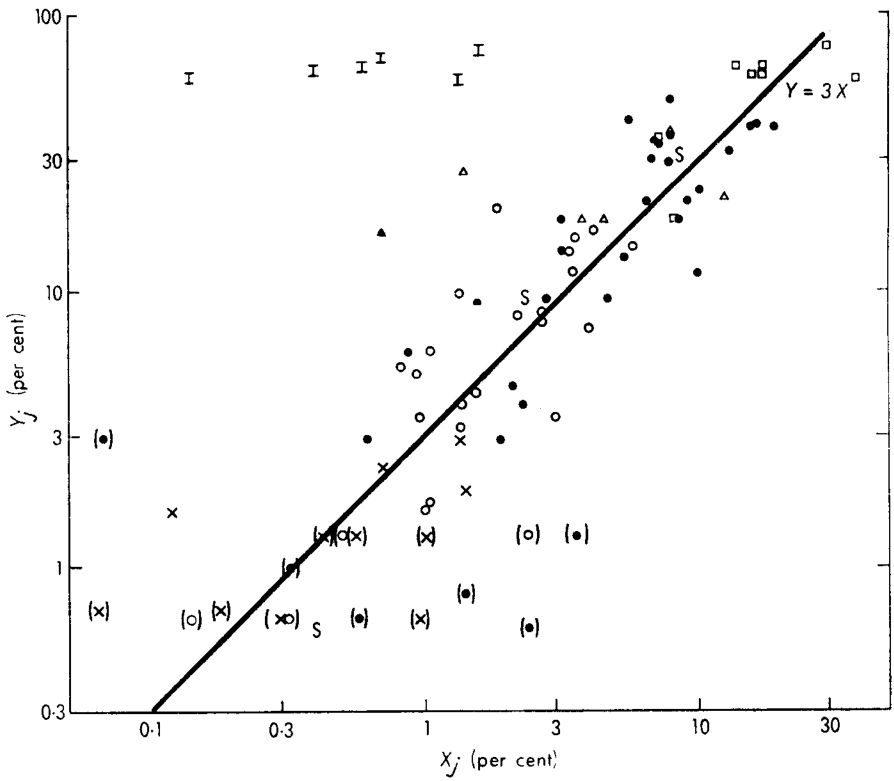


FIGURE 8—A PLOT OF THE PERCENTAGE FREQUENCY OF OCCASIONS (X_j) WHEN THE HOURLY MAXIMUM RADAR ECHO TOP EXCEEDS h_j AGAINST PERCENTAGE FREQUENCY OF DAYS (Y_j) WHEN Z_p EXCEEDS h_j

Bracketed points are those for which the sample was very small (one or two occasions or days in whole sample).
United States : ● $h_j > 50$ kft ○ $h_j > 55$ kft × $h_j > 60$ kft
Singapore : S $h_j \geqslant 50$, 55, 60 kft
Early Indian data : I $h_j \geqslant 50$ kft
Later Indian data (Rakshit[9]) : □ $h_j > 50$ kft △ $h_j > 60$ kft

and skewed towards low altitudes but with a fairly prolonged tail at high altitudes. This tail exhibits a reasonably straight line when plotted on probability paper (not shown here) with a slope corresponding to a nominal standard deviation of 8–10 kft — rather more than that observed for Z_p.

Singapore. Some limited data from a survey by Moore (unpublished) of the heights of cumulonimbus tops in the vicinity of Singapore were made available for the purposes of this paper. These were summarized to give the highest echo tops observed within 100 miles of the radar on about 350 occasions between the hours 06–11 local time (radiosonde ascents on which Z_p was based were released at 07 local time) during the period September–November 1969.

The resulting X–Y relationship is plotted on Figure 8 (symbol S) and is seen to fall well within the spread of observations exhibited by the United States data. This is gratifying and lends further support to the universality of this relationship which emerges even in tropical areas where the determination of Z_p is subject to larger error than in subtropical areas.

North India. The consistent picture that has so far emerged does not extend to North India. Radar studies in the vicinity of New Delhi (Kulshrestha[7]) and Calcutta (Bhattacharyya and De[8]) and observations from aircraft (Deshpande[13]) all seem to indicate that only 5–10 per cent of cumulonimbus tops exceed 50 kft in the monsoon season. Bhattacharyya and De give enough information to enable the *X–Y* relationship to be plotted on Figure 8 (symbol I).

It can be seen that these data have no relation to the rest of the data plotted. This discrepancy could be accounted for by the existence of a systematic error of about 10 kft arising from either the radar data or the Z_p data, or from both.

However, two more sources of data from India have recently appeared :

(a) Rakshit[9] of the India Meteorological Department has evaluated the number of days on which radar storm-top echoes exceeded given heights in Calcutta (Dum Dum Airport) in the years 1959–64. These observations are plotted in Figure 8. The values of *X* may be an underestimate as they refer to a whole day and not just part of a day as for the United States, but it will be seen that on the whole these data also lie reasonably well within the United States spread of data.

(b) A recent photogrammetric survey of pre-monsoon cumulonimbus heights from an aircraft (from U.K.) over Bengal in May 1969 showed storms consistently reaching 60–65 kft. Cornford and Spavins state (report in preparation) that while there appeared to be little correlation between the highest observed top and Z_p on a given day (which is not surprising since the total spread of top height and Z_p was little more that 5 kft), nevertheless the mean value of the height of storm top was only 2–4 kft below the mean value of Z_p. Cornford and Spavins consider that most of this difference may be accounted for by a systematic underestimate of storm-top height from an aircraft flying at least 40 kft below the storm-top height.

The conflict between early and recent Indian data cannot be explained; it can only be emphasized that the recent data confirm expectations based on the values of Z_p obtained as part of this study.

Discussion. The relationship between parcel-top height, Z_p, and observed tops, Z_s, from individual case studies (Figure 2) suggests that the distribution of Z_s may be expressed as a function of Z_p which varies somewhat with the degree of organization of the storms (e.g. whether of air-mass or frontal type), and that this could form the basis of a simple forecasting model.

The comparison of radar data with the climatology of Z_p (Figure 8) demonstrates some qualitative consistency with Figure 2 (in the sense that there is a significant statistical relationship between Z_p and Z_s which may be to some extent dependent upon the degree of storm organization — see Figure 9) but it is necessary to establish some quantitative consistency between Figures 2 and 8 before confidence can be placed in a simple forecasting model based on either source of data.

An attempt to make such a quantitative comparison is described in Appendix II, and although imprecise in nature, it does serve to show that at

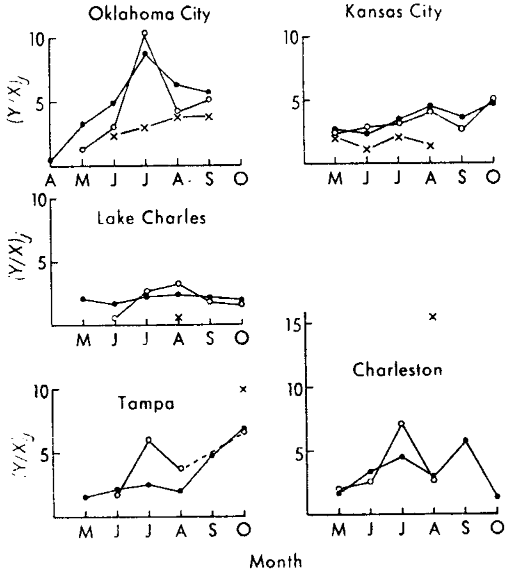


FIGURE 9—SEASONAL TREND OF $(Y/X)_j$ FOR SOME STATIONS (BASED ON FIGURE 8)

least there is no obvious inconsistency between the sources of data. That being so, the results of Appendix II have been of significant assistance in formulating the simple forecasting model proposed below.

Suggested forecasting model

(a) On any given day, the forecaster will estimate the value of Z_p likely to occur at the time of maximum diurnal heating. If frontal storms are expected then it is essential that Z_p is evaluated from a sounding representative of the warm, moist air *ahead* of the front.

(b) The distribution of storm-top height, h, for a given Z_p is taken to be normal (Gaussian) with the following parameters :

Type of storm	Mean height (H)	Standard deviation (σ_h)
Air-mass	$0.7\, Z_p$	$0.15\, Z_p$
Frontal	$0.85\, Z_p$	$0.1\, Z_p$

This implies that the fraction of storm tops $\geqslant Z_p$ at any given time varies from about 1 in 50 to 1 in 10, depending upon the degree of organization.

(c) This model does not apply to the distribution of maximum heights reached by *individual* storms during their lifetime.

(d) This model says nothing about the areal density of storms which is determined by factors other than Z_p. However, observations suggest that the areal density of storms will actually lie between 1 and 40 storms per 10^5 km^2.

Aviation aspects. The model presented above in combination with Figure 5 could in principle form a basis for estimating the probability (neglecting avoidance procedures) of an aircraft encounter with a storm top. A characteristic storm-top dimension would have to be assumed, but the major uncertainty arises in the estimation of the number of storms in a given area.

It appears to be generally accepted that the severe organized storm constitutes the greatest hazard to aviation and is more dangerous than an air-mass storm of comparable height for the following reasons :

(a) Risk of encounter with large hail in severe storms.
(b) Risk of loss of control in major organized updraughts and downdraughts.
(c) The cold surface outflows from severe storms are particularly strong and constitute a major hazard to aircraft flying below about 5000 ft.
(d) The tendency for severe storms to form along lines, particularly in the United States where they constitute a formidable barrier which tends to cut across the main air routes.

As regards the turbulence hazard, it might be expected on general grounds that the intensity of turbulence would be roughly correlated with the strength of the main updraughts and downdraughts (presumably the prime cause of the turbulence) which in turn would be related to the 'positive area' energy, E.

The observation that the value of E for a severe storm of given Z_p appears to be significantly greater than for an air-mass storm and the more efficient conversion of E into kinetic energy which appears to take place in a severe storm, are factors which favour a greater intensity of turbulence in severe storms than in air-mass storms of comparable height.

This does not appear to have been investigated by research aircraft, but comparison of the turbulence experience of aircraft flying above severe storms in Oklahoma with that of those flying above tropical thunderstorms of comparable height near Singapore (predominantly air-mass), suggests that turbulent patches over severe storms are significantly larger, but not significantly more intense (Lee and McPherson[14]).

Conclusions. Further and more specific support is given in this paper to preliminary evidence (Roach[1,2]) of a significant and universal relationship between the distribution of storm-top heights and the 'parcel' height prediction (Z_p — Figure 1) on a given day.

This has resulted in the formulation of a simple model which could be used by bench forecasters, and is probably easiest to apply in situations of greatest aviation hazard.

Acknowledgements. The authors are indebted to Mr R. F. Jones, Mr M. H. Freeman and Mr S. G. Cornford for their encouragement and discussion of this phase of the work and to Miss R. Baxter and Mrs J. Willis who performed the tedious task of data extraction and tape punching.

REFERENCES

1. ROACH, W. T.; Giant convective storms as a potential weather hazard to supersonic aircraft. London, Aeronautical Research Council, 1966. (Unpublished, copy available in Meteorological Office Library, Bracknell.)
2. ROACH, W. T.; On the nature of the summit areas of severe storms in Oklahoma. *Q J R Met Soc, London*, **93**, 1967, pp. 318–336.
3. BROWNING, K. A. and LUDLAM, F. H.; Airflow in convective storms. *Q J R Met Soc, London*, **88**, 1962, pp. 118–135.
4. LUDLAM, F. H.; Severe local storms: a review. *Met Monogr, Boston*, **5**, 1963, No. 27, pp. 1–32.
5. GRANTHAM, D. D. and KANTOR, A. J.; Distribution of radar echoes over the United States. *Air Force Surv Geophys, Bedford, Mass*, No. 191, 1967.
6. KANTOR, A. J. and GRANTHAM, D. D.; A climatology of very high altitude radar precipitation echoes. *Air Force Surv Geophys, Bedford, Mass*, No. 207, 1968.

Photograph by Dr H. A. Lang

PLATE I—NOCTILUCENT CLOUD OBSERVED FROM NEWTON STEWART, WIGTOWNSHIRE, ON THE NIGHT OF 2–3 JULY 1971 AT 0005 UT
see page 182.

PLATE II (a)—NOCTILUCENT CLOUD OBSERVED FROM PERTH BRIDGE ON THE NIGHT OF 14 JULY 1971 AT 2350 UT

see page 182.

Photographs by Dr W. H. Findlay

PLATE II (b)—

Adjoins Plate II(a) on the right (slight overlap).

Photograph by Morgan W. Findlay

PLATE III—NOCTILUCENT CLOUD OBSERVED FROM DUNDEE, ANGUS, ON THE NIGHT OF 5–6 JUNE 1971 AT 0145 UT

see page 182.

Photograph by J. Östergaard Olesen

PLATE IV—NOCTILUCENT CLOUD OBSERVED FROM ALRO, DENMARK, ON THE NIGHT OF 17 JULY 1971 AT 2150 UT

see page 182.

7. KULSHRESTHA, S. H.; Heights of cumulonimbus cloud tops over north India: a radar study. *Indian J Met Geophys, New Delhi*, **13**, 1962, pp. 167–172.
8. BHATTACHARYYA, P. and DE, A. C.; Study of the heights of radar clouds in the Gangetic Valley of West Bengal. *Indian J Met Geophys, New Delhi*, **17**, 1966, pp. 591–596.
9. RAKSHIT, D. K.; A climatology of radar echoes observed at Dum Dum airport during the period 1959–64. (To be published in Indian J Met Geophys.)
10. Geneva, World Meteorological Organization. World distribution of thunderstorm days. WMO No. 21, Geneva, 1953.
11. JORDAN, C. L.; On the maximum vertical extent of convective clouds over the central and south-eastern United States. *Proc Ninth Weather Radar Conf, Boston, Mass*, 1961, pp. 96–101.
12. SAUNDERS, P. M. and RONNE, F. C.; A comparison between the height of cumulus clouds and the height of radar echoes received from them. *J Appl Met, Boston, Mass*, **1**, 1962, pp. 296–302.
13. DESHPANDE, D. V.; Heights of Cb clouds over India during the southwest monsoon season. *Indian J Met Geophys, New Delhi*, **15**, 1964, pp. 47–54.
14. LEE, J. T. and MCPHERSON, A.; Comparison of thunderstorms over Oklahoma and Malaysia based on aircraft measurements. Royal Aeronautical Society International Conference on Atmospheric Turbulence — Proceedings, May 1971. London, 1971, Paper B1.
15. BYERS, H. R. and BRAHAM, R. R.; The thunderstorm. Washington, U.S. Department of Commerce, Weather Bureau, 1949.
16. KESSLER, E.; Computer program for calculating average lengths of weather radar echoes and pattern bandedness. *J Atmos Sci, Boston, Mass*, **23**, 1966, pp. 569–574.
17. KESSLER, E., GRAY, K. and DOOLEY, J. T.; Towards a quantitative radar echo climatology. *Thirteenth Radar Met Conf Proc, Boston, Mass*, 1968, pp. 280–285.

APPENDIX I

Method of computation of maximum parcel height.

At the outset, tables specifying the layout of a standard British tephigram and tabulated at suitable intervals of the relevant variables were fed into the computer for use by the main programme. These tables consisted of:

(a) Dry-bulb temperature (T) as a function of wet-bulb temperature (θ_w), and pressure (p).

(b) Saturation vapour pressure (e_s) as a function of temperature.

(c) Physical spacing of pressure levels on tephigram (for the purposes of evaluating area).

The input data for each ascent consisted of:

(1) Temperature and relative humidity (or dew-point) for 850-mb and 1000-mb (or surface pressure if < 1000 mb) levels. Ascents without humidity data at either of these levels were rejected.

(2) Temperatures at all standard levels up to 50 mb. Linear interpolation between the nearest data points supplied missing data points and also temperatures at the pressure levels corresponding to 50, 55, 60, 65 kft ICAO Standard Atmosphere.

The saturation vapour pressure table ((b) above) was then searched in combination with the hygrometric equation to determine values of θ_w at 1000 mb and 850 mb.

The representative θ_w for parcel ascent was then taken as

$$\theta_w = (\theta_w)_{850} + K[(\theta_w)_{1000} - (\theta_w)_{850}]$$

where K (= 0·7) was empirically determined from a best-fit comparison of the areas obtained from the programme to the areas measured by planimeter on 30 given ascents. The representative θ_w for a parcel ascent measured by planimeter was determined using additional humidity data between 1000 and 850 mb where possible.

This value of θ_w was used to compute the temperature difference between the environment curve and θ_w at each level; the difference was converted into a physical distance on the tephigram.

The mean of these distances at two adjacent pressure levels multiplied by the separation of these pressure levels thus gave an increment of positive (or negative) area. This was converted to its energy equivalent and summed in the direction of increasing height from the level at which the programme first detected the existence of a positive area increment. On the completion of the positive area summation (i.e. at Z_e in Figure 1) the equivalent vertical velocity was printed out and the summation of the negative area commenced and continued until its (numerical) total exceeded that of the positive area. The final result stated whether Z_p was less than 50 kft, or $\geqslant$ 50, 55, 60, 65 kft. Otherwise it was stated whether there was :

(a) No positive area.
(b) Inadequate humidity data.
(c) An ascent which did not reach Z_p.

This information was printed in monthly blocks for each station, and the results are summarized in Figure 5.

APPENDIX II

In order to examine whether the relationship between X_j and Y_j described on pages 172–174 had any quantitative consistency with the earlier results from case studies (Figure 2), it was decided to construct models of the areal and vertical distribution of convective storms based on these results.

Let the distribution of the heights of cumulonimbus tops at any given time on a given day be a function of Z_p. This will not be the same as the distribution of the maximum height reached by each cell during its lifetime. (Even if all cells reached exactly the same height, there would still be a distribution of heights at any given instant as individual cells would be at different phases of their lives.)

Let the number of convective storms within a radius of 100 miles be n, and the number of storms exceeding height h_j be $f_j n$ where f_j is a function of h_j/Z_p.

The probability that a storm will not exceed h_j is $1 - f_j$.

The probability that of n tops none will exceed h_j is $(1 - f_j)^n$.

Hence the probability that of n tops at least one will exceed h_j is $1-(1-f_j)^n$.

Hence the number of occasions, Φ_j, in one month on which the highest cell observed on the radar screen at each hourly observation is above h_j is given by

$$\Phi_j = \sum_{i=1}^{M}[1 - (1 - f_{ji})^{n_i}] , \qquad \ldots (1)$$

where M = total number of observations in a period of one month,
f_{ji}, n_i = values of f_j and n on ith occasion,

and

$$X_j = 100\ \Phi_j/M, \qquad \ldots (2)$$

where X_j is the percentage frequency of occasions when the maximum echo height exceeded h_j, the statistic tabulated by Grantham and Kantor — see page 172.

We may also write

$$Y_j = 100\int_{h_j}^{\infty} P(Z_p)\ dZ_p\ , \qquad \ldots (3)$$

where $P(Z_p)$ is the probability that Z_p lies between Z_p and $Z_p + dZ_p$ and Y_j is the percentage frequency of days when Z_p exceeded h_j (the statistic tabulated in Figure 5).

In order to evaluate equations (1), (2) and (3) it is necessary to make assumptions about the distributions on the ith occasions of $(Z_p)_i$, f_{ji} and n_i, as follows :

(a) *Distribution of* $(Z_p)_i$. Figure 6 suggests that the distribution of Z_p over a given month at a given station exhibits a reasonable approximation to the tail of a Gaussian distribution. Thus it was assumed that a normal distribution of Z_p about a mean of 48 kft with a standard deviation of 6 kft was fairly representative of Figure 6 for the purposes of constructing a model.

(b) *Distribution of* f_{ji}. It was assumed that on the ith occasion the distribution of storm-top heights h was normal with a mean, H_i and standard deviation σ_h, both proportional to Z_p. This immediately gave values of f_{ji} from tables of Gaussian cumulative probability.

(c) *Distribution of* n_i. It is clear from a brief study of the large quantity of field and radar data on storms that the number of storms per unit area cannot usually be precisely defined. Byers and Braham[15] noted that the horizontal dimension of the radar echo of a storm cell was about the same as the vertical dimension. It is also well known that on a day of significant storm development, even relatively isolated storms consist of clusters of cells, and may attain diameters of 50 km in extreme cases. Such storms might contain up to 20 cells but would be considered as only one (giant) storm from the aviation viewpoint.

When these storm clusters form part of a line of severe storms their radar echoes become merged into one single belt which, even at large attenuation, does not always resolve clearly into individual storms.

In an analysis of photographs of severe storms taken from a U–2 aircraft, Roach[2] found that on a day of extreme storm activity storm tops were seen protruding through the cirrus anvil with a density of about one top per 500–1000 km^2. For a storm belt of about 300 km long by 50 km wide, this would make n about 20 for a point near the centre of the squall line. There may well have been another 20 tops hidden by the anvil cloud, so that a value of n of about 40 would probably be representative of that occasion.

Radar evidence (e.g. Byers and Braham,[15] Kessler[16] and Kessler *et alii*[17]) shows that as much as 40 per cent (3×10^4 km^2) of the PPI display may be occupied by radar echo during times of extreme storm activity. This compares with an average of 5–10 per cent during periods of echo occurrence. Dividing these figures for echo coverage by the average storm density gives an extreme value of n of about 40 and an average value of 5–10.

On this admittedly sketchy basis, it was decided that a plausible distribution of n over a given month might be a lognormal one applying only to the occasions of non-zero n (see Table II, p. 010) and having a standard deviation corresponding to $1 \leqslant n \leqslant 30$ on 95 per cent of occasions.

(d) *Summation of* $f_{ji}\ n_i$. While f_{ji} is largely a function of the vertical atmospheric structure, n_i at a particular hour and day will be largely a function of the synoptic-scale dynamics of the particular situation, thus it would be reasonable to suppose f_{ji} and n_i to be largely independent. Since we have no explicit observations of n_i with f_{ji}, it would clearly be useful to be able to make this assumption of independence of f_{jt} and n_t in order to simplify the evaluation of equation (1).

It was in fact found that if a mean value, N, was defined by the expression

$$1 - (1 - f_j)^N = \int_0^\infty [1 - (1 - f)^n]\, P(n)\mathrm{d}n, \qquad \ldots (4)$$

where $P(n)$ is the probability that n lies between n and $n + \mathrm{d}n$, then the variation of N is relatively insensitive to a large variation in f.

Now equations (1) to (4) can be combined to obtain an estimate of the percentage of occasions, X_j, when the maximum echo height exceeds h_j, within 100 miles of a given station in a given month as the sum over that month of the product of the probability that on a given day parcel height will lie between Z_p and $Z_p + \mathrm{d}Z_p$ and the probability that for the given value of Z_p, the highest storm top will exceed h_j. Thus equations (1) to (4) were combined to give a working expression for X_j:

$$X_j = 100 \frac{M_e}{M} \int_{h_j}^\infty [1 - (1 - f_j)^N]\, P(Z_p)\mathrm{d}Z_p, \qquad \ldots (5)$$

where M_e is the total number of occasions per month when echo was visible ($n \neq 0$).

The relationships between X_j and Y_j obtained by evaluating equations (3) and (5) for various values of H/Z_p, σ_h/Z_p and N (see Table III) are plotted in Figure 10 for comparison with the observed relationship of X with Y.

TABLE III—DETAILS OF MODELS (Figure 10)

Model	H/Z_p	σ_h/Z_p	N	M_e/M	Z_p kft	σ for Z_p kft
I	0·85	0·1	2	0·5 (Models I–VI)	48 (all models)	6 (all models)
II	0·85	0·1	5			
III	0·85	0·1	10			
IV	0·75	0·1	5			
V	0·8	0·15	5			
VI	0·7	0·15	5			
VII	0·7	0·15	10	0·8		

Models I, II and III investigate the effect of varying N. The lines lie close to the observed $Y = 3X$ line, and shift to the right with increasing N, but not very rapidly.

Model IV shows the effect of decreasing H/Z_p which in physical terms is roughly equivalent to decreasing the degree of organization of the storm airflow. This is very marked and shifts the curve well to the left and is consistent with Figure 9 in this sense.

Model V is to be compared with Model II. H/Z_p has been decreased by 0·05 and σ_h/Z_p increased by the same amount. Since V is to the *right* of II, clearly a change in σ_h/Z_p has an even larger effect than a change in H/Z_p.

Models VI and VII are chosen with parameters which probably correspond

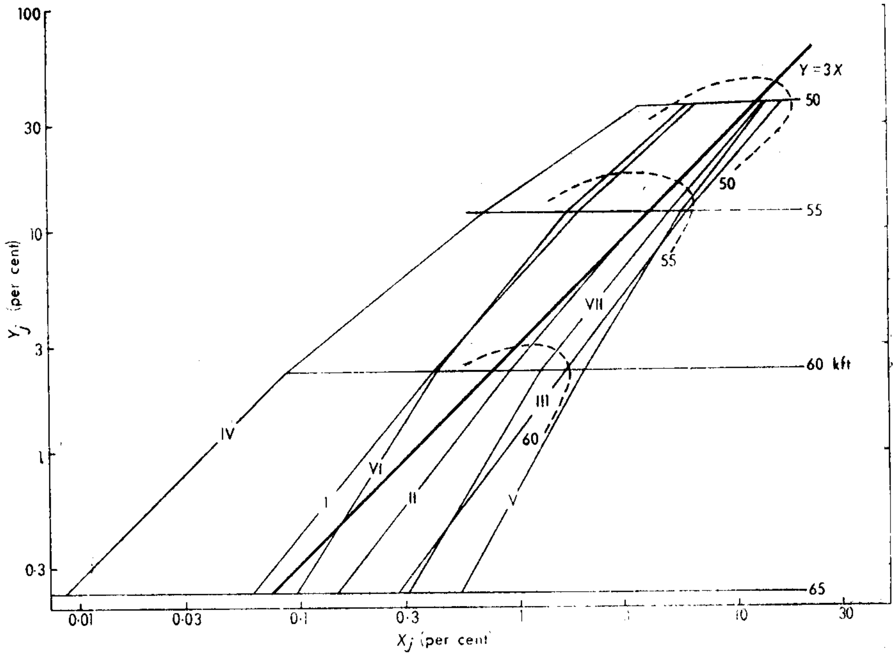


FIGURE 10—PLOTS OF Y_j AGAINST X_j FOR THE MODELS DISCUSSED IN TEXT

Individual points (X_j, Y_j) corresponding to each model I, II, etc. as listed in Table III are joined by straight lines labelled with the appropriate model number.
Horizontal lines indicate the appropriate value of h_j for the model. Dashed curves represent part of the envelope of observed points of (X_j, Y_j) for different h_j taken from Figure 8.

to air-mass type thunderstorms in moderate and high storm density situations respectively.

The broad conclusion to be drawn from these models is that they all (except IV) lie roughly within the observed scatter of points in Figure 8, indicated by pecked curves in Figure 10. Thus there does appear to be a reasonable degree of quantitative consistency between the radar echo data and the data from case studies of individual cumulonimbus situations (Roach[1,2]).

The models are fairly insensitive to variations in the areal density of storms, but are sensitive to variations in H/Z_p and σ_h/Z_p. However, it seems likely that changes in one of these ratios, due to changes in storm organization, are roughly offset by changes in the other ratio, and that therefore there is little merit in trying to distinguish between air-mass and frontal storms for the purpose of forecasting storm heights in general.

However, there appears to be a marked difference in the frequency of extreme storm-top heights — i.e. those that reach or exceed Z_p — between air-mass and frontal storms, which will be of significance to aviation interests. This difference is reflected in the simple forecasting model proposed on page 175.

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NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1971

By J. PATON

Department of Meteorology, Edinburgh University

Table I contains a summary of occurrences of noctilucent clouds (NLC), compiled from reports that were received during 1971 from observers in western Europe. The first three columns give the date, the period of time during which NLC were observed and records of the cloud forms and the progress of the display. On nights when the sky was sufficiently clear of ordinary clouds to permit the decision that no NLC were present, this is entered in the third column. 'Cloudy' appears in the third column when the extent of tropospheric clouds at most stations makes impossible a decision as to whether or not NLC are present.

The remaining four columns contain observations from selected stations giving latitude and longitude to the nearest half degree, the time of the observation in Universal Time (UT), the maximum elevation above the northern horizon and the limiting azimuths of the NLC.

Faint patches of ordinary thin cirrus may sometimes appear to be identical to NLC, so that it is often difficult to be certain that what is observed is true NLC. Cirrus can usually be distinguished from NLC by the fact that it remains visible up to and after sunrise and that it usually shows some perceptible movement, whereas NLC disappear in the growing light half an hour to an hour before sunrise and their movement is generally not detectable by eye but only by successive photographs. If a report of suspected NLC is received from one station only, when other stations with favourable observing conditions are reporting no NLC, it is therefore assumed that the occurrence is doubtful and the report is disregarded.

On those occasions when it was likely that the cloud field had been observed to be illuminated to its southern border at some time during the night, the approximate latitude of the southern border has been determined.

TABLE I—DISPLAYS OF NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1971

Date — night of	Times	Notes	Station position	Time	Max. elev.	Limiting azimuths
	UT			UT	*degrees*	
26–27 May		No NLC				
27–28		No NLC				
28–29	2145–2345	Faint band visible before	55·5°N 1·5°W	2245	7	320
		midnight. The NLC had		2345	7	320–360
		vanished by 0045 UT.				
29–30		No NLC				
30–31		No NLC				
31 May–1 June		No NLC				
1–2 June		No NLC				
2–3		No NLC				
3–4		No NLC				
4–5		No NLC				
5–6	2205–0400	Spectacular display of veil,	59·5°N 18°E	2205	13	335–360
		bands and billows first seen		2235	18	315–020
		from Stockholm and last from		2255	18	315–020
		an aircraft over western	56·5°N 7°W	2345	13	350–020
		Atlantic. The bands extended		0045	15	360–030
		continuously along northern		0145	20	010–040
		sky and were closely packed	56°N 4·5°W	2250	33	320–020
		showing a greenish tinge in	55·5°N 7·5°W	2250	16	345–045
		places. Observers in British		2344	12	315–045
		Isles reported the clouds at		0045	10	360–045
		their brightest at about one		0120	12	340–045
		hour before and one hour		0210	20	315–360
		after midnight.	55·5°N 5·5°W	2345	10	360–045

TABLE I—*continued*

Date — night of	Times UT	Notes	Station position	Time UT	Max. elev. *degrees*	Limiting azimuths *degrees*
			55°N 4·5°W	2320	11	360–045
				0040	10	360–045
				0115	15	360–045
				0200	30	360–045
			54·5°N 6°W	0200	17	345–040
				0230	16	330–040
			49°N 56·5°W	0400	12	
6–7	2215–2245	Belt of NLC composed of 5–6 faint parallel pearly-green bands observed from Stockholm. The lower edge was at 58° elev. and the upper at about 73°.	59·5°N 18°E	2215	73	360
7–8 and 8–9		No NLC seen in clear skies at Stockholm. Mainly cloudy over British Isles.				
9–10		No NLC				
10–11		No NLC				
11–12		Cloudy				
12–13		No NLC				
13–14	2205–2242	Four faint bands seen from Stockholm.	59·5°N 18°E	2205	18	010–020
14–15 June		No NLC				
15–16		No NLC				
16–17		No NLC				
17–18	2335–0045	Moderately bright display of bands and whirls seen through low cloud.	55·5°N 1·5°W	2335	18	330
				2345	10	315–360
				0050	35	320–030
18–19		Cloudy				
19–20		Cloudy				
20–21		Cloudy				
21–22		No NLC				
22–23		Cloudy				
23–24		Cloudy				
24–25		Cloudy				
25–26	0052–0203	Bands and billows seen from Ocean Weather Ship *Weather Surveyor*. Cloudy over western Europe.	59°N 19·5°W	0115	49	280–060
26–27		No NLC				
27–28		Cloudy				
28–29		No NLC				
29–30		No NLC				
30 June–1 July	2315	NLC seen through gaps in low cloud from Denmark. Cloudy over British Isles.	55°N 14·5°E	2315	12	020
1–2 July		No NLC				
2–3	2132–0120	Moderately bright display of bands and billows, brightest and most clearly defined before midnight. Faint whirls appeared after midnight.	59·5°N 18°E	2245	90	
			56·5°N 3°W	0005	14	343–055
			56°N 4·5°W	0043	16	360–030
			55·5°N 4·5°W	0030	22	010–040
				0055	15	010–040
			51°N 1·5°E	2132	28	340–010
3–4	2220–2235	Four faint bands seen from Stockholm.	59·5°N 18°E	2220	35	045
4–5		No NLC				
5–6		No NLC				
6–7	2240–0150	Veil and weak to moderately bright greenish bands forming a rather unspectacular display. Reported also from Denmark and Sweden.	57°N 2°W	2345	12	330–015
				0015	10	290–020
				0050	10	355–015
			56·5°N 3°W	2340	11	340–015
				0015	10	290–020
				0050	10	355–015
			56·5°N 7°W	2350	13	335–030
				0050	10	315–045
				0150	8	325–050
			56°N 10°E	2305	7	335–360
				2340	10	335–045
			56°N 3°W	2310	7	340
			56°N 4·5°W	2300	10	340–030
				0001	11	313–035
				0030	11	313–027
				0100	15	311–035
				0130	12	310–050
			55·5°N 4°5°W	2240	9	010–040
				0025	9	320–045
				0115	4	320–010
			55·5°N 7·5°W	2400	11	315–040
				0100	6	320–025
			55°N 3°W	2330	9	320–360
			54·5°N 6°W	2245		350–030
			54°N 4·5°W	2315	4	340–020
				2350	8	330–010
				0050	6	360–020

TABLE I—*continued*

Date — night of	Times UT	Notes	Station position	Time UT	Max. elev. degrees	Limiting azimuths degrees
7–8	0230	Very thin silvery band reported close to north horizon.	54·N 1°W	0230	5	025–035
8–9		No NLC				
9–10		No NLC				
10–11		No NLC				
11–12	2200–2230	Very faint bands seen in northern sky from Stockholm. No details.				
12–13	2145–0252	Fine display of moderately bright bands and billows, backed by a veil. Whirls appeared in the eastern portion of the display after 2335 UT. A single well-defined bluish band predominated during long periods in this display. The southern boundary of the clouds was situated approx. in latitude 56°N.	59·5°N 18°E	2145	35	
				2200	60	
			56·5°N 3°W	2335	11	340–040
				0020	12	330–040
				0046	13	335–050
			56°N 10°E	2145	30	335–360
				2307	15	315–045
				0130	18	
			56°N 4·5°W	2315	12	340–020
				0030	10	340–030
				0135	15	340–060
			55·5°N 3°W	2345	5	340–045
				0115	12	330–045
				0230	30	
			55·5°N 4·5°W	2330	5	350–050
				0105	8	010–050
				0205	21	350–070
			55°N 3°W	0001	9	340–020
				0200	15	340–020
			54·5°N 6°W	2345	8	335–025
				0145	9	360–050
			54°N 1·5°W	2325	7	330–020
				0145	12	035
			54°N 4·5°W	2350	7	320–020
				0225	22	340–030
			54°N 9°W	0010	5	320–020
				0112	7	010–040
				0245	9	
			53·5°N 3°W	0155	9	352–038
				0248	10	345–015
			53·5°N 7·5°W	2355	3	355–005
				0130	7	360–040
				0240	13	360–045
			53·5°N 8°W	0055	12	355–040
			53°N 1·5°W	0230	11	355–015
			52°N 8·5°W	0252	25	030–045
13–14		No NLC				
14–15	2255–0145	Bright display of groups of closely packed bands and billows, with small whirls appearing between 2340 UT and 0045 UT. An extensive veil was bordered in parts by a filigree pattern of fine billows. The southern boundary of the cloud was situated near latitude 58°.	57·5°N 3·5°W	0100	15	320–030
			57°N 2°W	2255	15	340–025
				2325	17	335–020
				0001	13	340–010
				0105	18	010–050
			56·5°N 3°W	2330	10	340–060
				2340	15	310–050
				0145	22	310–360
			56°N 3°W	0005	20	315–020
			55·5°N 3°W	2345	10	337–056
				0115	23	337–011
15–16		No NLC				
16–17		No NLC				
17–18	2045–0145	Extensive fine bands, some very well defined, others diffuse, colour mainly blue but greenish parts. Very bright especially before midnight. The clouds extended significantly further south over the Continent.	59·5°N 18°E	2100	90	
				2300	130	
			57°N 2°W	0001	10	360–010
			56·5°N 7°W	2350	7	330–020
			56°N 10°E	2100	50	340–045
				2335	8	315–045
			56°N 4 5°W	2315	8	320–350
				0015	10	330–020
				0045	7	330–040
			55·5°N 4·5°W	2315	9	340–030
				0001	6	320–045
				0045	5	335–040
				0145	5	330–360
			55·5°N 7·5°W	0020	10	330–020
				0050	7	340–040
				0145	8	360
			55°N 4·5°W	2050	21	
			54°N 4·5°W	2335	5	330–015
18–19		No NLC				
19–20		No NLC				
20–21		No NLC				
21–22	2150–0150	Bright blue 'delicate and lace-like' bands, extending further south over the Continent.	59·5°N 18°E	2150	60	
			57·5°N 7·5°W	2250	9	360–025
				0150		335–360

TABLE I—*continued*

Date — night of	Times UT	Notes	Station position	Time UT	Max. elev. *degrees*	Limiting azimuths *degrees*
22–23	2120–0020	Long parallel bands with billows, very bright at times, particularly around 2310 UT. 'By 2340 UT the upper bands had faded significantly but the lower ones curved slightly at the ends to produce sweeping bow-shaped arcs. When these appeared to cross at the ends, the luminosity was intense.' It was overcast over the British Isles.	60°N 10·5°E 59·5°N 18°E	2115 2120	50 26	340–045
23–24		No NLC				
24–25		Cloudy				
25–26		Cloudy				
26–27		Cloudy				
27–28		Cloudy				
28–29		No NLC				
29–30		No NLC				
30–31		No NLC				
31 July – 1 Aug.		Cloudy				
1–2 Aug.		No NLC				
2–3	0045–0300	Bands seen through low cloud.	55·5°N 4·5°W 55°N 4·5°W	0045 0300	8 6	010–050
3–4		No NLC				
4–5		Cloudy				
5–6		No NLC				
6–7		No NLC				

The frequency of occurrence of the clouds during 1971 (18 nights) was slightly greater than for 1970[1] (15 nights) but less than during the preceding six summers 1964–69, when they were observed on more than 20 nights, with a maximum of 33 nights in 1967. However, the displays on the nights of 5–6 June, 12–13, 14–15, 17–18 and 22–23 July were among the most spectacular observed during the past eight years, an experienced observer at Stockholm describing that of 22–23 July as the brightest he has ever seen. This display was hidden from observers in the British Isles by overcast skies. The dates of the first and last of the observed NLC occurrences, 28–29 May and 2–3 August, are normal.

This analysis has been made possible by the co-operation of a large number of observers who have supplied visual observations, photographs (see Plates) and sketches. Their assistance is gratefully acknowledged. These synoptic studies are continuing and observers are invited to send their observations to the Balfour Stewart Auroral Laboratory, The University, Drummond Street, Edinburgh, EH8 9UA, Scotland. Notes on the recording of observations of NLC will be gladly supplied from the laboratory.

REFERENCE

1. PATON, J.; Noctilucent clouds over western Europe during 1970. *Met Mag, London,* **100**, 1971, pp. 179–182.

REVIEWS

Introduction to ionospheric physics, International Geophysical Series, Volume 14, by H. Rishbeth and O. K. Garriott. 225 mm × 145 mm, pp. x + 331, *illus.*, Academic Press Inc. Publishers, 111 Fifth Avenue, New York, New York 10003, U.S.A. 1969. Price: $16.00.

It is always stimulating to consider the meteorology of strange worlds — the hot and massively cloudy atmosphere of Venus or the thin and dusty one of Mars. It is not necessary to go so far, however, to find a region where the familiar ideas of meteorology reappear with strange and often illuminating distortions induced by drastic changes in the relative importance of the various forces at work. Looking for analogies, one can see the ionosphere as the region where ions replace water as the minority component that is the focus of interest. Just as in the atmosphere clouds are the easiest feature to observe, the best clues to atmospheric processes and, controlling sunlight and rain, are of dominating practical importance, so in the ionosphere ionization, 'evaporated' by sunlight from the neutral atmosphere, can readily be measured by radio-wave probing, provides most of the information available about the atmosphere between 100 and 1000 km and is, of course, all-important for the transmission of radio waves. As differences from the lower atmosphere it is noted that diurnal changes are far greater, that small-scale eddies and turbulence seem less important (except at the base of the ionosphere) but that diffusion and 'ion drag' in the earth's magnetic field begin to rival the Coriolis force in controlling the circulation. Effects of topography are not apparent but the asymmetry of the magnetic poles plays a somewhat similar role. The ionosphere is driven by the sun, but at the wavelengths which do this driving the sun is far more variable than at the wavelengths which drive the lower atmosphere. Both the 11-year and the 27-day cycles in the sun, as well as numerous erratic short-period events, evoke an obvious response in the ionosphere, and one of the main interests for meteorologists is to see how far down in the atmosphere these responses can be traced (the other great interest is to see how far upwards the effects of ordinary meteorological disturbances can be followed).

To all of this strange yet interesting region this book is a clear and authoritative guide. As the title implies, it is an introduction; it summarizes the facts and theories, but leaves the details to be followed up in the original papers and is chary of making judgements between rival theories. The first chapter is a concise review of the structure and behaviour of the neutral atmosphere, the medium in which all ionospheric events occur. Then, after an account of experimental techniques, the basic processes of production and loss of ions are described. From these foundations later chapters go on to consider more complicated processes, the transport of ions both vertically and horizontally, the resulting structure of the ionized layers and the disturbances of the normal structure, directly by solar events and less directly by interactions between the sun, the earth's magnetic field and the ionosphere. The general style of the book is admirably lucid, with free use of introductory and summarizing paragraphs which keep the detailed discussions within a unifying framework.

K. H. STEWART

Earth sciences, Volumes 1 to 3, edited by Professor S. K. Runcorn for the Royal Institution Library of Science. 223 mm × 148 mm, Volume 1, pp. xx + 502; Volume 2, pp. xvi + 539; Volume 3, xvi + 499; *illus.*, Applied Science Publishers Ltd, Ripple Road, Barking, Essex, 1971. Price: £20.

Volume I is a collection of all the Friday Discourses concerned with Earth Sciences given at the Royal Institution between 1851 and 1880 and since in each case the lecturer was a well-known authority on his subject the volume reflects the state of the sciences during these years. Two quotations show that this was a different age from ours: Dr J. T. Bigsby on Lake Superior writes 'The water is clear, greenish, extremely pure, pleasant to the taste and soft..... An imperial pint contains only 1/5000 part of a grain of mineral matters' and Mr Palgrave on central and eastern Arabia 'By commerce, by arms, or by knowledge and scientific inquiry, the world seems the destined inheritance of England.' But if our environment and political outlook have been radically changed, the spirit of scientific inquiry has not. The writers here have the same exacting standards of presentation and proof as we have today; if anything they seem a little more assured that their scientific explanations are correct and their English is frequently much better than is met in today's journals.

The Discourses cover a wide range of subjects, from Airy on pendulum experiments in a mine to determine the weight of the earth, to Huxley on the Challenger expedition. Two overall impressions emerge; the wide range of scientific knowledge of individual contributors, who appear less specialized than scientists are today, and that many of them were 'doers', actively taking part in the field work: Tyndall, at the age of 53, being the first to struggle under the falls at Niagara and later bouncing about in a small boat at the very foot; Ramsay on the rock at Gibraltar; Palgrave in Arabia ('I assumed the disguise of a native travelling physician'); Samuel Baker searching for the sources of the Nile; and the geologists and mineralogists — active mountaineers — all observing and reporting their findings in fresh prose. There are very few disappointments, notably Thompson (Kelvin) on tides and this because of oblique reporting, summarizing in a few paragraphs what Thompson said.

Naturally, there is a good deal to do with oceanography and meteorology. Some of it is hidden, as in Rogers on *Geology and physical geography of North America*, but a number of discourses deal directly with these subjects, and they are well worth reading, for example: Carpenter on *Temperature in the Atlantic*, among other things upsetting the widely held view that the sea bottom temperature is sensibly constant and showing how temperatures at depth do not respond to rapid surface temperature changes; and Frankland on *The Glacial epoch*, arguing that the effect of a warmer sea adjacent to a glaciated land area increases the glaciation.

There are two discourses of the greatest interest to meteorologists given by R. H. Scott on *Work of the Meteorological Office, past and present* (1869) and *Recent progress in weather knowledge* (1873). The first was given when Scott had taken over the direction of the Office after Admiral Fitzroy's death and shows how the work changed from weather forecasting and storm prediction to mainly gathering and examining marine data ('Marine meteorology must ever be considered the prime object of its attention...') with no forecasts and only limited information about the weather from which recipients were expected to draw their own conclusions as to the imminence of storms and gales, with the aid of the Fishery Barometer Manual! The second, 10 years later, shows the research that was being carried on and the road back to prediction. These two discourses deserve to be read with close attention for some of what is here could well be written today. It is of interest to note, as Scott does, 'We spend at the outside £4000 a year on our weather telegraphy . . . while the vote for the U.S. Signals Office is no less than 250,000 dollars.'

Any reader will find this volume fascinating, will browse and expand his sense of history, and realize that many of the questions that were being asked a century ago have not yet been answered.

Continuing the pattern of Volume 1, Volumes 2 and 3 contain the Friday Discourses given at the Royal Institution relating to Earth Sciences between 1881 and 1937, and they show the changing face of the scientist. At the beginning of the period the discourses show the scientist with very wide interests; at the end he has become much more specialized, his interests focused on much narrower fields, and much more professional — perhaps a little duller. The discourses cover a wide field exemplified by the titles *Rainbows, Krakatoa, Gold Mining in Klondike, Diamonds, The Propagation of Earthquakes* and the lecturers are distinguished as could be expected, including Geikie, Tyndall, Schuster, Crookes, Strutt (Rayleigh), Love, Knott, and Appleton. There is fare here for everyone, and it is not necessary to have deep knowledge to learn from these discourses, for they assume practically nothing save an inquiring interest, as, for example, Chrystal on *Seiches in the Lakes of Scotland,* Bonney on *The Building of the Alps* and Joly on *The Age of the Earth.*

Meteorology has come off remarkably well for about one-third of the discourses are directly concerned with the physics of the atmosphere and weather forecasting. We are able to see the development of state meteorology through the Meteorological Office through the discourses of successive Directors, Scott on *Weather Knowledge* (1883), Shaw on *Some Aspects of Modern Weather Forecasting* (1904) and on *Illusions of the Upper Air* (1916) and Simpson on *Weather Forecasting* (1932). It is a story of the realization that fresh observational evidence reveals only that the problems of forecasting are very deep indeed, that the hopes pinned on some new departure, such as obtaining upper air observations, are not to be completely fulfilled and indeed of the early realization that providing a national service is not a problem of science alone, but of logistics and especially communication. It is a story well worth reading by any meteorologist and is not without its humour. Scott certainly had a dry way with words, as in ' . . . . the same wording (for the forecast) will not suit a whole district, unless it be judiciously phrased so as to bear more than one interpretation.' And we catch a glimpse of the devotion to duty of meteorologists in Mr Wragge who climbed the 4000 ft of Ben Nevis every day before 9 a.m. to take observations, telegraphing them from Fort William on his return.

There is much more about meteorology than about the development of the state service: Frankland contrasting country and urban climates, discoursing on the pollution of the atmosphere in London and calling for the banning of bituminous coal and the use of the readily available smokeless fuel — in 1882; Langley on *Sunlight in the Earth's Atmosphere* and a dozen more papers including the most recent ones by masters whose work is familiar to us: Dobson on *Ozone in the Stratosphere*; Simpson on *Ice Ages*; Walker on *Clouds*. These papers give us a perspective on what were considered the growth points at the time, on how the emphasis has changed, sometimes without answering the scientific problems but leaving them, and remind us that the emphasis that we give today to particular problems will not be echoed by our successors.

These are books to browse in, and it will come as no surprise to find that we are reading Captain Scott on his forthcoming Antarctic expedition, Younghusband on Mount Everest or Baker on the Nile Dams when we started out on something quite different. They cannot fail to broaden our outlook.

E. KNIGHTING

Protection of plants against adverse weather, WMO Technical Note No. 118, by G. W. Hurst and R. P. Rumney. 275 mm × 213 mm, pp. iv + 64, *illus.*, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1971. Price: Sw.Fr. 12.

Farmers the world over complain about the weather — different crops in different stages have different weather needs and it is almost always bad weather for some aspect of agriculture.

The authors of this substantial review (modestly called a mere 'note') on protection against adverse weather understandably deal separately with temperature, radiation, precipitation and wind, though 'weather' is really concerned with interactions of these parameters; high temperature may be acceptable if humidity is also high, but not under arid conditions.

Most of the literature cited seems concerned with shifting each parameter in one direction only — there is little about *reducing* excessive temperature; workers are more concerned with mitigating the effects of too-low temperature. Shading is dealt with, but while increasing available light is unlikely to be economically feasible, ways of reducing ambient temperature might enable some crops to be grown in otherwise inhospitable localities. Few of the papers cited mention coping with excess precipitation (erosion is dealt with elsewhere in WMO literature) and the authors state that agricultural water problems are nearly all concerned with lack of water; this is to ignore the importance of drainage and the associated techniques of cropping peatlands (incidentally the language of para. 4.1 p. 13 is involved and difficult to follow).

Considerable attention is paid to sheltering crops from wind, but insufficient distinction is made between protection from mechanical damage by high winds and the remarkable growth effects which follow the sheltering of crops from breezes of 4·5 m/s and less; yield increases up to 25 per cent have been obtained with diverse crops including tea, lettuce, carrots and anemones ('wind flowers'!). The authors' statement on p. 19 that the main aim of walled gardens was wind reduction needs qualification — the object was protection from adverse weather in the broadest sense. This includes increasing temperature and insolation by reflection from the walls whose windbreak function was only incidental; indeed a solid wall is the worst form of windbreak, subject to eddying in its lee. To circumvent this windbreaks must be about 60 per cent permeable.

Although planting at a defined soil or air temperature instead of by calendar date is discussed, no mention is made of the use of accumulated day-degrees in, for example, the culture of peas. In general, however, the literature coverage is excellent; a useful feature is the provision of brief comments on each paper following its bibliographical entry.

One irritating fault is the collecting together of all figures and plates in a section right at the end of the book. Even if the figures could not have been placed, as is usual, in the text, single pages of figures only might have been bound in adjacent to each relevant piece of text. The lateral arrangement of captions on multiple-figure pages would have been made clearer by the insertion of the words 'right', 'left', 'above' or 'below' (pp. 54, 55, 59). There are a few typographical errors (e.g. 'Ryzchov' spelled differently on pp. 22 and 42) and some quaint syntax (last sentence of para. 2 p. 20) but these are minor complaints.

This slim volume represents a tremendous amount of work in reading and commenting on more than 175 references and it provides a valuable starting point for literature surveys on crop aspects of the main weather parameters.

The minor nature of most of the criticisms levelled above is itself evidence of the excellence of the work which will be useful and thought-provoking to anyone studying outdoor crops.

A pertinent point is made by the authors' reminder that protection from weather is expensive, difficult and not always successful, and that it is better to pre-plan or select the site to avoid meteorological extremes than to attempt to ameliorate bad conditions when they arise.

E. J. WINTER

Use of weirs and flumes in stream gauging, WMO Technical Note No. 117 (Report of a working group of the Commission for Hydrology). 275 mm × 213 mm, pp. viii + 57, *illus.*, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1971. Price: Sw.Fr. 10.

Here is a booklet which should find a place on the personal bookshelves of most practising water engineers and hydrologists who are associated with the problems of channel flow gauging. In a detailed manner, it sets down the predictable stage-discharge relationships applicable to a wide range of standard weirs and flumes.

The British reader will be struck by the similarity between the *Technical Note* and *British Standard* 3680: *Parts 4A* and *4B*, which, of course, is no bad thing. At a price of 10 Swiss Francs it has a distinct price advantage over the British Standards Institution publication and, in addition, it offers wider scope by including coverage of the Parshall and trapezoidal critical-depth flumes.

It is surprising to find so few examples of the Parshall flume in the U.K., especially so in view of the considerable range of sizes this gauging control offers with established calibrations. Throat widths varying from 2 in to 50 ft are standard. The promotion of these flumes through the medium of a WMO publication is commendable in that we are provided with an enhanced number of accredited designs to choose from.

An interesting and useful section of the note deals with the derivation of calibrations for trapezoidal throated, critical-depth flumes. B.S.3680 suffers from the omission of this type of structure, which is rather strange in view of the work done on them by Ackers and Harrison of the Hydraulics Research Station. The Working Group of WMO are to be complimented on their decision to include them in the *Technical Note.*

In common with the B.S.3680, a very full treatment is given to sharp-edged or thin plate weirs, together with broad-crested and Crump weirs. The familiar dictum of full-height divide walls for compound weirs is made and one is dismayed at the prospect of many unsightly structures appearing in rivers throughout the world as a consequence. I think it must be accepted that much lower divide walls are sufficient to preserve two-dimensional flow, even though they become submerged at high flows, and that a little extra trouble with the calibration is worth while in view of their better appearance. An authorative statement on this matter would have been welcomed.

Crest tappings are recommended as a form of double gauging with Crump weirs. Several such installations have been made on river gauging stations in this country and my own and others' experience with the arrangement is disappointing. Frequent silting up of the crest tapping box is not unusual and a word of warning for the unwary would not have been amiss on this point.

Several times in the note a caution is given that difficulties may arise with Froude Numbers exceeding 0·5 in the approach channel. As this is not an uncommon occurrence, it would have been helpful to go into a little more detail on the matter. With the normal float-well and balance-pipe arrangement, the depth of submergence of the latter will tend to reduce the errors arising with high approach velocities and accompanying surface waves.

When the deservedly high demand has exhausted stocks of the present edition of this *Technical Note* and a revision is prepared, there are a few matters which could be included in order to increase the value of the publication. Under the heading of 'Selection of structure' some space could be given to the establishment of approximate site-rating curves which I have always regarded as an important matter forming a necessary early step in the design of river gauging stations. A word or two on sensitivity would be appropriate here also. The range of standard gauging controls could be enhanced by the inclusion of Flat-Vee weirs. Some guidance on weir design should be given in regard to the problems encountered with migratory fish in rivers. To complete the treatment of the hydraulic design of gauging structures, a section on energy dissipation and stilling-basin geometry would be welcome.

P. R. LANGFORD

NOTES AND NEWS

Successful high-altitude balloon space experiments

A joint U.K./U.S. high-altitude balloon space research project involving the Science Research Council's Astrophysics Research Unit (ARU), Culham, the Pure and Applied Physics Department at Queen's University, Belfast and the U.S. Air Force Cambridge Research Laboratories, Massachusetts, together with the Meteorological Office, Bracknell, has provided some valuable data on ultra-violet emissions from the sun.

The Culham/Belfast astronomical ultra-violet measurements were the first to be made by U.K. research groups using balloon-borne instrumentation. Preliminary analysis of the data is showing good correlation with previous rocket-flight observations. These data on the quiet and active solar regions should help to extend our understanding of the processes occurring in the solar chromosphere.

In addition to the Culham/Belfast instruments the balloon carried equipment prepared at the Meteorological Office to measure atmospheric transmission in the ultra-violet. The Meteorological Office sensor, as well as supplying photometric measurements of the ozone distribution at different altitudes, provided the Belfast experiments with the in-flight indications of ultra-violet atmospheric transmission which they needed to calculate the exact exposures to give their equipment which is activated by ground control. The American Air Force Cambridge Research Group studied vertical distribution of particulate matter in the earth's atmosphere.

The high-altitude balloon flight was made from Holloman Air Force Base New Mexico in August. A total payload of some 900 lb ($\approx$ 415 kg) was carried to a float altitude of 133 000 ft ($\approx$ 41 km) by a 10·6-million-ft^3, helium-filled balloon for one hour before a controlled descent and successful parachute recovery. The 100-lb U.K. instrument package was oriented towards the sun by the balloon platform and final stabilization of the solar image to a few arc seconds was achieved by a secondary fine-guidance system. The U.K. part of the experimental payload was designed to record spectra of the sun in near ultra-violet wavelengths (around 2800 Å (1Å = $10^{-4}\mu$m)) with a high spectral resolution of about 0·016Å.

The spectrograph and its chamber were built at Queen's University. It comprised an echelle interferometer optical system contained in a temperature- and pressure-controlled chamber. During ascent through the densest region of the atmospheric ozone and at float some 140 useful interferograms were photographically recorded using commands from the ground to activate the control system.

The fine-guidance and control system required for the Culham/Belfast experiment was built at the ARU Culham. The U.S. balloon platform stabilizer was designed to achieve pointing accuracy of about 5 arc minutes. The ARU servo-controlled mirror equipment, originally designed for SKYLARK rockets and specially adapted for this balloon flight, then took over, aiming for a pointing accuracy of 5 seconds of arc or better — the equivalent of 1½ inches in a mile.

Among the advantages offered by balloon-borne experiments are the cost, which is considerably less than the cost of stabilized rocket platforms, the increased observing time and the flexibility of using ground-activated control. There are, however, no suitable sites in the U.K. for flights by balloons of the size required for this experiment.

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THE ACCURACY OF SOME RECENT RADAR ESTIMATES OF SURFACE PRECIPITATION

By T. W. HARROLD and C. A. NICHOLASS

Summary. Results of some recent quantitative radar measurements of precipitation, made in many geographical locations, are reviewed.

Reasons for variations in the measurements are discussed and methods for improving the accuracy of future measurements are considered.

Introduction. Ever since it was realized (30 years ago) that a radar could be used to detect the presence of precipitation, attempts have been made also to measure the quantity. However, although the qualitative use of radar is now well established, progress in the quantitative measurements of precipitation has been slow. This has been largely because of uncertainties in the accuracy of the measurements and the technical difficulties in processing the large amount of data obtained when echo intensity is measured at all points over an area under observation. Over the last decade progress has accelerated. In particular, many workers have investigated the accuracy of the radar-derived estimates of precipitation. The purpose of this article is to review the results of these experiments, in order to estimate the magnitude of the errors which have been obtained up to now and to suggest possible ways in which these errors might be reduced.

Firstly, it is worth while summarizing the advantages of this method of measuring precipitation compared with the only practical alternative of using some form of rain-gauge. The advantages are :

(a) the measurements are made :
  (1) over an area, (and most users, if not all, require measurements over an area),
  (2) in real-time, and
  (3) from a single location,

(b) snowfall can be measured and

(c) short-term forecasts of precipitation movement and intensity can be made.

The main disadvantages are:

(a) A possible reduction in accuracy compared with that of a rain-gauge. However, although this is certainly true for a point measurement, it may not be the case when measurements are extended to an area.

(b) Cost. However, the cost, including maintenance, of a radar installation may be similar to that of the network of telemetering rain-gauges which may be required for real-time information of comparable accuracy over an area.

The following sections will be concerned only with the accuracy of the system, but the advantages listed above should also be remembered since they are important when considering the practical use of radar as an alternative means of measuring precipitation.

Theory. Estimates of precipitation using radar depend on the relationship between measurements of the echo power reflected by the precipitation particles and the rate of precipitation.* Probert-Jones[1] and Borovikov *et alii*[2] have shown theoretically that, when precipitation uniformly fills the pulse volume,

$$\overline{P}_r = C_1\, C_2 \frac{\sum D^6}{r^2} K,$$

where :

$\overline{P}_r$ is the average of the power P_r received from reflection from precipitation at range r, the average being over a sufficient number of radar pulses to ensure that the random fluctuations of the precipitation signal are averaged out (see for example Marshall and Hitschfeld[3]).

C_1 is a function of the radar parameters and can be evaluated by calibration procedures.

C_2 is a constant (for practical purposes) related to the dielectric properties of the precipitation particles.

$\sum D^6$ is the summation over unit volume of the sixth powers of the drop diameters D.

r is the range of the precipitation from the radar.

K is a measure of the attenuation of the radiation as it traverses the precipitation.

Probert-Jones, and other workers since, have shown that this equation is accurate to within the accuracy of the measurements of P_r.

Measurements of precipitation intensity are based on an empirical relationship of the form

$$\sum D^6 \equiv Z = AR^B ,$$

where Z is defined as the radar reflectivity factor, A and B are empirically determined constants and R is the rate of precipitation.

Thus

$$\overline{P}_r = \frac{C_1\, C_2\, AK}{r^2} R^B .$$

This expression forms the basis of the use of radar for measuring precipitation.

* An alternative method is to relate the attenuation at a short wavelength to the rate of rainfall, but it seems unlikely that this is a practical means of estimating rainfall over an area. However, it may provide an additional means of calibration — see pages 201–203.

Possible sources of error.

The R–Z relationship. There is no unique drop-size distribution for a given rainfall rate, hence there is no unique *R–Z* relationship. The variations which occur have been summarized by, for example, Stout and Mueller[4] or Borovikov *et alii.*[2]

World-wide there are differences in excess of 500 per cent in *R* at a given *Z*. These large variations are associated primarily with differences in geographic locality. At a given locality the maximum difference is reduced to about 150 per cent. Thus, when estimating *R* from *Z*, it is preferable to use the *R–Z* relationship derived for that particular locality. A difficulty arises since such relationships are only known for a few localities in the world, but for practical applications this problem has been at least partially overcome by Cataneo,[5] who has shown that the relationship can be estimated from climatological data available as routine.

These variations show the approximate magnitude of the error in an estimate of instantaneous rate of rainfall at a point using a known value of *Z*. In most practical operations the rainfall amount over a period of time is required. In time integration much of the variation will be averaged out. For example, an analysis of drop-size distributions measured by Andrews in London (see for example Mason and Andrews[6]) indicates that when estimating the total rainfall from a storm using the average *R–Z* relationship for that locality (or Cataneo's estimate) the mean error is only 20 per cent. A similar analysis based on a small amount of the data published by Stout and Mueller[4] produced a mean error of about 18 per cent.

It was stated on page 193 that one of the major practical advantages of the radar method of measuring precipitation is that the measurements are made over an area. Very little is known about the variations in the *R–Z* relationship over an area. Apparently the only study in the literature is by Sims,[7] who measured drop-size distributions at three locations a few kilometres apart and found significant variations in one out of the three storms he studied. It is therefore possible that estimates of area rainfall based on area values of *Z* might be more accurate than is suggested by the studies of relationships at a point.

To summarize, the numerous studies of drop-size distributions show that rainfall at a point over a period of time can be estimated to within a few tens of per cent from known values of *Z* and that the error may be less for an area measurement.

It will be shown on pages 201–203 that the variability in the *R–Z* relationship may not determine an upper limit to the accuracy of a radar estimate of precipitation; it may be possible to calibrate the radar values using an independent estimate of *R*, for example that obtained using a rain-gauge.

Variation of Z with height. When radar is used, *Z* is measured within the pulse volume (determined by the beam width and pulse length). This value is used to estimate the precipitation at the surface. If *Z* varies with height then the measured *Z* differs from that at the ground, increasing the error in the estimate of *R* at the surface compared with that arising purely from *R–Z* variations. Figure 1 shows average profiles of *Z* for three types of precipitation. The data were obtained by Joss and Waldvogel[8] in Switzerland but are probably representative of precipitation in most parts of the world (see for

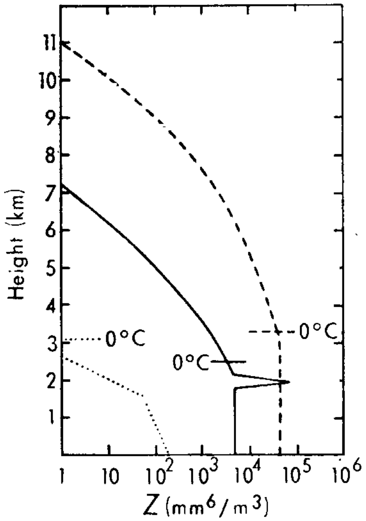

FIGURE 1—MEAN RADAR REFLECTIVITY PROFILES FOR THREE TYPES OF PRECIPITATION (after Joss and Waldvogel[8])

...... Drizzle ——— Widespread rain – – – Thunderstorms

example Harper[9], Donaldson[10]). Figure 2 shows the vertical extent of radar beams 2°, 1° and 0° wide as a function of range. From these figures it is clear that the errors in a surface estimate of precipitation will depend strongly on precipitation type, the vertical-beam width and the range of the measurement.

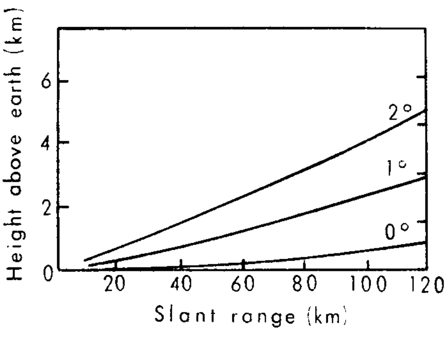

FIGURE 2—HEIGHT OF RADAR BEAMS AT ELEVATION 2°, 1° AND 0° ASSUMING STANDARD ATMOSPHERIC REFRACTION

These factors should be remembered when the errors obtained by various experimenters are considered (pages 201–203). As an example of the magnitude of the error involved, Harrold[11] has shown that when the radar beam intersects the 0°C level, a common occurrence in winter outside the tropics, the rate of rainfall will be overestimated by several tens of per cent unless corrections allowing for the variation of Z are made. In most cases the variation of Z near the 0°C level (the bright band — so called because the brightness of the echo on a range–height display is increased) constitutes the most marked variation of Z with height. However, there is evidence, e.g. Bergeron,[12] that in regions of orographic precipitation considerable enhancement of precipitation rate, perhaps by a factor of two (e.g. Harrold[13]), occurs within the lowest kilometre of the atmosphere; such growth should be allowed for when radar is used to estimate the precipitation at the surface in these regions.

Attenuation. The signal intensity is attenuated as it traverses precipitation. This attenuation is a function of the wavelength of the radiation. It is negligible at 100 mm, but at 30 mm in rain it is so much greater that almost all workers agree that radars with this wavelength cannot be used operationally to measure quantitatively anything except light rainfall rates. However, in the past some experimental investigations have been made at this wavelength by including various devices (none of which can be used operationally) to correct for the attenuation. These experiments, some of which are included in pages 197–203, provide useful information on the accuracy which should be attained by a practical system, but must not be interpreted as endorsing the use of 30-mm radar as a practical quantitative instrument.

Variations in radar characteristics. The rainfall estimate is derived from quantitative measurements of the echo intensity. Any errors in the calibration of the radar system will lessen the accuracy of the rainfall estimate. Such errors can be large, even with an apparently well-calibrated radar. As a practical example, Wilson[14] showed there was a 15-dB error (equivalent to about a factor of six in rainfall rate) in the data he was analysing. Much smaller, but undetected, radar errors have probably occurred in almost all the experiments reported in the following pages. From a practical viewpoint it should be noted that the problem of large undetected errors is alleviated to some extent if an independent measurement of R is made somewhere within the area of radar coverage (pages 201–203).

Processing errors. In a practical operation errors will also arise if measurements are made other than continuously (sampling interval errors) and if echo intensity is quantized into discrete levels (quantizing errors). Neither of these aspects will be discussed specifically here since they are a function of the way in which the radar system is used, rather than inherent in the system itself.

Although some definite statements can be made about the probable magnitude of particular sources of error, it is not possible, *a priori,* to determine the overall accuracy of operational systems. Experimental results are required for this purpose. These are summarized in the following sections.

Experimental results.

Point and small-area comparisons. Table I summarizes some experiments using radar to measure the rainfall over small areas. Generally clusters of a few rain-gauges, about a hundred metres apart, were used to provide the standard with which to compare the radar estimate. The accuracy is expressed in terms of a mean percentage difference defined by

$$X = 100 \left| \frac{G-R}{G} \right|_m$$

TABLE I—COMPARISON OF RADAR AND GAUGE ESTIMATES OF PRECIPITATION AT A POINT OR OVER A SMALL AREA

Reference	Precipitation type	Radar λ	Radar φ	Radar ε	Range	Z-R relation A	Z-R relation B	Number of observations or of days	Period of summation	Differences between radar and rain-gauge estimates X (a)	Y (a), (b)
		mm	*degrees*		*km*					*per cent*	
Austin[25] (U.S.A.)	All	107	3	1	28	200	1·6	480	1-minute comparisons	35 (b)	42
Dimaksyan *et alii*[26] (U.S.S.R.)	All	30 (?)	3		32, 22, 12	Calibration from previous season.		56 days	5-minute comparisons (?)	18	
Joss *et alii*[17] (Switzerland)	All	47		90	0·2	250	1·6	18 days 14 days	Daily (1965)	44 (all rain) (b) 22 (totals >2 mm only)	71
	All	47		90	0·2	300 Derived from same season's drop-size data.	1·5	47 days 33 days	Daily (1967)	28 (b) 24 (totals >5 mm only)	43 34
						Function of rain type.		47 days	Daily (1967)	15 12 (totals >5 mm only)	
Woodley *et alii*[27] (U.S.A.)	Mostly thunder-storms	100	2	0·5	Gauges up to 87 km	300 Derived for same location from independent data.	1·4	50	Daily	51 all totals (b) 34 total >2 mm only	73 45

Notes : λ = wavelength φ = vertical beam width ε = beam elevation

(a) Different authors have expressed accuracies in different forms. Here we have, wherever possible, recomputed the accuracy in terms of

(1) mean percentage difference $X = 100\left|\frac{G-R}{G}\right|_m$,

and (2) root-mean-square percentage difference $Y = 100\ \left(\sum((G-R)/G)^2/(N-1)\right)^{\frac{1}{2}}$ where G is the rain-gauge estimate and R is the radar estimate of precipitation; this enables comparisons between experiments to be made.

(b) Values computed by the present authors from the published data.

where G is the gauge estimate and R is the radar estimate of the rain, and suffix m indicates the mean of the modulus over a series of comparisons, and/or in terms of a root-mean-square percentage difference defined as

$$Y = 100\left(\sum\left((G-R)/G\right)^2/(N-1)\right)^{\frac{1}{2}}.$$

Although the experiments were conducted in different parts of the world and used differing equipments, the results are reasonably consistent, the mean percentage difference varying between 18 and 35 per cent excluding some results from light rains, when a small absolute difference can produce a large percentage difference. The lower end of this range of accuracies is similar to the magnitude of the difference expected when R is estimated from Z using an R–Z relationship; this implies that errors from all other sources can be very small at times.

Experiments using radar to estimate the precipitation over small areas are comparatively easy to set up since a few rain-gauges provide a standard measure of rainfall which is accurate to a few per cent, provided the gauges are adequately exposed (e.g. Green[15]). However, radar is better suited to making measurements over an area, as point estimates using radar include two possible sources of error which might be reduced in an areal measurement. These are : (a) precipitation within the pulse volume may not fall in the rain-gauge(s) even if careful allowance is made for wind drifts; (b) R–Z variations may be less when averaged over an area than the variation at a point. Thus it is not possible to relate the accuracy of the point measurements directly to that which might be attained over an area.

Area comparisons. Table II summarizes some published results of radar measurements of area rainfall. Accuracies are again expressed in terms of mean percentage difference and root-mean-square percentage difference and also, as an addition compared with Table I, the density of rain-gauges which would be required to give the same accuracy in the rains measured. In this last method the authors assumed that the estimate using their complete experimental network was correct and then the area rainfall was computed from simulated sparser networks.

The table shows that accuracies vary widely — the mean percentage difference, for example, ranging between experimenters from 20 to 66. The reasons for some of the larger differences can sometimes be deduced from the published papers. Thus, Borovikov *et alii*[2] recognized that much of their error may be attributed to attenuation of the 32-mm wavelength and to possible day-to-day variations in the stability of the radar. The other experiments at 32-mm wavelength also will have some error due to attenuation.

Despite the expectation that radar measurements would be more accurate over an area than at a point, the results in Tables I and II reveal a tendency for errors over an area to be larger. This may not be a real effect since the experiments are not directly comparable, having been performed in different rains using different radars. On the other hand, it is possible that the apparent inaccuracies over an area reflect inadequacies in the area rain-gauge network, the rain-gauge errors in an area estimate being significant. In the experiments it was assumed that the network provided an accurate measure of the actual rainfall. Typically the density of gauges used has been about 1 gauge/25 km^2. According to the data of Golubev *et alii*[16] the accuracy of rainfall estimates using such a network is only about 30 per cent. This figure may not be

TABLE II—COMPARISON OF RADAR AND GAUGE ESTIMATES OF PRECIPITATION OVER AN AREA

Reference	Precipitation type	Radar λ	Radar φ	Radar ε	Max. range	Z–R relation A	Z–R relation B		Number of observa-tions	Period of summa-tion	Area	Number of gauges used	Differences X (a)	Differences Y (a)	Gauge density required to give the same accuracy
		mm	degrees	degrees	km						km²		per cent	per cent	number per 10^4 km²
Aoyagi[18] (Japan)	Showers	32 (c)	1	1	50	200	1·6		28	10 minutes	638	27		57 (d)	103
	Continuous					200 100	1·6 1·4	(e)	66	10 minutes				34 (d)	78
	Showers					200	1·6		5	Storm			25 (b)		187
	Continuous					200 100	1·6 1·4	(e)	4	Storm			20 (b)		71
Borovikov *et alii*[2] (U.S.S.R.)	All	32 (f)	1		60	Matched radar and gauge totals over the season.			400	Storm	100	100	58 (b)	79 (b)	30
Jones[28] (U.S.A.)	Mostly thunder-storms	100		0?		Calibrated radar using one storm. Used three Z–R relations.			12	Storm	1000	49	66 (b)	105 (b)	—
						435 370 311	1·48 (thunderstorm) 1·31 (showers) 1·43 (continuous)		10	Storm			34 (b) (g)	45 (b) (g)	
Volynec *et alii*[29] (U.S.S.R.)	Snow	30			60	Matched 4-day totals over 100-km² area.			4	Storm	100 200 400 800	53	88 (i) (55 (h)) 59 (i) (53 (h)) 52 (i) (57 (h)) 39 (i)		—
									99	3 hours			91 (77 (j))		
Wilson[14] (U.S.A.)	All	100	2		90	200	1·6		28	Storm	2590	168	58 (b)	99 (b)	20

Notes :
(a) and (b) as for Table I.
(c) Assumed attenuation 0·02*R*.
(d) Author's value for 'standard deviation'.
(e) $Z = 100R^{1·4}$ used for diffuse echo on PPI.
(f) Attenuation apparently only allowed for inasmuch as seasonal calibration was a function of range.
(g) Excluding 2 cases with very large differences.
(h) Falls > 5 mm only.
(i) These values are 'mean square relative error'.
(j) Falls > 2 mm only.

representative of other localities, but it does emphasize the possibility that the 'standard' with which the radar estimate has been compared was itself in error. This was realized by Borovikov *et alii*[2] who used a network of 1 gauge/km^2 in order to obtain a reliable measure of the actual rainfall. Unfortunately any improvement in the radar estimate resulting from this network was masked by the other sources of error in their radar system which have been mentioned already.

The possible uncertainties in the accuracy of a rain-gauge based estimate of area rainfall emphasize that in any experimental comparison of radar and rain-gauge measurements as much attention should be devoted to the operation of the network of gauges as to the radar.

Possibilities of increasing the accuracy of radar estimates of precipitation by the use of additional calibration techniques. The majority of experimenters listed in Tables I and II used a fixed R–Z relationship in estimating R from the observed echo intensity. The study of R–Z relationship variations by Stout and Mueller[4] indicates that the accuracy of an estimate of R using a known Z is improved if (a) different relationships for different synoptic types are used or, to a smaller extent, if (b) the rainfall is classified into different types. The former stratification of data does not appear to have been investigated by means of radar, but Joss *et alii*[17] (Table I) and Aoyagi[18] (Table II) have verified that classification by rain type does improve the accuracy of a radar estimate of rainfall. Joss *et alii* found that the difference between the radar and gauge estimates was about halved.

Most of the error in a radar estimate of rainfall probably arises from variations in the R–Z relationship and in the radar calibrations. It has been suggested that the influence of these variations might be reduced if the radar estimates were calibrated directly against an independent estimate of the precipitation, the simplest technique being to match the radar and gauge totals over a point or small area and then apply the same calibration elsewhere over the area of radar coverage. Table III summarizes some results of experiments using this type of calibration. Wilson[19] and also the data of Borovikov *et alii*,[2] analysed for this purpose by the authors of this paper, confirm that a significant improvement can be obtained by this method upon results obtained using a fixed radar equation. Huff[20] investigated in some detail various possible calibrating techniques of which those listed in Table III are a representative sample. The accuracy of his results compares very favourably with the other radar estimates of rainfall over an area, but he concluded that it was preferable to improve direct measurements of rainfall from the radar echo presentation (viz. echo type) rather than use rain-gauge adjustment. He pointed out that, if calibration is made using a single gauge, the accuracy of the results may be less than that of the results obtained with the radar equation — if the gauge is not representative of the rainfall, in particular the drop-size distribution, over the area of interest. Huff's work indicates that further investigation of the use of gauge(s) to calibrate the radar estimate is needed before the potential value can be assessed fully; however, the other data in Table III suggest that, overall, the accuracy of the estimate of precipitation over an area is increased using this technique.

Russian workers, for example Berjulev *et alii*[21] have used a different method of calibrating the radar-derived precipitation field. They used the attenuation

TABLE III—COMPARISON OF RADAR AND GAUGE ESTIMATES USING ADDITIONAL CALIBRATION METHODS

Reference	Precipitation type	Radar λ	Radar φ	Max. range	Number of observations	Period of summation	Area	Calibration method	Differences X (a) Without calibration	Differences X (a) With calibration	Gauge density required to give the same accuracy
		mm	*degrees*	*km*					*per cent*	*per cent*	*number per 10^4 km²*
Berjulev *et alii*[21] (U.S.S.R.)	All	32 and 8·6			22	Storm		Attenuation at 8·6-mm wavelength.		24 (n)	
Borovikov *et alii*[2] (U.S.S.R.)	As in Table II							Matched over 100-km² and used this calibration over 2 other 100-km² areas.	58 (b)	41 (b)	
Carlson[24] (Canada)	Snow	32	0·9	67	1	Storm	20 pts	Using one gauge value to calibrate.	—	21 (b) (46 (k))	
				67–117			36 pts		—	34	
				117–159			19 pts		—	36	
Huff[20] (U.S.A.)		10	2		15	Storms	500 km²	25 gauges over adjacent 500 km².	—	30 (l)	25
					15	Storms	340 km²	Used outer two-thirds of network.		12 (l)	150
					19	Storms	1000 km²	Calibrating network: 1 gauge/580 km².		60	
					19	Storms	3100 km²	1 gauge/250 km².		40	
					19	Storms		1 gauge/75 km².		20	
									r.m.s. error function (m)		
Wilson[19] (U.S.A.)	As in Table II							One central gauge matched to the radar total over surrounding 130 km².	1·96	1·59	
								Three calibrations using three gauges.		1·48	
								Mean of three-gauge calibrations.		1·53	

Notes : (a) and (b) as for Table I.
(k) 21 per cent was the mean percentage difference obtained by simulating calibrating gauges. 46 per cent was the greatest percentage difference obtained when the least representative gauge was used for the calibration.
(l) Median percentage difference.
(m) 'Root-mean-square error expressed as a factor in rainfall. The error is measured as the logarithmic difference between the estimated and actual rainfall.'[19]
(n) Root-mean-square error expressed as a percentage.

of 8·6-mm radiation along a fixed path as a measure of the mean rate of rainfall along that path. The accuracy of the calibration would depend on the variability of the relationship between attenuation (K) and rate of rainfall (R). This relationship, like the R–Z relationship, depends upon the drop-size distribution; but both theory and experiment show that the K–R dependence is less sensitive. Harrold[22] showed, experimentally, that the mean error in 23 estimates of storm rainfall along a 7-km path was 15 per cent. Since this technique would provide a calibration along a line, rather than at isolated points, it is possible that it would provide a more representative calibration for an area measurement than would the use of gauges. The results of Berjulev *et alii* (Table III) indicate that the method may well have practical applications.

Other possible means of increasing the accuracy of radar estimates of area precipitation. On pages 195–197 it was shown that, at low levels Z is sometimes a function of, height, particularly in orographic precipitation or when the bright band is low. Thus, a critical parameter in any measurement of precipitation is vertical-beam width. Greater accuracy is to be expected with narrower beams, and at shorter ranges. The effect of the vertical extent of the beam on precipitation estimates has been partially investigated by Wilson[23] and Carlson,[24] both of whom classified their results according to range. However, in both these experiments Z probably did not vary significantly at low levels, so their results may not be directly applicable to other studies. In general, the experimental results listed in the tables are influenced by an unknown amount by the vertical extent of the beam.

Other radar parameters are not as critical as the vertical-beam width in affecting the accuracy of radar estimates of precipitation. Provided that the problem of attenuation at 30-mm wavelength is avoided by use of a longer wavelength, very little improvement in accuracy would be expected if other parameters of most conventional weather radars were changed.

Discussion. This article has reviewed the results of some quantitative measurements of precipitation using radar. The measurements have been made by several workers in various parts of the world and over a wide range of meteorological conditions. The reported accuracies, compared with the rainfall measured by rain-gauges, vary widely. For example, in experiments using a conventional 100-mm weather radar with a 2° beam width, the average difference in the rainfall total obtained with radar and conventional techniques varies between experimenters over the range 30 to 100 per cent. Radar errors have been reduced by using one or more rain-gauge values to calibrate the radar, the point calibrations being applied over the area of radar coverage. For example in one experiment this technique almost halved the error in the radar estimates. Theoretical considerations, supported by a few experiments, suggest that further significant improvements should be obtainable especially if radars with narrower beams in the vertical are used, and/or quantitative measurements are limited to shorter ranges than has often been the case in past experiments.

Even without these modifications, in some parts of the world radar can already provide a better estimate of area rainfall than the existing rain-gauge network. Since it has the additional advantages that (a) the measurements are made in real-time, (b) snowfall can also be measured and (c) short-term forecasts can be made, it seems very probable that the radar technique will become an increasingly important operational method of measuring precipitation over areas. However, further experimental work is required before the full quantitative potential of a weather radar can be assessed. Work of this type is being undertaken as part of the Dee Weather Radar Project. This is a joint study by the Water Resources Board, the Dee and Clwyd River Authority, Plessey Radar Ltd and the Meteorological Office, to investigate the accuracy and operational problems of using weather radar to measure precipitation.

REFERENCES

1. PROBERT-JONES, J. R.; The radar equation in meteorology. *Q J R Met Soc, London*, **88**, 1962, pp. 485–495.
2. BOROVIKOV, A. M., KOSTAREV, V. V., MAZIN, I. P., SMIRNOV, V. I. and CHERNIKOV, A. A.; Radar measurements of precipitation rate. Gidrometeorologicheskoe Izdatel'stvo, Leningrad, 1967. Translation by Israel Program for Scientific Translations, Jerusalem, 1970.
3. MARSHALL, J. S. and HITSCHFELD, W.; The interpretation of the fluctuating echo for randomly distributed scatterers. Part 1. *Can J Phys, Toronto*, **31**, 1953, pp. 962–994.
4. STOUT, G. E. and MUELLER, E. A.; Survey of relationships between rainfall rate and radar reflectivity in the measurement of precipitation. *J Appl Met, Lancaster, Pa*, **7**, 1968, pp. 465–474.
5. CATANEO, R.; A method for estimating rainfall rate–radar reflectivity relationships. *J Appl Met, Lancaster, Pa*, **8**, 1969, pp. 815–819.
6. MASON, B. J. and ANDREWS, J. B.; Drop-size distributions from various types of rain. *Q J R Met Soc, London*, **86**, 1960, pp. 346–353.
7. SIMS, A. L.; Case studies of the areal variations in drop-size distributions. *Proc Eleventh Weather Radar Conf, Boulder, Colorado*, 1964, pp. 162–165.
8. JOSS, J. and WALDVOGEL, A.; A method to improve the accuracy of radar measured amounts of precipitation. *Proc Fourteenth Radar Met Conf, Tucson, Arizona*, 1970, pp. 237–238.
9. HARPER, W. G.; Variation with height of rainfall below the melting level. *Q J R Met Soc, London*, **83**, 1957, pp. 368–371.
10. DONALDSON, R. J.; Radar reflectivity profiles in thunderstorms. *J Met, Lancaster, Pa*, **18**, 1961, pp. 292–305.
11. HARROLD, T. W.; Estimation of rainfall using radar — a critical review. *Scient Pap, Met Off, London*, No. 21, 1965.
12. BERGERON, T.; Mesometeorological studies of precipitation, IV. Report No. 20, Meteorologiska Institutionen, Uppsala, 1970.
13. HARROLD, T. W.; The structure and mechanism of widespread precipitation. (Unpublished, copy available in the Meteorological Office Library, Bracknell.)
14. WILSON, J. W.; Radar measurements of rainfall for operational purposes. Washington, Environmental Science Services Administration, National Severe Storms Laboratory, Contract E 22-23-69 (N). Final report 7488-360. 1969.
15. GREEN, M. J.; Some factors affecting the catch of rain-gauges. *Met Mag, London*, **99**, 1970, pp. 10–20.
16. GOUBEV, V. S., SOTIMAOV, N. V. and SYKOV, M. A.; Some results of the investigation of liquid precipitation in the district of Valday Upland. *Trudy Gos Gidrol Inst, Leningrad*, No. 123, 1965, pp. 5–14.
17. JOSS, J., SCHRAM, K., THAMS, J. C. and WALDVOGEL, A.; On the quantitative determination of precipitation by radar. Eidgenössische Kommission zum Studium der Hagelbildung und der Hagelabwehr. Wissenschaftliche Mitteilung Nr 63, Zurich, 1970.
18. AOYAGI, J.; Areal rainfall amounts obtained by a 3·2 cm radar and a raingauge network. *Proc Eleventh Weather Radar Conf, Boulder, Colorado*, 1964, pp. 116–119.
19. WILSON, J. W.; Integration of radar and raingage data for improved rainfall measurements. *J Appl Met, Lancaster, Pa*, **9**, 1970, pp. 489–497.
20. HUFF, F. A.; The adjustment of radar estimates of storm mean rainfall with raingauge data. *Proc Twelfth Radar Met Conf, Norman, Oklahoma*, 1966, pp. 198–203.
21. BERJULEV, G. P., KOSTAREV, V. V. and CHERNIKOV, A. A.; A new method of radar areal rainfall measurements. *Trudy Tsent Aerol Obs, Moscow*, Vyp. 100, 1970, pp. 115–124.
22. HARROLD, T. W.; Attenuation of 8·6 mm wavelength radiation in rain. *Proc Instn Elect Engrs, London*, **114**, 1967, pp. 201–203.
23. WILSON, J. W.; Relationship between gauge measured precipitation rates and radar echo intensities. *Proc Tenth Weather Radar Conf, Washington, D.C.*, 1963, pp. 241–246.
24. CARLSON, P. E.; Problems of snowfall measurement by radar. *Proc Fourteenth Radar Met Conf, Tucson, Arizona*, 1970, pp. 245–248.

25. AUSTIN, P. M.; Radar measurements of precipitation rate. *Proc Eleventh Weather Radar Conf, Boulder, Colorado*, 1964, pp. 120–125.
26. DIMAKSYAN, A. M. and ZOTIMOV, N. V.; Results of radar measurements of liquid precipitation. *Sov Hydrol, Washington*, No. 6, 1965, 530–537.
27. WOODLEY, W. and HERNDON, A.; A raingage evaluation of the Miami reflectivity-rainfall rate relation. *J Appl Met, Lancaster, Pa*, **9**, 1970, pp. 258–264.
28. JONES, D. M. A.; The correlation of raingauge-network and radar-detected rainfall. *Proc Twelfth Radar Met Conf, Norman, Oklahoma*, 1966, pp. 204–207.
29. VOLYNEC, L. M., KONONENKO, L. G., MARKOVICH, M. L. and MUCHNIK, V. M.; On the experience in radar measuring of snow amount. *Met Gidrol, Moscow*, No. 9, 1970, pp. 96–100. (Translation available in the Meteorological Office Library, Bracknell.)

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CLASSIFIED CENTRAL-ENGLAND TEMPERATURES AND ENGLAND AND WALES RAINFALL

By N. E. DAVIS

Summary. Monthly mean central-England temperatures since 1698 are ranked for each month and divided into five equal classes (T_1 to T_5). A comparison between the class boundaries for each month over the whole period 1698 to 1970 and boundaries applying only to the period 1873 to 1970 show that the temperature of the summer months has not changed over the last 270 years but that the temperature of the winter months is higher in the more recent period, the greatest difference being about ½ degC in January.

Monthly rainfall totals for England and Wales since 1727 are also ranked for each month and divided into three equal classes (R_1 to R_3). A comparison between the class boundaries for each month over the whole period 1727 to 1970 and boundaries applying only to the period 1873 to 1970 also shows that the rainfall of the summer months has not changed over the last 240 years but that the winter months are wetter in the more recent period, the greatest difference being about ½ inch (13 mm), again in January.

An examination of the runs of warm and cold months shows that there is considerable temperature persistence in the summer and possibly in cold months in the spring, but no persistence in the autumn. Rainfall shows no persistence. Consideration of the numbers of T_1 or T_2 Januarys and Julys in 25-year periods shows that fluctuations in the temperature in central England have occurred with a period of about 70 years. The July fluctuations are mostly out of phase with the January fluctuations. The frequencies of rainfall classes R_1 or R_3 in 25-year periods show fluctuations in January also with a period of about 70 years in phase with the temperature fluctuations. In July the rainfall fluctuations have a period of about 50 years. The temperatures of the three winter months (December, January and February) have recently varied in phase with each other but out of phase with most other months.

Derivation of temperature data. Manley[1] published monthly mean temperatures for central England for the period 1698 to 1957 and has provided in an unpublished communication data for the period 1958 to 1965. The climatological branches of the Meteorological Office have estimated values for the last 5 years 1966 to 1970. The values over the whole period 1698–1970 for each month and each season (e.g. winter = December, January, February) were ranked and divided into five equal (as far as possible) classes with the lowest 20 per cent for each month being classified quintile 1, the next 20 per cent quintile 2 up to the highest 20 per cent quintile 5. For example the coldest January was January 1795 with a mean temperature of −3·1°C and the warmest was in 1916 with a mean temperature 7·5°C. There were 53 years with mean January temperatures 1·6°C or less, 57 years between 1·7°C and 2·8°C inclusive, 56 years between 2·9°C and 3·8°C inclusive, 55 years between 3·9°C and 4·7°C inclusive and 52 years with mean January temperatures greater than or equal to 4·8°C. It was not possible to make the number of years in each class more nearly equal than this as there were 5 Januarys with a mean temperature of 1·7°C and 6 with a mean temperature of 4·7°C.

Tables of the temperature data. Table I gives (a) the lower and upper boundaries for each quintile for each month and each season for the period 1698 to 1970 and (b) similar boundaries determined only from the period 1873 to 1970. Cases in which the differences between corresponding boundaries in the two periods are greater than or equal to 0·2 degC are marked with an asterisk*. Apart from the boundary between quintiles 1 and 2 in April and between quintiles 4 and 5 in summer, all the cases of such differences occur in the months October to March and in the autumn and winter seasons. The greatest differences occur in January in the boundaries between quintiles 1 and 2 and between 2 and 3 where they amount to 0·7 degC. This is equivalent to about 1·0 degC when the 98-year period 1873 to 1970 is compared with the earlier 175 years 1698 to 1872.

TABLE I—QUINTILE BOUNDARIES FOR PERIODS (a) 1698–1970 AND (b) 1873–1970

	December		January		February		March		April		May	
	a	b	a	b	a	b	a	b	a	b	a	b
	degrees Celsius											
T_5 lower	5·6	5·7	4·8	5·3*	5·7	5·7	6·7	6·8	9·0	9·0	12·3	12·2
T_4 upper	5·5	5·6	4·7	5·2*	5·6	5·6	6·6	6·7	8·9	8·9	12·2	12·1
lower	4·6	4·7	3·9	4·3*	4·6	4·8*	5·9	6·2*	8·4	8·3	11·5	11·5
T_3 upper	4·5	4·6	3·8	4·2*	4·5	4·7*	5·8	6·1*	8·3	8·2	11·4	11·4
lower	3·7	3·9*	2·9	3·6*	3·6	3·8*	5·0	5·2*	7·7	7·7	10·9	10·9
T_2 upper	3·6	3·8*	2·8	3·5*	3·5	3·7*	4·9	5·1*	7·6	7·6	10·8	10·8
lower	2·8	2·9	1·7	2·4*	2·4	2·6*	4·0	4·2*	6·9	7·2*	10·3	10·3
T_1 upper	2·7	2·8	1·6	2·3*	2·3	2·5*	3·9	4·1*	6·8	7·1*	10·2	10·2
	June		July		August		September		October		November	
	a	b	a	b	a	b	a	b	a	b	a	b
	degrees Celsius											
T_5 lower	15·3	15·2	17·0	17·1	16·5	16·5	14·4	14·4	10·6	10·7	7·2	7·4*
T_4 upper	15·2	15·1	16·9	17·0	16·4	16·4	14·3	14·3	10·5	10·6	7·1	7·3*
lower	14·6	14·5	16·1	16·2	15·8	15·8	13·7	13·7	9·9	10·2*	6·4	6·7*
T_3 upper	14·5	14·4	16·0	16·1	15·7	15·7	13·6	13·6	9·8	10·1*	6·3	6·6*
lower	14·1	14·1	15·6	15·5	15·4	15·3	13·0	13·0	9·4	9·5	5·7	6·1*
T_2 upper	14·0	14·0	15·5	15·4	15·3	15·2	12·9	12·9	9·3	9·4	5·6	6·0*
lower	13·5	13·5	15·1	15·0	14·7	14·6	12·5	12·5	8·5	8·8*	4·8	5·3*
T_1 upper	13·4	13·4	15·0	14·9	14·6	14·5	12·4	12·4	8·4	8·7*	4·7	5·2*

	Winter		Spring		Summer		Autumn	
	a	b	a	b	a	b	a	b
	degrees Celsius							
T_5 lower	4·9	5·2*	8·9	8·9	16·0	15·8*	10·4	10·5
T_4 upper	4·8	5·1*	8·8	8·8	15·9	15·7*	10·3	10·4
lower	4·2	4·5*	8·4	8·5	15·5	15·5	9·8	10·1*
T_3 upper	4·1	4·4*	8·3	8·4	15·4	15·4	9·7	10·0*
lower	3·5	4·0*	8·0	8·1	15·1	15·1	9·5	9·7*
T_2 upper	3·4	3·9*	7·9	8·0	15·0	15·0	9·4	9·6*
lower	2·7	3·0*	7·4	7·5	14·7	14·6	9·0	9·2*
T_1 upper	2·6	2·9*	7·3	7·4	14·6	14·5	8·9	9·1*

Cases in which the differences between corresponding boundaries in the two periods are greater than or equal to 0·2 degC are marked with an asterisk*.

The differences mean that the winter climate in central England has warmed as between the two periods 1698 to 1872 and 1873 to 1970 in such a way that in January the colder T_1T_2 classes are about a degree Celsius warmer in the latter period but that the warmer (T_4T_5) classes are only about half a degree warmer. On the other hand, the constant boundary values in the summer months show that the summer climate in central England has not apparently changed at all in the 273-year period. Any explanation of the winter warming must account for both of these facts.

Table II gives the quintile values for every month and season from 1698 to 1971. Modern years (i.e. years since 1873) which would be classified one quintile lower according to boundaries determined from the period 1873 to 1970 are marked with an asterisk*, those which would be classified one quintile higher are marked with a dagger†.

Table III gives the warmest and coldest months and seasons and Table IV the seasons with persistently very cold, average or very warm months, i.e. seasons with all 3 months quintiles 1, 3 or 5 respectively. As the probability of a quintile 1 month is 1/5, the probability of all 3 months of a particular season being quintile 1 is 1/125 so that over the 273 years some 2 or 3 of each of the seasons could be expected by chance to have all 3 months quintile 1.

Table IV shows that temperature persistence in summer and to a less extent in winter for both very cold (T_1) and very warm months (T_5) and for very cold months in spring, is such that the frequency of continuous cold or continuous warmth throughout a season is three or four times the chance expectancy.

From Table II the longest run of quintile 1 months is 8 from February to September 1816, the longest run of quintile 5 months is also 8 from March to October 1959, but the longest run of quintile 3 is only 6 months from October 1718 to March 1719. The longest run of quintile 1 or 2 months is 15 from November 1878 to January 1880 and of quintile 4 or 5 months is 13 from April 1947 to April 1948. There were no cold or very cold months for two years from October 1833 to September 1835 and no warm or very warm months for 22 months from January 1838 to October 1839. The expected lengths of these runs are 5, 9 and 16 months respectively and the chance of getting runs of lengths 8, 14 and 23 months respectively is about 1 per cent, 1 per cent and 3 per cent. Again, it may be concluded that there is significant persistence of temperature from one month to the next. Indeed by counting the frequencies of runs of various lengths it can be shown that the actual probability of getting a quintile 1 month following a quintile 1 month is nearly 1/3 (instead of the chance probability of 1/5) but the actual probability of getting a quintile 5 month following a quintile 1 month is only 1/9 (instead of the chance probability of 1/5).

The maximum number of years with the same quintile of temperature for a particular month is 5, occurring in October from 1764 to 1768 which were all quintile 2, in July from 1839 to 1843 which were all quintile 1 and in April from 1942 to 1946 which were all quintile 5. The chance expectancy in a period of 273 years is a run of 5 years. Temperature persistence for a particular month from one year to the next is thus no greater than chance.

Derivation of rainfall data. Monthly rainfall percentages (of the 1881–1915 normal) for England and Wales as a whole were given by Nicholas and Glasspoole[2] for the period 1727 to 1931. Similar monthly percentages have been given since in the annual issue of *British Rainfall*. These percentages were converted by the Meteorological Office to actual values in inches to the nearest tenth of an inch. The 244 values for each month from 1727 to 1970 were ranked and divided into three equal (as far as possible) classes with the lowest 33⅓ per cent for each month being classified tercile 1, the next 33⅓ per cent tercile 2 and the highest 33⅓ per cent tercile 3. For example the driest January was 1766 with a total of 0·3 in (1 in = 25·4 mm) and the wettest

TABLE II—QUINTILES OF MONTHLY AND SEASONAL CENTRAL-ENGLAND TEMPERATURES, 1698–1971

	J	F	M	A	M	J	J	A	S	O	N	D	W	S	S	A
1698	2	1	2	2	1	2	3	3	2	3	1	3		1	2	1
9	3	3	1	1	2	4	5	1	3	4	2	3	3	1	3	3
1700	4	2	1	5	4	1	1	2	2	2	2	3	3	3	1	2
1	3	2	1	1	2	3	5	4	4	1	4	3	2	1	5	2
2	4	5	4	1	2	1	1	4	4	3	1	2	5	1	2	3
3	2	3	3	3	1	1	2	3	1	1	5	4	2	2	1	1
4	2	2	3	4	2	2	4	4	1	2	4	3	3	3	4	1
5	2	2	1	2	1	1	2	5	1	2	1	4	2	1	2	1
6	2	3	4	4	4	5	3	4	1	5	3	4	3	4	4	3
7	3	2	3	3	3	5	5	4	4	1	4	2	3	3	5	3
8	5	3	5	5	2	2	1	5	5	1	5	2	4	5	3	4
9	1	1	1	4	4	3	3	3	3	4	5	4	1	3	3	5
1710	2	2	4	1	4	3	1	3	3	3	5	5	3	3	2	4
1	5	1	3	5	3	5	1	2	2	3	5	2	5	4	3	4
2	2	3	3	3	3	4	4	1	2	3	3	5	3	3	3	2
3	2	4	1	1	1	1	1	2	4	3	1	3	4	1	1	3
4	4	4	3	2	1	3	5	1	2	5	3	3	4	2	4	4
5	4	4	5	5	3	2	1	2	4	5	4	1	4	5	1	5
6	1	2	2	4	2	2	3	2	1	3	2	2	1	3	2	2
7	4	2	2	2	1	2	1	2	3	3	2	4	2	1	1	2
8	1	2	3	3	3	3	5	5	5	3	3	3	2	3	5	4
9	3	3	3	1	4	3	5	5	4	2	3	2	3	2	5	3
1720	4	3	1	2	3	1	4	1	3	1	3	5	3	2	1	2
1	5	1	1	3	1	2	1	3	4	2	3	3	3	1	1	3
2	4	4	4	3	2	2	1	2	3	4	5	3	4	3	1	5
3	1	3	5	4	4	4	2	3	3	5	5	5	2	4	3	5
4	5	3	2	2	3	5	1	4	5	2	2	2	5	2	4	2
5	4	2	3	3	2	1	1	1	2	3	4	3	3	3	1	3
6	1	3	2	4	5	5	3	3	5	4	3	1	2	4	5	4
7	4	4	3	5	5	4	4	5	5	5	1	2	3	5	5	4
8	4	2	5	3	5	5	4	4	2	2	5	1	2	5	5	3
9	1	1	1	2	2	4	4	3	5	4	5	4	1	1	4	5
1730	4	4	4	4	5	2	2	4	5	5	5	2	4	5	3	5
1	2	1	4	1	4	5	4	5	5	5	5	4	1	3	5	5
2	2	5	4	4	3	4	3	5	5	5	3	1	4	4	4	5
3	5	5	4	5	3	4	5	4	2	2	4	5	5	5	5	2
4	4	5	5	5	3	3	4	4	3	1	3	3	5	5	4	2
5	4	3	3	4	3	1	1	4	4	4	3	4	3	4	2	4
6	5	2	5	4	2	5	4	5	5	4	4	5	5	4	5	5
7	5	3	4	4	5	5	5	1	4	2	3	4	5	5	4	3
8	4	4	3	5	3	3	4	4	2	4	3	5	4	5	4	3
9	4	5	3	1	4	4	3	2	3	3	1	2	5	4	3	1
1740	1	1	1	1	1	1	2	2	4	1	1	1	1	1	1	1
1	2	3	2	2	1	4	3	5	5	5	5	3	2	1	4	5
2	2	3	2	1	2	4	3	4	1	2	1	1	2	1	4	1
3	3	4	3	1	5	5	1	5	4	2	5	4	2	3	4	5
4	1	2	2	1	2	3	4	3	2	3	4	2	2	2	3	3
5	3	1	2	2	3	1	4	2	4	4	3	1	2	2	1	4
6	2	1	1	2	5	3	3	4	4	1	1	4	1	2	3	1
7	3	5	1	3	4	4	4	5	5	3	4	4	4	2	5	4
8	2	1	1	1	2	4	2	4	4	2	4	5	2	1	3	4
9	5	3	3	1	5	1	5	3	4	4	4	4	3	3	2	4
1750	4	5	5	3	2	3	5	2	5	2	1	3	5	5	4	3
1	4	1	4	2	1	4	2	1	2	1	1	2	2	2	2	1
2	3	2	3	1	2	4	3	3	4	5	4	3	2	2	3	4
3	2	3	4	2	4	4	2	3	3	4	1	3	2	4	3	2
4	3	2	1	1	4	2	1	3	4	4	3	2	3	2	2	4
5	2	1	1	5	1	5	1	1	3	1	1	3	1	2	3	1
6	4	4	4	1	1	2	4	2	3	3	1	2	4	1	2	2
7	1	3	2	3	2	2	5	2	3	1	4	2	1	2	4	3
8	2	3	3	2	5	4	1	4	1	1	3	3	2	4	3	1
9	5	5	4	4	4	4	5	4	3	5	2	1	5	5	5	4
1760	2	3	4	5	4	4	4	4	5	2	3	5	2	5	5	4
1	5	5	5	5	4	3	3	4	4	3	3	3	5	5	4	4
2	4	3	1	5	5	5	5	2	3	1	1	2	4	5	5	1
3	1	4	3	4	1	4	2	2	3	1	3	5	1	3	3	2
4	3	3	1	2	4	2	4	2	2	2	1	2	4	2	3	1
5	5	1	3	2	3	2	3	2	3	2	1	1	2	3	2	1
6	1	1	2	3	1	2	3	5	3	2	5	2	1	1	3	4
7	1	4	2	2	1	1	1	4	4	2	4	2	2	1	1	4
8	1	4	2	3	4	2	3	4	1	2	2	4	2	3	3	1
9	2	2	3	3	3	1	4	2	2	1	3	4	2	3	2	1
1770	3	4	1	1	1	1	2	4	4	2	2	2	4	1	2	2
1	1	2	1	1	4	3	3	1	1	2	3	5	1	1	2	2
2	1	1	2	1	1	5	4	4	3	5	5	4	2	1	5	5
3	4	2	4	3	2	4	3	4	1	4	2	3	3	4	4	2
4	1	3	4	4	3	4	4	4	2	4	2	2	1	4	4	2
5	4	5	4	5	5	5	4	4	4	2	2	3	4	5	5	3
6	1	3	4	5	2	3	4	2	2	4	3	3	1	5	3	4
7	2	1	5	2	4	2	2	4	5	4	4	1	1	4	2	5
8	2	2	2	3	2	5	5	5	1	1	4	5	1	2	5	1
9	3	5	5	5	4	3	5	5	5	5	3	2	5	5	5	5
1780	1	1	5	1	5	3	4	5	5	2	1	2	1	5	5	3
1	2	4	4	5	4	5	5	5	4	5	4	4	2	5	5	5
2	5	1	2	1	1	4	3	1	3	1	1	2	4	1	2	1
3	3	2	1	5	2	4	5	4	2	3	3	1	2	2	5	3
4	1	1	1	1	5	2	2	1	5	1	2	1	1	1	1	2
5	3	1	1	4	5	5	4	1	3	2	2	2	1	1	3	2
6	2	2	1	3	3	5	1	2	1	1	1	2	2	1	3	1
7	3	5	5	2	4	2	3	3	2	3	1	3	3	4	3	2
8	4	3	1	5	5	3	4	3	3	3	3	1	3	5	4	4
9	1	4	1	2	5	2	2	5	3	2	1	5	1	1	3	1
1790	4	5	4	1	4	4	1	3	1	4	3	3	5	3	2	3
1	1	4	4	5	2	4	2	4	4	2	3	1	4	5	3	3
2	2	3	4	5	1	1	2	5	1	2	5	3	1	4	3	2
3	2	4	2	1	3	2	5	2	1	5	3	4	3	1	3	3
4	2	5	5	5	3	5	5	3	2	3	3	3	4	5	5	2
5	1	1	1	3	3	1	2	5	5	5	1	5	1	2	2	5
6	5	4	2	5	2	2	1	4	5	1	1	1	5	3	2	2
7	3	4	2	2	3	2	5	4	2	1	1	4	1	2	4	1
8	3	3	3	5	5	5	4	4	3	4	1	1	3	5	5	2
9	2	2	1	1	1	3	2	1	2	1	2	1	1	1	1	1
1800	2	1	2	5	5	2	5	5	4	2	2	2	1	4	5	3
1	4	4	5	3	4	4	4	5	4	4	2	1	4	5	5	3
2	1	3	3	4	2	2	1	5	4	4	2	2	1	4	2	3
3	2	2	4	5	2	2	5	4	1	2	2	3	2	4	4	1
4	5	2	2	2	5	5	3	3	4	5	4	1	4	3	4	5
5	2	3	4	3	1	1	3	4	5	1	2	2	2	3	3	2
6	4	3	3	1	4	4	2	4	3	5	5	5	3	3	4	5
7	2	3	1	3	4	3	5	5	1	5	1	1	4	2	5	1
8	2	2	1	1	5	4	5	5	2	1	3	1	1	2	5	1
9	2	5	4	1	5	2	2	2	2	4	1	3	2	3	1	2
1810	2	2	2	3	1	4	2	1	4	3	2	2	2	2	2	3
1	1	4	5	4	5	3	4	1	4	5	5	2	2	5	2	5
2	2	4	1	1	3	1	1	1	3	2	2	1	3	1	1	2
3	2	5	5	2	4	2	1	1	2	1	1	2	2	4	1	1
4	1	1	1	5	1	1	3	2	2	1	1	3	1	1	1	1
5	1	5	5	3	5	3	1	2	3	4	1	1	3	5	2	2
6	2	1	1	1	1	1	1	1	1	4	1	2	1	1	1	1
7	4	5	3	2	1	4	1	1	3	1	5	1	4	1	1	3
8	4	2	2	2	3	5	5	2	3	5	5	2	2	2	5	5
9	4	3	5	4	4	1	4	5	3	2	1	1	3	5	4	1
1820	1	2	2	4	3	2	3	2	1	1	2	4	1	3	2	1
1	3	1	3	5	1	1	1	4	5	4	5	5	3	3	1	5
2	4	5	5	3	5	5	3	2	1	5	5	1	5	5	5	5
3	1	2	3	1	4	1	1	1	2	1	4	4	1	3	1	2
4	4	2	2	2	1	3	2	4	3	5	4	4	4	2	2	4
5	3	3	3	5	4	3	5	4	5	5	2	4	4	4	4	5
6	1	5	4	4	3	5	5	5	3	5	1	5	3	4	5	3
7	2	1	4	4	4	3	4	2	4	5	4	5	2	5	3	5
8	5	4	4	3	5	5	3	2	4	4	5	5	5	5	4	5
9	1	3	2	1	5	4	2	1	1	1	1	1	3	2	2	1
1830	1	1	5	4	4	1	4	1	1	4	4	1	1	5	1	3
1	1	4	5	5	4	5	4	5	4	5	2	5	2	5	3	5
2	3	2	3	4	3	3	3	3	5	3	4	3	3	4	4	4
3	1	4	1	3	5	4	3	1	1	4	4	5	3	5	2	3
4	5	4	5	3	5	5	4	4	4	5	4	5	5	5	5	5
5	3	5	3	4	3	4	4	5	3	2	4	2	4	4	5	3
6	3	2	3	2	3	5	2	1	1	2	2	3	2	3	3	1
7	2	4	1	1	1	5	4	3	2	4	2	4	3	1	5	2
8	1	1	2	1	2	3	3	2	2	3	1	3	1	1	2	2
9	2	3	2	1	1	3	1	1	1	2	5	3	3	1	1	3

TABLE II—*continued*

	J	F	M	A	M	J	J	A	S	O	N	D	W	S	S	A
1840	4	3	1	5	3	3	1	4	1	1	3	1	3	3	1	1
1	1	2	5	3	5	1	1	1	3	2	2	3	1	5	1	2
2	1	3	4	3	3	5	1	5	3	1	2	5	2	4	4	1
3	4	1	3	4	2	1	1	2	5	1	3	5	4	3	1	2
4	3	1	2	5	2	4	2	1	3	2	3	1	4	4	1	3
5	3	1	1	4	1	4	1	1	1	3	4	4	1	1	1	2
6	5	5	4	3	5	5	4	5	5	3	4	1	5	4	5	5
7	2	2	3	1	5	2	5	2	1	5	5	4	1	3	4	4
8	1	5	4	3	5	3	3	1	2	3	3	5	3	5	1	2
9	4	5	4	1	4	2	2	3	3	2	4	2	5	3	2	3
1850	1	5	2	5	1	5	4	1	1	1	5	4	3	2	3	2
1	5	4	3	2	2	3	1	3	2	5	1	4	5	2	2	1
2	5	4	3	3	2	1	5	4	2	1	5	5	4	3	4	3
3	5	1	1	2	3	3	1	2	1	4	2	1	4	1	1	2
4	3	3	5	5	2	1	2	2	5	3	2	4	2	4	1	3
5	2	1	1	2	1	1	4	3	3	3	2	1	1	1	3	2
6	3	4	2	3	1	2	2	5	2	5	2	3	3	1	3	2
7	2	3	3	2	3	5	4	5	5	5	4	5	3	3	5	5
8	3	1	2	3	2	5	1	4	5	3	1	4	4	2	4	3
9	5	5	5	2	4	4	5	4	2	3	2	1	5	4	5	2
1860	3	1	2	1	4	1	1	1	1	3	1	1	1	2	1	1
1	2	4	4	2	2	4	1	4	3	5	1	3	2	3	3	3
2	4	4	3	4	5	1	1	1	3	4	1	5	4	5	1	1
3	5	5	4	4	2	2	2	3	1	4	5	5	5	4	2	3
4	2	1	2	4	5	2	2	1	3	3	2	3	3	4	1	3
5	2	1	1	5	5	5	4	2	5	3	4	5	2	4	4	5
6	5	3	2	4	1	5	2	2	2	5	4	5	5	2	3	4
7	1	5	1	3	3	3	1	4	3	2	2	2	4	2	3	2
8	4	5	5	4	5	5	5	5	4	1	2	5	4	5	5	2
9	5	5	1	5	1	1	5	3	5	3	3	2	5	2	3	4
1870	3	2	2	5	4	4	5	3	2	3	1	1	2	4	5	2
1	1	5	5	4	3	1	2	5	2	3	1	2	1	5	3	1
2	5	5	5	3	1	3	5	2	3	1	4	4	5	3	4	3
3	5	1	3	3	1	3	4	3	1	2*	3	4	3	2	3	1
4	5	3	5*	5	1	2	5	2	3	4	2	1	5*	4	3	4*
5	5	1	3*	4	5	3	1	4	5	2	2	3	2*	4	3	4*
6	3*	4	2	3	1	3	5	5	2	5	3	5	3	1	5	4
7	5	5	2	2*	1	4†	1	2	1	2	4	4	5	1	3	2
8	4	4	3	4	4	4	4	4	3	4	1	1	5*	4	4†	2*
9	1	2	2	1	1	1	1	1	2	2	1	1	1	1	1	1
1880	1	5	4	3	2	2	2†	4	5	1	2	4	1	3	3	2*
1	1	2	3	2	4	2	4	1	2	1	5	3	1	3	1†	3*
2	5*	5	5	4	4	1	2	2	1	4*	3*	3	5*	5	1	2
3	4	5	1	3	2	2	1	2†	3	3	3*	4*	4	1	1†	3*
4	5	4	4	2	3	3	4	5	5	3*	2	3	5	3	4†	3
5	3*	5	2	3	1	2	4	1	1	1	3*	3*	4*	1	1†	1
6	2*	1	2	2	2	2	3	4	3	5	4*	1	1	2*	3	5
7	2	3	1	1	1	5	5	3	1	1	1	1	2*	1	5	1
8	3*	1	1	1	2	1	1	1	1	1	5	4	1	1	1	2
9	3*	2	2	2*	5	5	2	2	2	2*	4	2	3*	3	3	2
1890	5	2	4	2*	4	2	1	1	5	3*	3*	1	3	3	1	4*
1	1	3	1	1	1	4	2	1	4	3*	2	3	1	1	1†	3
2	2*	3*	1	2	4	1	1	2	1	1	4*	1	2	1	1	1
3	2*	4*	5	5	5	5	4	5	2	4*	2*	4	2*	5	5	2
4	3*	4	5*	5	1	2	3	1	1	2	5	4	4*	4	1	3*
5	1	1	3*	3	5	4	2	4	5	1	5	3	1	4	3	4*
6	5*	4*	5*	5	4	5	4	1	3	1	1	3	4*	5	4	1
7	1	5	4	2*	1	4	4	4	1	4*	5	4	3*	2	4†	4*
8	5	4	2	4	1	2	2	5	5	5	5*	5	5	2	3	5
9	5*	4	3*	3	1	5	5	5	3	2	5	1	5	2	5	4
1900	4	2	1	3†	2	4	5	2	3	3	5*	5	2	2*	4†	4
1	3*	1	2*	4	4	2	5	3	4	3	2*	2	4*	3	4†	3*
2	4	1	5*	2	1	2	1	1	2	3	4	4*	2	2	1	4*
3	4*	5	5	1	3	1	2	1	3	4	4*	2	5	3	1	4*
4	4*	2	2	4	3	1	5	2	2	3	2*	3*	3*	3*	3	2
5	3	4	5	2	2	4	5	2	1	1	2*	4	3	3	4	1
6	5	2	3*	2	2	3	3	5	4	5	5*	2	4*	2	4	5
7	3	2	4	2	2	1	1	1	3	3	4*	4*	2	3	1	4*
8	2	4	2	1	5	3	3	1†	2	5	5	3	3	2	2	5
9	3*	2	1	4	3	1	1	3	1	4	2*	3	2	2	1	2*
1910	3*	4	4*	2	3	4	1	2	2	5*	1	5	4*	3	2	1
1	3	4	3	2	5	3†	5	5	4	2	3	5	5*	4	5	4*
2	3	4	5	4	4	2	4*	1	1	1	3	5	5*	5	1	1
3	4	4	4	3	3	3	1	2	4	5	5	4	5	4	2	5
4	3	5	4*	5	2	3†	3	4	3	4	4	4*	5	5	3	4
5	4*	3	3	3	2	3	1	2†	3	2	1	4	4*	3*	2	1
6	5	3	1	3	4	1	2	4	3	5*	4	1	5	2	1	4
7	1	1	1	1	5	4†	4*	2†	4	1	5	1	1	1	4	4*
8	3	5	3	1	5	1	2	4	1	2	2	5	4*	4	2	1
9	3*	1	1	2*	5	3	1	3	2	1	1	4	3*	3	2	1
1920	5*	5	5	3	4	3	1	1	3	4	4	3	5	5	1	4
1	5	4	5	3	4	4	5	3	4	5	1	5	5	5	5	5*
2	3	3	2	1	5	2	1	1	1	1	3*	5	5*	2	1	1
3	5	4	4	2	1	1	5	2	2	3	1	3*	5	2	3	1
4	4	2	2*	2*	4	2	2	1	3	4*	4	5	3*	2	1	4
5	5	4	2	2	4	4	4	3	1	4	1	2*	5	3*	4	1
6	4	5	4	5	1	2	5	4	5	1	3*	3	4	4	4	2
7	4	3	5	3	3	1	3	3	2	4	3	1	4*	4	2	3
8	5*	5	4	4	3	1	4*	2†	2	4*	5	2	4*	4	2	4
9	1	1	4	1	3	1	3	3	5	3	4	5	1	3	2	5
1930	5	2	3	3†	2	5	2	3	3	4	3	3	4	3	3	4
1	3*	3	2	3	3	3	2	1	1	2	5	4	3*	2	2	2
2	5	2	2	2*	2	3	4*	5	2	2	4*	5	4	2*	4	2
3	2*	3	5	4	4†	5	5	5	5	4*	2	1	3	5	5	4
4	4*	3	2	3	3	4	5	3	5	5*	3	5	2	3	5	5*
5	4	5	4	3	1	4	5	5	3	3	4	2*	5	3	5	4*
6	3	2	5	1	4	4	2	4	5	3*	2	4	3	3	3	4*
7	5*	4	1	5	4†	3	4*	5	3	4	2*	2	5	3	4	3*
8	5	4	5	2	2	3	2	4	4	4	5	3	4	5	3	5
9	4*	4	3	4	3	3	2†	4	4	1	5	2	4	4	3	5*
1940	1	2	4*	4	5	5	2	3	2	3	4	3*	1	5	4	4*
1	1	2	3*	1	1	4	5	2	5	4	4*	5*	1	1	4	5
2	1	1	3	5	3	3	2†	5	3	4	2*	5	1	4*	4	3
3	5*	5	4	5	4	3	4	4	3	5*	3	2	5	5	4	4
4	5	3*	3	5	3	2	4	5	2	2	3	2	4*	5	4	2
5	1	5	5	5	4†	4	4	4	5	5	5*	4	3*	5	4	5
6	2	5	3*	5	2	1	4	2	4	3	5	2	4	4	2	5
7	2*	1	1	4	5	5	5*	5	5	5*	5*	4	1	4	5	5
8	5	4*	5	5	3	2	3	2	4	4*	5*	5	5*	5	2	5*
9	5	5	3*	5	3	5	5	5	5	5	4*	5	5	4	5	5
1950	4*	4	5	2	3	5	3	3	2	3	3*	1	5*	4	4†	2
1	4*	3*	2*	1	1	2	4	2	4	3*	5	4	2*	1	3	5
2	2	2	4	5	5	3	4	4	1	2	1	2*	3*	5	4	1
3	3*	3	3	2	5	3	2†	4	4	3	5	5	3*	4	3	5
4	3*	2	3	2	3	1	1	1†	2	5	4	5	3	3	1	5
5	2	1	1	5	1	2	5	5	4	2	4	4	3*	2*	5	4
6	3	1	4	2*	4	1	3	1	4	3*	3*	5	2*	3	1	4*
7	5	4	5	4	2	4†	4	3	2	5	4*	3	5	5	4	4*
8	3*	4*	1	2	3	3	3	4	5	5	4*	4	4*	2*	3	5
9	1	3	5	5	5	5	5	5	5	5	4	5	3*	5	5	5
1960	3	3	4	4	5	5	2	2	3	4	5	3	4	5	3	4
1	3	5	5	5	3	3	2	3	5	5	3*	1	4	5	2	5
2	4	3	1	3	2	2	2	1	2	4	2	1	3*	1	1	3*
3	1	1	4*	4	2	4	2	1	2	5	5	1	1	4*	2	5
4	3*	4*	2	4	5	2	4*	3	4	2	5	3*	3*	4	3	4
5	3*	2	3	3	4	3	1	3	1	5	1	3	3*	3	1†	2
6	2	5	4	2	3	4†	1	2	4	4	2	4	4*	4	2	4*
7	4	4	5	3	2	3	4	3	4	5	2*	3	5*	4	4	4*
8	4*	1	4	3	1	4	2	3	4	5	4*	2	2	3	3	5
9	5	1	1	2	3	2	4	4	3	5	2	2*	2*	1	4	5
1970	3	2	1	1	5	5	2	4	5	5	5	3	2	2	4†	5
1	4	4*	3*	3	4	1	4	4	4	5	3	5	4*	3	3	5

Note: Modern years (since 1873) which would be classified one quintile lower according to boundaries determined from the period 1873 to 1970 are marked with an asterisk*; those which would be classified one quintile higher are marked with a dagger†.

TABLE III—WARMEST AND COLDEST MONTHS AND SEASONS IN PERIOD 1698 TO 1970

	J	F	M	A	M	J	J	A	S	O	N	D
Warmest months												
Year	1916	1779	1957	1865	1833	1846	1783	1947	1729	1969	1818	1934
Temperature (°C)	7·5	7·9	9·2	10·6	15·1	18·2	18·8	18·6	16·6	13·1	9·5	8·1
Coldest months												
Year(s)	1795	1947	1785	1701 1837	1698	1909 1916	1816	1912	1807	1740	1782	1890
Temperature (°C)	−3·1	−1·9	1·2	4·7	8·3	11·8	13·4	12·9	10·5	5·3	2·3	−0·8

	Winter	Spring	Summer	Autumn
Warmest seasons				
Year(s)	1869	1893	1826	1730 1731
Temperature (°C)	6·8	10·2	17·6	11·8
Coldest seasons				
Year(s)	1740	1837	1725	1740 1786
Temperature (°C)	−0·4	5·6	13·1	7·5

TABLE IV—SEASONS WITH ALL 3 MONTHS OF QUINTILES (a) 1, (b) 3 OR (c) 5

	Winter	Spring	Summer	Autumn
(a) All 3 months quintile 1				
	1729	1713	1812	1786
	1766	1740	1816	1829
	1784	1770	1823	1887
	1830	1799	1841	
	1917	1816	1862	
	1963	1837	1879	
		1887	1888	
		1891	1907	
			1954	
(b) All 3 months quintile 3				
	1699	1707	1709	1788
	1719	1712		
	1931	1718		
		1769		
(c) All 3 months quintile 5				
	1863	1893	1778	1730
	1869	1959	1781	1731
	1877		1826	1741
	1943		1868	1947
	1949		1899	1970
			1933	
			1947	
			1949	
			1959	

1948 with a total of 7·0 in. There were 83 Januarys with England and Wales rainfall totals 2·2 in or less, 80 between 2·3 and 3·5 in and 81 with 3·6 in or more. It was not possible to make the number of years in each class more nearly equal than this as there were 6 years with a total of 2·2 in.

Tables of the rainfall data. Table V gives (a) the upper and lower boundaries of each tercile for each month and each season for the period 1727 to 1970 and (b) similar boundaries determined only from the period 1873 to 1970. Cases in which differences between the corresponding boundaries in the two periods are greater than or equal to 0·2 in are marked with an asterisk*. Apart from the boundary between terciles 1 and 2 in

TABLE V—TERCILE BOUNDARIES FOR ENGLAND AND WALES RAINFALL FOR PERIODS (a) 1727–1970 AND (b) 1873–1970

	December		January		February		March		April		May	
	a	b	a	b	a	b	a	b	a	b	a	b
	inches											
R_3 lower	4·0	4·2*	3·6	4·1*	3·1	3·3*	2·8	2·8	2·7	2·7	2·8	2·8
R_2 upper	3·9	4·1*	3·5	4·0*	3·0	3·2*	2·7	2·7	2·6	2·6	2·7	2·7
lower	2·7	3·1*	2·3	2·8*	1·9	1·9	1·7	1·8	1·8	1·9	1·9	2·0
R_1 upper	2·6	3·0*	2·2	2·7*	1·8	1·8	1·6	1·7	1·7	1·8	1·8	1·9

	June		July		August		September		October		November	
	a	b	a	b	a	b	a	b	a	b	a	b
	inches											
R_3 lower	3·1	3·0	3·8	3·8	3·8	3·9	3·8	3·5*	4·3	4·4	4·0	4·4*
R_2 upper	3·0	2·9	3·7	3·7	3·7	3·8	3·7	3·4*	4·2	4·3	3·9	4·3*
lower	2·0	1·9	2·5	2·5	2·7	2·9*	2·4	2·3	2·9	3·0	2·8	2·9
R_1 upper	1·9	1·8	2·4	2·4	2·6	2·7*	2·3	2·2	2·8	2·9	2·7	2·8

	Winter		Spring		Summer		Autumn	
	a	b	a	b	a	b	a	b
	inches							
R_3 lower	9·9	10·9*	7·5	7·7*	9·9	10·0	11·1	12·0*
R_2 upper	9·8	10·8*	7·4	7·6*	9·8	9·9	11·0	11·9*
lower	7·7	8·5*	6·2	6·4*	7·8	7·6*	9·1	9·2
R_1 upper	7·6	8·4*	6·1	6·3*	7·7	7·5*	9·0	9·1

Cases in which differences between the corresponding boundaries in the two periods are greater than or equal to 0·2 in are marked with an asterisk*.

August, all cases of such differences occur in the autumn and winter months, September to February. As the seasonal rainfall is a total for the three months, the significant seasonal differences occur in the boundary between terciles 2 and 3 in winter and autumn and between terciles 1 and 2 in winter, with differences between 0·8 and 1·0 in. The winter and to a less extent the autumn climate has become wetter as between the two periods 1727 to 1872 and 1873 to 1970.

Table VI gives the tercile values for every month and season from 1727 to 1971. Modern years (since 1873) which would be classified one tercile lower according to boundaries determined from the period 1873 to 1970 are marked with an asterisk*, those which would be classified one tercile higher are marked with a dagger†. Table VII gives the wettest and driest months and seasons, and Table VIII gives the seasons with persistently dry or wet months, i.e. seasons with all 3 months terciles 1 or 3. As the probability of a tercile 1 month is 1/3, the probability of all 3 months of a particular season being tercile 1 is 1/27 so that over the 244 years some 9 of each of the seasons could be expected by chance to have all three months tercile 1. The numbers in Table VIII, which vary from 7 to 12, do not differ significantly from the expected frequency.

From Table VI the longest run of consecutive dry months is 8 from January to August 1741 and of wet months 7 from July 1960 to January 1961. For 17 months from April 1873 to August 1874 there were no wet months and for 26 months from July 1967 to August 1969 there were no dry months. These figures are about the chance expectation, which is about 7 or 8 consecutive months all with the same tercile and 22 to 23 months all with terciles 1 or 2, or with terciles 2 or 3. It may be concluded that, unlike central-England temperatures, there is no tendency for high or low rainfall terciles to persist from one month to the next.

TABLE VI—TERCILES OF MONTHLY AND SEASONAL ENGLAND AND WALES RAINFALL, 1727–1971

	J	F	M	A	M	J	J	A	S	O	N	D	W	S	S	A
1727	3	2	3	1	3	2	3	1	2	1	1	3		3	1	1
8	3	1	3	3	2	2	3	1	1	3	2	2	3	3	2	2
9	1	1	2	2	2	1	2	2	3	2	3	2	1	2	1	3
1730	1	2	3	1	2	3	2	1	2	2	2	1	1	3	1	2
1	1	1	1	1	2	1	3	1	1	1	1	1	1	1	2	1
2	1	2	2	3	3	1	1	1	1	3	1	2	1	3	1	1
3	1	2	3	2	1	3	1	3	1	1	1	3	1	1	3	1
4	1	3	3	1	3	3	1	3	1	2	1	3	3	3	2	1
5	2	2	3	2	2	2	3	2	2	1	3	2	3	2	3	2
6	3	3	3	1	2	1	3	1	1	3	1	3	3	1	3	1
7	1	3	3	2	1	1	1	3	3	1	1	2	2	2	3	1
8	2	1	2	1	2	3	1	1	2	2	1	1	1	1	1	1
9	3	3	1	3	3	2	2	2	2	1	2	2	3	3	2	1
1740	1	1	1	1	1	1	2	3	2	1	2	3	1	1	2	1
1	1	1	1	1	1	1	1	1	3	2	2	1	2	1	1	2
2	2	1	1	2	2	2	2	1	1	3	3	1	1	1	1	3
3	1	1	2	2	1	1	3	1	1	3	1	1	1	1	1	1
4	1	1	2	3	1	3	1	1	3	3	2	1	1	3	1	3
5	1	1	3	3	1	3	1	3	1	2	2	2	1	3	3	2
6	2	2	3	1	1	3	2	1	1	2	2	1	2	1	1	2
7	3	2	2	2	3	2	1	1	2	1	3	3	3	2	1	1
8	1	1	3	3	2	3	3	1	1	1	1	3	2	3	2	1
9	3	2	3	1	1	3	1	1	1	1	1	2	3	2	1	1
1750	1	2	1	3	1	2	1	1	1	1	2	2	1	1	1	1
1	3	1	3	3	3	2	3	1	2	1	2	1	2	3	3	2
2	3	2	2	2	3	3	3	2	1	1	1	2	2	2	3	1
3	2	3	1	2	1	1	2	3	1	2	3	3	3	1	3	2
4	1	1	2	2	2	3	3	2	1	1	1	3	2	2	3	1
5	1	1	2	3	1	2	2	3	2	1	3	1	2	2	2	3
6	2	1	2	3	1	3	2	3	2	1	1	1	1	3	3	1
7	2	1	3	3	2	1	3	3	1	1	2	2	1	3	3	1
8	1	3	2	1	1	2	3	2	2	1	1	2	2	1	3	1
9	1	1	3	3	2	3	1	3	2	2	1	1	1	3	3	1
1760	1	3	1	1	1	3	1	3	3	3	3	2	1	1	2	3
1	1	2	1	1	3	3	1	3	3	3	2	2	1	1	2	3
2	3	2	2	1	1	1	1	3	3	3	1	1	2	1	1	3
3	1	3	1	2	3	3	3	3	3	1	2	3	1	2	3	2
4	3	2	2	2	2	2	3	2	1	2	2	2	3	1	3	1
5	2	1	3	3	1	1	1	3	1	3	1	1	1	3	1	2
6	1	2	1	2	3	3	2	1	2	2	1	1	1	2	2	1
7	2	3	3	1	2	1	3	2	2	2	2	1	2	2	2	2
8	3	3	1	3	1	3	3	2	3	3	3	2	3	1	3	3
9	1	2	1	1	2	3	1	2	3	1	2	2	2	1	2	1
1770	1	2	2	2	2	3	1	1	2	2	3	3	1	2	2	3
1	2	1	2	1	1	1	1	3	2	3	1	2	2	1	1	2
2	2	3	3	1	2	3	1	2	3	2	3	1	2	2	2	3
3	2	2	1	2	3	1	1	2	3	3	2	3	1	3	1	3
4	3	3	2	2	2	2	2	2	3	1	1	1	3	2	3	1
5	2	3	2	1	1	2	3	3	3	3	2	1	2	1	3	3
6	1	3	2	1	1	3	2	3	3	1	2	1	2	1	3	2
7	1	2	2	2	3	3	3	2	1	3	2	1	1	2	3	2
8	2	1	2	1	3	2	3	1	1	3	3	3	1	2	2	3
9	1	1	1	2	2	2	3	1	3	2	2	3	1	1	2	3
1780	1	2	1	3	1	1	1	1	3	2	1	1	2	2	1	2
1	1	3	1	2	1	3	1	2	3	1	3	1	1	1	2	1
2	3	1	3	3	3	1	3	3	3	2	1	1	1	3	3	2
3	2	3	2	1	3	3	1	2	3	1	1	1	2	1	2	2
4	2	1	2	3	2	3	2	2	1	1	2	1	1	2	3	1
5	2	1	1	1	1	1	2	3	3	2	2	2	1	1	3	3
6	3	1	1	1	3	2	1	3	3	2	2	2	2	1	2	3
7	1	2	3	1	1	1	3	2	1	3	2	3	2	2	3	2
8	1	2	1	1	1	2	2	2	2	1	1	1	2	1	2	1
9	2	3	1	2	3	3	3	1	3	3	2	3	2	2	3	3
1790	2	1	1	2	3	2	2	2	1	1	3	3	2	1	2	2
1	3	3	1	2	1	1	3	2	1	2	3	2	3	1	2	2
2	2	1	3	3	3	2	2	3	3	2	1	3	2	3	3	2
3	2	3	2	2	1	1	1	2	2	1	2	2	3	1	1	1
4	1	3	2	3	2	1	1	2	3	3	3	2	2	2	1	3
5	1	2	2	2	1	3	1	2	1	3	3	2	1	1	2	2
6	3	2	1	1	3	1	3	1	2	2	1	1	3	1	1	1
7	2	1	1	2	3	3	2	3	3	1	2	3	1	3	3	3
8	2	1	1	1	1	1	3	2	2	2	2	1	2	1	2	3
9	2	3	1	2	2	1	3	3	3	2	2	1	2	1	3	3
1800	3	1	1	3	2	1	1	1	3	2	3	2	1	3	1	3
1	2	2	3	1	2	1	3	1	3	2	2	2	1	2	1	3
2	1	3	1	2	1	2	3	2	1	3	1	2	2	1	3	1
3	2	2	1	2	2	3	1	1	1	1	3	3	2	1	1	1
4	3	1	2	2	2	1	2	2	1	3	3	1	3	3	2	2
5	2	2	2	2	2	2	2	2	1	1	1	2	1	1	2	1
6	3	2	2	1	1	1	3	3	2	1	3	3	3	1	3	2
7	1	2	1	1	3	2	1	1	2	1	3	1	2	2	1	2
8	1	1	1	3	2	1	2	2	2	3	2	1	1	1	2	2
9	3	2	1	3	2	2	2	3	3	1	1	2	3	1	2	1
1810	1	2	3	1	2	1	3	3	1	2	3	3	1	2	2	3
1	1	2	2	2	3	2	2	1	1	2	2	2	3	3	2	2
2	1	3	3	1	3	3	2	1	1	3	2	1	2	3	2	2
3	1	3	1	1	3	2	2	1	2	3	2	1	1	2	1	2
4	2	1	2	3	1	2	2	2	1	3	3	3	1	2	2	2
5	1	2	3	2	3	2	1	2	2	2	1	2	2	3	2	2
6	2	2	2	2	2	2	3	1	2	2	2	3	2	2	3	2
7	2	2	2	1	3	3	3	3	1	1	2	3	3	2	3	1
8	3	2	3	3	2	1	1	1	3	2	3	1	3	3	1	2
9	3	3	2	3	3	2	1	1	2	1	1	3	2	3	1	1
1820	2	2	1	2	3	2	2	2	2	2	1	2	2	2	2	1
1	2	1	3	3	2	1	2	2	3	2	3	3	1	3	1	3
2	1	2	3	3	2	1	3	1	1	3	3	1	3	3	2	3
3	2	3	2	2	2	2	3	3	2	3	1	3	2	2	3	2
4	1	2	3	2	2	3	1	2	3	3	3	3	2	3	2	3
5	1	1	2	2	3	2	1	2	2	2	3	3	2	3	1	3
6	1	3	2	1	1	1	1	1	3	2	2	2	2	1	1	2
7	2	1	3	1	3	1	1	2	2	3	1	3	1	3	1	3
8	3	2	1	3	2	2	3	2	2	1	1	3	3	3	3	1
9	1	1	1	3	1	3	3	3	3	1	1	1	1	2	3	2
1830	1	2	1	3	3	3	2	3	3	1	3	1	1	3	3	2
1	2	3	3	2	1	2	2	2	3	3	2	3	2	3	2	3
2	1	1	2	2	2	3	1	3	1	3	3	2	1	2	3	2
3	1	3	2	3	1	3	1	2	2	2	2	3	3	1	2	2
4	3	1	2	1	1	2	3	2	1	1	1	1	3	1	3	1
5	1	3	3	1	3	2	1	1	3	3	2	1	1	3	1	3
6	2	2	3	3	1	2	2	1	3	3	3	2	1	3	2	3
7	2	3	1	2	1	1	2	2	1	2	2	2	3	1	2	1
8	1	2	2	1	2	3	2	2	2	2	3	1	1	1	2	2
9	2	2	3	1	1	3	3	2	3	2	3	2	1	1	3	3
1840	3	2	1	1	3	2	2	1	3	1	3	1	3	1	1	2
1	2	2	2	2	3	3	2	3	3	3	3	2	1	2	3	3
2	2	2	3	1	2	2	2	1	2	1	3	1	2	2	1	3
3	2	2	1	3	3	2	2	3	1	3	2	1	2	3	3	2
4	2	3	3	1	1	2	2	2	2	2	3	1	1	1	2	2
5	2	1	2	1	2	2	2	3	2	2	2	3	1	2	3	2
6	3	1	2	3	2	1	2	3	1	3	1	1	2	3	2	2
7	2	2	2	2	3	2	1	1	2	3	2	3	1	3	1	2
8	1	3	3	3	1	3	2	3	3	3	1	3	3	3	3	3
9	2	2	1	3	3	1	2	1	3	2	1	2	2	3	1	2
1850	1	2	1	3	2	1	3	2	2	1	2	1	2	2	2	1
1	3	1	3	2	1	2	2	2	1	2	1	1	2	2	2	1
2	3	2	1	1	2	3	2	3	3	3	3	3	3	1	3	3
3	3	1	2	3	1	3	3	2	2	3	1	1	3	1	3	2
4	2	1	1	1	3	2	2	1	1	2	1	2	1	1	1	1
5	1	2	2	1	2	3	3	1	1	3	1	1	1	1	3	2
6	2	2	1	3	3	2	1	3	2	1	1	2	1	2	2	1
7	3	1	2	3	1	2	2	3	2	3	1	1	2	2	2	2
8	1	1	1	3	2	1	2	2	2	2	1	2	1	2	1	1
9	1	2	2	3	1	2	2	2	3	2	2	2	1	2	2	3
1860	3	1	3	1	3	3	2	3	2	2	2	3	3	3	3	2
1	1	3	3	1	1	2	3	1	2	1	3	1	2	1	2	2
2	2	1	3	2	3	3	2	2	2	3	1	2	1	3	2	2
3	3	1	1	1	1	3	1	2	3	2	2	1	2	1	2	3
4	1	2	3	1	2	1	1	1	2	1	2	1	1	2	1	2
5	3	3	2	1	3	1	2	3	1	3	3	1	2	2	3	3
6	3	3	2	2	1	2	2	3	3	1	2	2	3	1	2	3
7	3	2	3	3	2	1	3	1	2	2	1	1	3	3	2	1
8	3	2	3	2	1	1	1	3	2	2	1	3	2	2	1	2
9	3	3	2	2	3	1	1	1	3	1	2	3	3	3	1	2

TABLE VI—*continued*

	J	F	M	A	M	J	J	A	S	O	N	D	W	S	S	A
1870	2	2	2	1	1	1	1	1	1	3	1	2	2	1	1	2
1	2	2	2	3	1	3	3	1	3	2	1	1	2	2	2	2
2	3	3	3	3	2	3	3	2	3	3	3	3	3	3	3	3
3	3	2	3	1	2	2	2	2	2	2	1	1	3	2	2	1
4	2	2	2*	2	1	1	1	2	3	2	2	2	1	1	1	3
5	3	2	1	1	2	3	3	1	3	3	3	1	3*	1	3	3
6	1	3	3	3	1	2	1	2	3	2	3	3	2*	3*	1	3
7	3	2	3	3	3	1	3	3	2	2	3	2	3	3	3	3
8	2	2	1	3	3	3	1	3	2	2	3	2*	2*	3	3	3*
9	2	3	1	3	3	3	3	3	2†	1	1	1	3*	2	3	1
1880	1	3	2	2	1	3	3	1	3	3	2	3	1	1	3	3
1	1	3	3	1	2	3	2	3	2	2	3*	3	3*	2	3	2
2	2	2	2	3	2	3	3	2	2	3	3	3	2	3	3	3
3	3*	3	1	1	2	3	2	1	3	2	3	1	3	1	2	3
4	3	2	2	2*	1	1	3	1	2	1	1	2	2	1	1	1
5	2	3	2	2	3	2	1	1	3	3	2	1	3*	2	1	3
6	3	1	3	2	3	1	3	1	2	3	2	3	1	3	1	3*
7	2	1	2	1	2	1	1	1	2	1	2	2*	2	1	1	2
8	1	1	3	2	1	2	3	2	1	1	3	2*	1	3*	3	2
9	1	2	3	3	3	1	2	3	2	3	1	1	1	3	2	1
1890	3	1	2	1	2	2†	2	2	1	1	3	1	2*	2*	3	1
1	2*	1	2	2	3	2	2	3	2	3	2	3	1	2	3	3
2	1	2	1	1	2	3	2	3	2†	3	1	1	2	1	2	3*
3	2*	3	1	1	1	1	2	1	1	2	2	2	2	1	1	1
4	2	3	2	2	2	2	3	2	1	3	3*	2	3	2	3	2
5	3	1	3	2	1	1	3	2	1	3	3	2	2*	1	2	2
6	1	1	3	1	1	2	1	1	3	3	1	3	1	1	1	3
7	2*	3	3	3	1	3	1	3	3	1	2	3	3	3	2	1
8	1	2	1	2	3	2	1	2	1	3	2	2	2*	2	1	2
9	3	2	1	3	3	1	1	1	2	2	2	2	3	3*	1	2
1900	3	3	1	1	2	2†	1	3	1	2	2	3	3	1	2	2†
1	1	1	3	2	1	2	2	2	1	1	2	3	2	2	1†	1
2	1	1	2	2	3	2	1	2	1	2	2	2	2	2	2	1
3	3*	2	3	2	3	2	3	3	3	3	1	2*	2	3	3	3
4	3*	3	2	2*	3	1	2	2	1	1	1	2*	3*	2	1†	1
5	1	1	3	3	1	3	1	3	1†	1	3	1	1	3	2	2
6	3	2	2	1	3	2	1	1	1	3	3*	2	2	2	1	3*
7	1	2	2*	3	3	3	1	2	1	3	2	3	1	3	2	2
8	1	2	3	3	2	1	2	3	2	1	1	2*	2	3	2	1
9	1	1	3	2	1	3	3	2	2	3	1	3	1	3	3	2
1910	3*	3	1	3	2	2	2	3	1	2	3	3	3	2	3	2
1	1	2	2	2*	1	2†	1	1	2	2	3	3	2	1	1	2
2	3	2	3	1	2	3	3	3	1	2	2	3	3	2	3	2
3	3	1	3	3	2	1	1	1	2	2	2	1	3*	3	1	2
4	1	3	3	1	2*	2	3	1	1	1	3	3	1	3*	2	1
5	3	3	1	1	2	1	3	1	1	1	2	3	3	1	2	1
6	1	3	3	2	2	2	1	2	1	3	3	2	3	3	2	3*
7	2*	1	2	2	2	2	2	3	1†	3	1	1	1	2	3	2
8	3*	2	1	2	2	1	3	1	3	1	2*	3	2*	1	2	3
9	3	2	3	2	1	1	1	2	1†	1	2	3	3	3	1	1
1920	3	2	3	3	3	2	3	1	2	1	1	2	3	3	2	1
1	3	1	2	1	2*	1	1	3	1	1	1	2	2*	1	1	1
2	3	3	2	3	1	1	3	3	2	1	1	3	3	2	3	1
3	2*	3	2	2	2	1	2	3*	2	3	2	3*	3	2	1	3
4	3*	1	1	3	3	2	3	3*	3	3	2	3	2	3	3	3
5	2	3	1	3	3	1	2	2	3	2	2	3*	3	3	1	2
6	3	3*	1	3	2	3	2	2	1	2	3	1	3	2*	2	3
7	2	3	3	2	1	3	3	3	3	2*	3*	2	2*	2	3	3
8	3	2	3	1	1	3	1	2	1	3	3	2	3	2	2	3*
9	1	1	1	1	2	1†	2	2	1	3	3	3	1	1	1	3
1930	3	1	2	3	2	1	3	3	3	2	3	3*	3	3	3	3
1	2	3	1	3	3	3	3	3	2	1	3	1	3*	3	3	2
2	2	1	2	3	3	1	3	1	2†	3	1	1	1	3	1	3
3	2	3	3	1	2	2	1	1	2	2	1	1	2	2	1	1
4	2	1	3	3	1	1	1	2	2	2	1	3	1	3*	1	1
5	1	3	1	3	1	3	1	1	3	3	3	2	3	2*	1	3
6	3	3*	2	2	1	3	3	1	2†	1	3*	2	3	1	3	2
7	3	3	3	3	3	1	2	1	2	2	1	3	3	3	1	1
8	3	1	1	1	2	2	2	2	1	3	3	3	3*	1	2	3
9	3	2	2	3	1	2	3	2*	1	3	3	1	3	2*	3	3
1940	2	3	3	2	1	1	3	1	1	2	3	2*	3*	2	1	3
1	3*	3	3	1	2	1	2	3	1	2	2	1	2	3*	2	1
2	3	1	2	1	3	1	2	2	2	2	1	3*	1	3	1	1
3	3	1	1	1	3	2	1	2	2	2	1	1	3	1	1†	2
4	2	1	1	2	1	2	2	2	3	3	3	2*	1	1	2	3
5	2	3*	1	1	2	2	2	2	2	2	1	3*	2	2*	2	1
6	2	3	1	2*	3	3	2	3	3	1	3	3*	3	2*	3	3
7	2	2	3	3	2	2	2	1	1	1	2	2	2	3	1	1
8	3	2	1	2	2	3	1	3	2	2	1	3	3	1	3*	1
9	1	1	2*	2	2	1	1	1	1	3	3*	2	2*	2	1	3
1950	1	3	1	3	2	1†	3	3	3	1	3	2*	3*	2	3	3
1	3*	3	3	3	3	1	1	3	2†	1	3	3*	3	3	2	3
2	2	1	3	2	2	2	1	3	3	2	3*	2	2	3	1	3*
3	1	2	1	3	2	2	3	2	2	2*	2*	1	1	2	2	1
4	2*	3	3	1	3	3	2	3	2†	3	3	2	1	2	3	3
5	2	2	2	1	3	3	1	1	1	2	1	3	2	3	1	1
6	3	1	1	1	1	2	3	3	2†	1	1	3	3*	1	3	1
7	2	3	2	1	2*	1†	3	3	3	2	1	2	3	1	3	2
8	2	3	2	1	3	3	3	3*	3	2	1	3*	3	2*	3	2
9	3*	1	2	3	1	1	2	1	1	2	3	3	2*	2	1	1
1960	3	3*	2	2*	1	1†	3	3	3	3	3	3	3	1	3	3
1	3	2	1	3	1	1	2	2	2	3	1	2	3	1	1	2
2	3	1	2*	3	2	1	1	3	3	1	2*	2*	2	2	1	1
3	1	1	3	3	2	3	1	3	2	1	3	1	1	3	2	2
4	1	1	3	2	2	3	1	1	1	1	1	2	1	3	1	1
5	3*	1	3	2	2	2	3	2	3	1	3*	3	2*	3*	2	2
6	1	3	1	3	2	3	2	3	1	3	2	3	3	3	3	2
7	2*	3	2	2*	3	1	2	2	3	3	2	2	3*	3	1	3
8	2	2	2	2	3	3	3	2	3	2	2	2	2*	3	3	3
9	3*	2	3	2	3	2	2	2	1	1	3	2	2	3	2	1
1970	3	3*	2	3	1	1	2	2	2	1	3	1	3	2	1†	3*
1	3	1	2	2	2*	3	1	3	1	1	2	1	1	2	3	1

Note : Modern years (since 1873) which would be classified one tercile lower according to boundaries determined from the period 1873 to 1970 are marked with an asterisk*; those which would be classified one tercile higher are marked with a dagger†.

TABLE VII—WETTEST AND DRIEST MONTHS AND SEASONS IN PERIOD 1727 TO 1970

	J	F	M	A	M	J	J	A	S	O	N	D
Wettest months												
Year(s)	1948	1923 1833	1947	1756	1773	1860	1758	1737	1918	1903	1852	1914
Rainfall (in)	7·0	6·0	6·8	5·6	5·7	5·9	7·3	7·6	7·2	8·3	8·1	8·0
Driest months												
Year(s)	1766	1890	1742	1938 1912 1817	1844	1925	1825	1742 1747	1743 1754	1781	1945 1748	1799 1788 1780
Rainfall (in)	0·3	0·1	0·1	0·3	0·3	0·1	0·3	0·4	0·2	0·5	0·8	0·5

Wettest seasons	Winter	Spring	Summer	Autumn
Year(s)	1915	1782	1763 1912	1852
Rainfall (in)	17·4	12·4	15·9	17·9
Driest seasons				
Year	1964	1741	1800	1748
Rainfall (in)	3·3	1·9	2·9	4·4

Note : 1 in = 25·4 mm.

TABLE VIII—SEASONS WITH ALL 3 MONTHS TERCILES (a) 1 OR (b) 3

	Winter		Spring		Summer		Autumn	
(a) All 3 months tercile 1								
	1731	1808	1740	1798	1732	1869	1731	1834
	1743	1858	1741	1863	1741	1870	1733	1904
	1744	1964	1760	1893	1780	1887	1749	1921
	1745		1785	1956	1800	1899	1754	1964
			1788		1818	1913	1805	
					1826	1949		
(b) All 3 months tercile 3								
	1774	1910	1751	1889	1763	1912	1760	1852
	1791	1915	1782	1920	1829	1957	1768	1872
	1869	1926	1792	1931	1879	1958	1794	1875
	1883	1960	1877	1951			1824	1935
							1836	1944
							1841	1960

Climatic variations. As well as the trend in temperatures and rainfall in the winter half year, Tables II and VI also reveal fluctuations in the frequency of the high or low quintiles or terciles. For example, the 25 Januarys ending in January 1787 are distributed amongst the five temperature classes as follows :

T_1	T_2	T_3	T_4	T_5
10	5	6	2	2

whilst the 25 Januarys ending in January 1939 are distributed :

T_1	T_2	T_3	T_4	T_5
2	1	5	7	10

Table IX gives for January the 25-year periods with a maximum number of cases of temperature in quintiles 1 or 2 or in quintiles 4 or 5. (T_{12} means temperature in either quintile 1 or quintile 2) and also the 25-year periods with a maximum number of cases of rainfall totals in tercile 1 or in tercile 3. Table IX shows a tendency to alternating warm and cold periods with an interval of about 70 years between successive warm periods. The rainfall

TABLE IX—25-YEAR PERIODS WITH MAXIMUM NUMBER OF TEMPERATURES IN QUINTILES 1 OR 2 AND 4 OR 5 AND OF RAINFALLS IN TERCILES 1 AND 3 FOR JANUARY

Period		Temperature quintiles T_{12}	T_3	T_{45}
		number of cases		
1714–1738	Warm	7	1	17
1763–1787	Cold	15	6	4
1782–1806	—	12	5	8
1807–1831	Cold	17	2	6
1851–1875	Warm	7	5	13
1874–1898 up to 1879–1903	—	10	5	10
1915–1939	Warm	3	5	17
1940–1964	Cold?	10	7	8

Period		Rainfall terciles R_1	R_2	R_3
		number of cases		
1757–1781	Dry	13	8	4
1782–1806	—	5	13	7
1807–1831	Dry	14	7	4
1851–1875	Wet	5	6	14
1887–1911	Dry	12	5	8
1918–1942 and 1919–1943	Wet	2	8	15
1944–1969	—	6	11	8

shows an approximation to alternating wet and dry periods also with an interval of about 70 years between successive wet periods. The rainfall variations are mostly in step with the temperature variations, the warm periods being wet and the cold being dry.

Table X gives similar information for July. Temperature oscillations with a period of about 70 years again occur but these are largely out of phase with the January temperature oscillations. For July rainfall the oscillations are less definite but the period is about 50 years.

TABLE X—25-YEAR PERIODS WITH MAXIMUM NUMBER OF TEMPERATURES IN QUINTILES 1 OR 2 AND 4 OR 5 AND OF RAINFALLS IN TERCILES 1 AND 3 FOR JULY

Period		Temperature quintiles T_{12}	T_3	T_{45}
		number of cases		
1702–1726	Cold	14	4	7
1726–1750	Warm	5	6	14
1759–1783	Warm	4	7	14
1839–1863 and 1840–1864	Cold	17	1	7
1863–1887 to 1865–1889	—	11	1	13
1907–1931	Cold	13	4	8
1932–1956 and 1933–1957	Warm	7	3	15

Period		Rainfall terciles R_1	R_2	R_3
		number of cases		
1729–1753	Dry	12	7	6
1775–1799	Wet	7	7	11
1803–1827	—	9	10	6
1828–1852 and 1829–1853	—	4	16	5
1854–1878	—	9	9	7
1871–1895	Wet	5	8	12
1889–1913	Dry	11	9	5
1917–1941 and 1918–1942	Wet	6	8	11
1940–1964 to 1942–1966	—	9	9	7

Table XI gives 25-year periods with a maximum number of cases of temperature in quintiles 1 or 2 or in quintiles 4 or 5 and Table XII gives 25-year periods with a maximum number of cases of rainfall in tercile 1 or in tercile 3 for all months and seasons. These are taken from the most recent 150 years.

TABLE XI—25-YEAR PERIODS* (ENDING AT YEAR(S) NAMED) WITH MAXIMUM NUMBER OF TEMPERATURES IN QUINTILES 1 OR 2 AND 4 OR 5 FOR EACH MONTH AND SEASON

			T_{12}	T_3	T_{45}			T_{12}	T_3	T_{45}			T_{12}	T_3	T_{45}			T_{12}	T_3	T_{45}
December	1970	?	8	6	10	1934	Warm	6	4	15						1893	Cold	12	5	8
January	1964	Cold?	10	7	8	1939	Warm	3	5	17	1898–1903	?	10	5	10	1875	Warm	7	5	13
February	1971	?	10	5	10	1927–28	Warm	7	4	14	1909–10	?	12	3	10	1885	Warm	7	2	16
March	1957–63	Warm	5	8	12											1888–89	Cold	14	4	7
April	1961	Warm	8	0	17	1925–26	Cold	15	5	5						1878	Warm	6	6	13
May	1971	?	7	8	10	1931–34	Warm	6	7	12	1900	Cold	15	1	9					
June	1954	Warm	5	9	11	1929–31	Cold	12	8	5	1900	?	12	2	11	1886	Cold	13	6	6
July	1956–57	Warm	7	3	15	1931	Cold	13	4	8						1887–89	?	11	1	13
August	1955–56	Warm	6	3	16	1924	Cold	16	4	5						1880	?	9	4	12
September	1969–71	Warm	7	2	16	1928	Cold	13	6	6										
October	1971	Warm	3	4	18											1896	Cold	15	4	6
November	1961–64	Warm	3	5	17	1925	?	11	3	11	1908–09	Warm	8	2	15	1875	Cold	17	2	6
Winter	1970/71	?	7	8	10	1934/35	Warm	3	4	18						1893/94	Cold	12	4	9
Spring	1961	Warm	4	3	18						1909	Cold	14	7	4					
Summer	1955–57	Warm	4	5	16	1931	Cold	17	3	5						1878–80	?	5	11	9
Autumn	1969–71	Warm	3	1	21											1894	Cold	14	6	5

* Taken from the most recent 150 years

TABLE XII—25-YEAR PERIODS* (ENDING AT YEAR(S) NAMED) WITH MAXIMUM NUMBER OF RAINFALLS IN TERCILES 1 AND 3 FOR EACH MONTH AND SEASON

			R_1	R_2	R_3			R_1	R_2	R_3			R_1	R_2	R_3			R_1	R_2	R_3
December						1930	Wet	3	7	15						1858	Dry	13	8	4
January	1968	?	6	11	8	1942–43	Wet	2	8	13	1911	Dry	12	5	8	1875	Wet	5	6	17
February	1965–66	?	11	5	9	1936–37	Wet	8	4	13	1909–10	Dry	11	8	6	1885	Wet	2	12	11
March						1948	Dry	12	5	8	1918–20	Wet	6	6	13					
April	1960	?	10	8	7	1937	Wet	6	7	12	1915–16	?	8	10	7					
May	1969	Wet?	4	12	9						1919	?	8	10	7					
June	1968–69	?	9	6	10	1942	Dry	14	5	6						1853	Wet	4	11	10
July						1941–42	Wet	6	8	11	1913	Dry	11	9	5	1895	Wet	5	8	12
August	1964–71	Wet	5	7	13	1949	?	8	11	6	1912	Wet	5	10	10					
September	1968	Wet	6	8	11						1917	Dry	17	5	3	1833	Wet	2	12	11
October	1970	Dry	11	8	6											1865	Wet	5	9	11
November						1950–52	Wet	8	2	15						1895–96	Wet	6	7	12
Winter						1938/39 1939/40	Wet	4	5	16	1908/09 1909/10	?	8	11	6	1883/84 1884/85	Wet	4	10	11
Spring	1969–71	Wet	5	9	11						1920–21	Wet	5	8	12	1897–98	?	10	7	8
Summer						1949	Dry	12	6	7	1907–08	Dry	11	9	5	1852–53	Wet	5	9	11
Autumn						1946–47	Wet	7	4	14	1921–22	Dry	10	11	4	1883	Wet	3	9	13

* Taken from the most recent 150 years

Table XI shows that for the most part the three winter months and the winter season vary out of phase with other months, being at the maximum frequency for T_{45} around the period 1911–35 when most other months were at a maximum frequency for T_{12}. The recent decline in the frequency of T_{45} months in the winter months has to date, only produced 25-year periods with distributions close to the expected (average) frequency of 10 T_{12}, 5 T_3 and 10 T_{45}. All other months are close to or have just passed a 25-year period with a maximum frequency of T_{45} months. This is especially so in the case of autumn — no less than 21 out of the last 25 autumns have been classified T_4 or T_5.

For rainfall, the picture is less clear cut. Rainfall oscillations in January are largely in phase with February but July oscillations are out of phase with August.

REFERENCES

1. MANLEY, G.; Temperature trends in England 1698–1957. *Arch Met Geoph Bioklim, Wien*, B, 9, 1959, pp. 413–433.
2. NICHOLAS, F. J. and GLASSPOOLE, J.; General monthly rainfall over England and Wales, 1727 to 1931. *Brit Rainf*, 1931, *London*, 1932, pp. 299–306.

REVIEWS

Problems of satellite meteorology, edited by I. P. Vetlov and G. I. Morskoi. 245 mm × 173 mm, pp. v + 102, *illus.* (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), Keter Press Ltd, 15 Provost Road, London, NW3 4ST, 1970. Price: £3·80.

There are many problems of satellite meteorology and meteorologists may find the title of this book something of a misnomer. We are told on the cover leaf however that 'this collection contains articles pertaining to processing, interpretation and use of data collected by meteorological satellites for weather analysis and prediction. It is intended for specialists in synoptic and dynamic meteorology, and workers of operational units of hydrometeorological services'.

Of the 11 articles by different authors, 4 are limited by their geographical context and will have only casual interest for most meteorologists. These are :

T. P. Popova; The cloudiness structure in cyclones in southern European U.S.S.R.
I. A. Alekseeva; The intertropical convergence zone in the eastern Pacific from meteorological satellite observations.
I. R. Egorova; Features of atmospheric fronts in the southern hemisphere from satellite observations.
E. P. Dombkovskaya; Relationship between cloud masses observed from a satellite and their precipitation zones.

The first of these shows how satellite television photographs can be used to interpret the evolution of depressions originating over the Black Sea and the Caspian Sea and subsequently affecting the U.S.S.R. It is similar to case studies prepared elsewhere and has local interest only. The paper by I. A. Alekseeva examines the spatial structure of the cloud field in the eastern part of the tropical Pacific with the aid of satellite observations during 1967, the approach being purely climatological.

Many practising forecasters are somewhat disappointed with the interpretation of radiation data from satellites as a means of analysis. The paper on atmospheric fronts in the southern hemisphere deals with this problem but is limited in value primarily because of the sparse coverage of orthodox meteorological data which are a necessary background to satisfactory interpretation. The author considers some features of fronts in the South Pacific for March–April 1967 using satellite radiation data from the METEOR system. Average and extreme values are presented of the radiation characteristics in the region of the front for two latitudinal belts (27–45°S and 45–60°S) and for a number of specific frontal zones.

The article by E. P. Dombkovskaya examines the relationship between precipitation and cloud cover as deduced from satellite pictures, the data applying to the European U.S.S.R. A list of rules is given relating precipitation and cloudiness, e.g. 'As a rule, precipitation zones occupy a relatively small proportion of cloud masses. In 87·2 per cent of the cases the total precipitation-occupied area was less than one-third of the cloud mass, while in 97·7 per cent it was less than half'.

Most meteorologists will find strange the use of the word 'nephelometer' instead of 'nephanalysis', presumably due to mistranslation.

The use of visual satellite data as a means of specifying the wind field is dealt with in two papers. The first, by L. A. Anekeeva, 'Use of cloud data obtained by meteorological satellites for an objective analysis of the wind field', is based on a statistical analysis of the relation between wind and cloud bands in large spiral cloud vortices. The data refer to the period March 1966–March 1967 over the Soviet Union, Western Europe and the north-eastern Atlantic. On page 4, in the reference to Bykov's programme, there is of course no vertical component as stated. The other paper by T. D. Dzyubenko and A. M. Tsar'kova deals with the determination of the jet-stream axis from satellite cloud data. The study uses data from the North Atlantic, Europe, west Siberia and central Asia and reaches the following conclusions :

(a) The jet stream is seen on TV cloud photographs in 46 per cent of the cases. The jet-stream sections most frequently seen are those located in the forward part of the 'altitudinal' trough.

(b) The cloud mass is usually located on the warm side of the jet-stream axis and its boundary in 72 per cent of the cases coincides with this axis.

(c) The average wind speed at the jet-stream axis, traced on TV photographs, ranges from 44 to 52 m/s; the wind shear per 100 km perpendicular to the jet-stream axis is 7·6 m/s at the cold side and 6·2 m/s at the warm side.

M. Nazirov, in the paper 'Shadow on satellite photographs as a source of information on the height of cloud', deals with the application of correction factors depending on the distance between the shadows and the sub-satellite point.

The most practical paper, by K. P. Vasil'iv, 'Use of meteorological satellite data as a navigational aid', describes methods for interpreting TV pictures of sea ice and the difficulties encountered in this work. As might be expected, this is well done. The less satisfactory part of the paper deals with the significance of cloud-vortex photographs for 'gale-swell' zones in the ocean, intended as an aid to ship routeing.

'A qualitative analysis of satellite infra-red data' by E. V. Dzybenko and V. V. Puchkov examines the possibility of determining the radiative-surface temperature and altitude of an upper cloud boundary using METEOR infra-red data in the 8–12 μm range. It is claimed that a quantitative analysis of infra-red information from METEOR satellites can be carried out in 'operative times'. Another investigation of satellite infra-red data by V. G. Boldyrev, D. M. Sonechkin, V. I. Tulupov, and I. S. Khandurova determines correlation functions and spectral densities of the intensity of outgoing radiation over the spectral range 0·6–0·8 μm using measurements of the COSMOS-45 satellite. The results confirm the presence of a deep mesoscale minimum in the spatial spectrum of reflected radiation, and of a maximum corresponding to the characteristic dimensions of synoptic formations (cyclones and anticyclones).

The last paper in the book, by G. I. Morskoi, is a review article on studies of large-scale vertical motion in the atmosphere and is perhaps valuable for its extensive bibliography.

As might be expected in a book of this kind, the reproduction of satellite photographs is in general rather less than satisfactory and this deficiency is made worse by the quality of the paper, which is not sufficiently opaque. The main interest for most meteorologists is the information afforded by an independent approach to problems already treated in a somewhat different fashion elsewhere — primarily in the U.S.A.

T. H. KIRK

Random functions and turbulence. International series of monographs in natural philosophy, Volume 32, by S. Panchev. 257 mm × 183 mm, pp. xii + 444, *illus.*, Pergamon Press Ltd, Headington Hill Hall, Oxford, 1971. Price: £7·00, $18·75.

This book is based on a Russian edition first published in 1967 and is primarily intended to serve as an introduction to the statistical theory of turbulence. Thus the first two parts are devoted to a comprehensive description of the theory of random functions and their use in the investigation of turbulence. The final part considers the application of this theory to some selected topics; namely small- and large-scale atmospheric turbulence and numerical weather analysis and prediction. There is also an appendix written by Professor S. K. Kao of the University of Utah, which discusses large-scale Lagrangian aspects of turbulence in the atmosphere.

The author is professor of meteorology at the University of Sofia, Bulgaria, and as expected, his treatment of the topic is based on both the Western and Russian approaches — though there is a strong bias towards the latter. This should make the book quite useful to a research worker as it provides a fairly comprehensive description of the techniques and theories used by the Russians, though in later editions it would be helpful if the section on the modified Kolmogorov Hypothesis were extended. However, this book cannot really be recommended as an introduction to the subject as it is highly mathematical and the 'physics of the problem' tends to be rather obscured by the Russian approach which is based on structure and correlation functions. Before starting to refer to this book the student would probably be better advised to consult a book such as Hinze's* which is based more on the spectral approach to this topic. Interestingly enough, Panchev himself tends to underline this advice, as in Chapter 6 he admits that the spectral method gives a clearer physical insight into the subject.

The final sections of the book present some quite interesting results, though again, there is a strong emphasis on the Russian work. This is not really a disadvantage as many of the significant advances in these fields have originated from that part of the world and it will be useful to have a summary of this work available.

There are a number of misprints in the present edition and the reader needs to keep a critical eye on the equations, though here most of the errors relate to their numbering. The index could also be improved somewhat.

Despite its faults this book should serve as quite a useful reference for workers in this and allied fields provided they are willing to spend a little time familiarizing themselves with its layout and the notations used.

C. J. READINGS

OFFICIAL PUBLICATIONS

The following publications have recently been issued :

British Rainfall 1964. (London, HMSO. Price: £10.)

This publication provides a comprehensive summary of the rainfall of 1964 with discussion of both the incidence of rainfall and its variation from place to place, based on data from about 6000 observers. It contains numerous tables, graphs and maps.

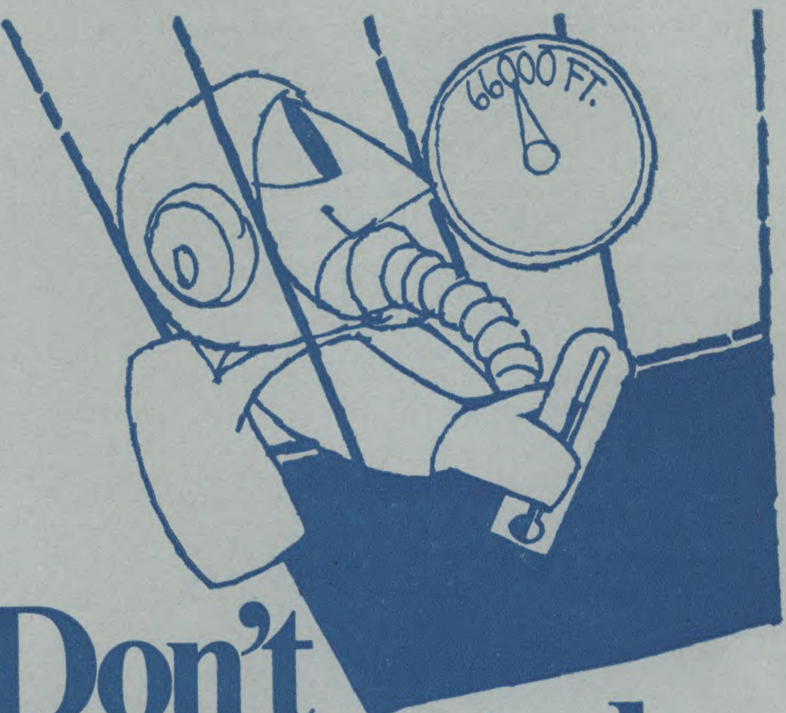
The 'General Table of Rainfall' forms Part I of the volume and contains annual and monthly rainfall totals and the rainfall of the wettest day where daily values are available. Part II discusses the main characteristics of the year and contains sections dealing with monthly, annual and seasonal rainfall, spells of rainfall deficiency and excess, frequency distribution of daily amounts of rainfall, heavy falls on rainfall days and in short periods, also Penman estimates of potential evapotranspiration. Part III contains the annual report of the 'Snow Survey of Great Britain' for the season 1963–64 by R. E. Booth, and 'Potential Evapotranspiration Data, 1964' by F. H. W. Green.

Marine climatological summaries for the Atlantic Ocean east of 50°W and north of 20°N. (London, HMSO. Price: £6.)

These summaries are part of a series of similar summaries covering the oceans of the world, which are to be published by nine countries, including the United Kingdom, in accordance with an internationally agreed scheme sponsored by the World Meteorological Organization. This first summary is for 1964 and it is intended eventually to publish similar summaries for each of the years from 1961 onwards.

The information in the tables relates entirely to observations made aboard ships on passage, or at ocean weather stations by observers of countries co-operating in the scheme. The results included in the tables depend upon large numbers of observations and production of the tables was facilitated by processing the data by means of programmes written for the KDF9 computer at the Meteorological Office, Bracknell.

* HINZE, J. O.; Turbulence. London, McGraw-Hill, 1959.



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A STUDY OF SNOWMELT FLOODS IN A MOUNTAINOUS CATCHMENT USING LIMITED METEOROLOGICAL DATA

By J. S. HOPKINS

Summary. A firm of consulting engineers required estimates of a plausible 'upper limit' to snowmelt flood discharge from a small mountainous catchment in the Elburz Mountains of northern Iran. Twenty years' daily maximum temperatures at the lower end of the catchment were analysed to derive plausible critical sequences of daily maximum temperature which were then applied to run-off/temperature relationships derived from observed snowmelt discharges.

Introduction. The catchment of the River Lar above Pulur in northern Iran has an area of about 725 km^2 and lies within the altitude range 2400 m (at Pulur) to over 5600 m (summit of Mount Demavend) — see Figure 1. The 20-year average daily maximum temperature at Pulur is below 0°C until the middle of February, and then rises to about 20°C by early June.

The rapid growth of Tehran has necessitated major water-storage projects in the Elburz Mountains[1] and a firm of British consulting engineers designing the spillway for a proposed dam just above Pulur required 'upper limits' to both snowmelt and rainfall flood discharge which could be considered feasible under the present climatic régime. This paper describes the technique adopted to compute a likely 'upper limit' to snowmelt discharge using the very limited meteorological data available.

Meteorological data available. The meteorological factors determining the rate of melt of a snow pack are :

(a) incident short-wave radiation,
(b) long-wave radiation exchange between the pack surface and the atmosphere,
(c) turbulent transfer of sensible and latent heat between the pack and the atmosphere,
(d) sensible heat gained from rain falling on the pack, and
(e) heat conduction from underlying soil.

An energy-balance equation can be constructed and measurements of long- and short-wave radiation fluxes, dry- and wet-bulb temperatures and wind speed over the snow surface inserted to compute the melt rate. In certain well-instrumented catchments, variations in snowmelt run-off have been very successfully simulated by this method.[2] The basic problem in the

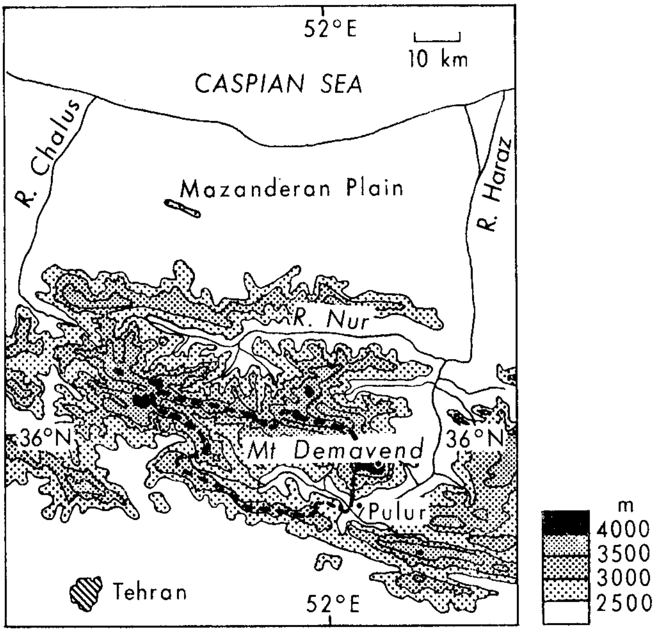

FIGURE 1—TOPOGRAPHY OF THE LAR AREA

Pecked lines denote catchment boundary.

Lar catchment was that the only meteorological variable available for any reasonable length of record was daily maximum dry-bulb temperature measured at Pulur since 1950. It was necessary to assume, therefore, that this one variable would provide a reasonable index of melt rate within the catchment (factors (a) to (d) above are undoubtedly well correlated with air temperature) and also of peak run-off from the catchment at Pulur.

Temperature/run-off relationships. Figure 2 shows the schematic snowmelt hydrograph at Pulur resulting from the diurnal variation of air temperature. The time of concentration, t, is a function of catchment size, shape, slope and soil; the depth and density of remaining snow will also affect the rate of run-off. For the Lar catchment, t is about 12 hours. Because of this reasonably short time of concentration, the peak flow Q_{max} can be separated simply into the base flow Q_b, which is the estimated flow which would have occurred without the latest flood event, and the direct run-off ΔQ. ΔQ is some function of the preceding day's maximum temperature (T_1) and Q_b some function of the maximum temperature 2 days before (T_2). A small component Q'_b could be considered a function of the maximum temperature 3 days before (T_3), but the size and water-retaining properties of the catchment are such that there is very little influence on the hydrograph 3 days after an initial event, be it rainfall or snowmelt.

To estimate the likely dependence of snowmelt rate on temperature at Pulur, an idealized catchment can be considered, as shown in Figure 3. The dimensions are :

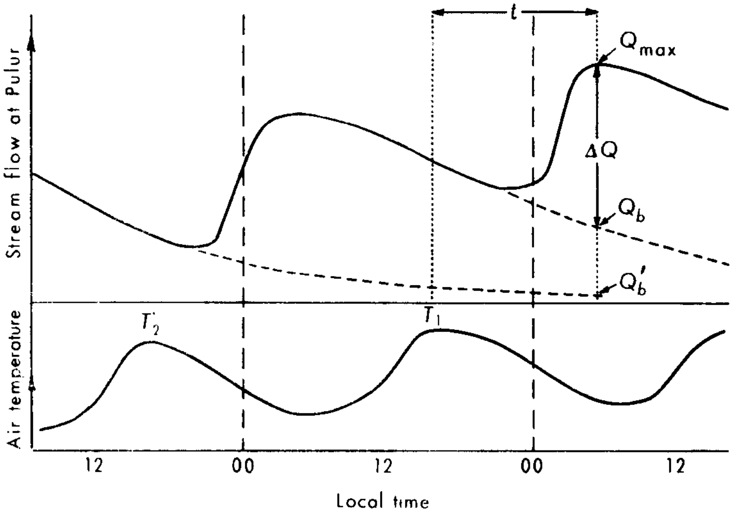

FIGURE 2—SCHEMATIC VARIATION OF AIR TEMPERATURE AND SNOWMELT RUN-OFF

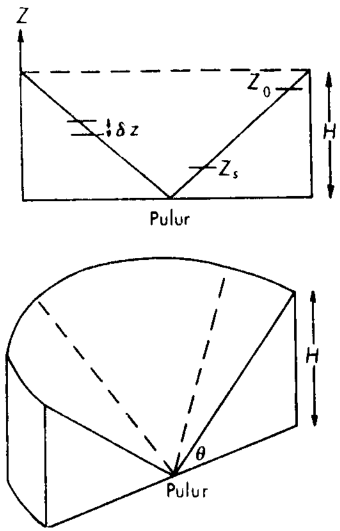

FIGURE 3—SIMPLIFIED CATCHMENT MODEL

H, the height of the watershed above Pulur
Z_s, the height of the snow-line above Pulur
Z_0, the height of the 0°C level above Pulur
δz, an element of the height variable z
and θ, the slope of the catchment.

Assume that heat transfer to the snow surface is linearly dependent on air temperature, T, alone, then :

Heat transfer $= kT$, where k is constant.

Melt rate per unit area of snow surface $= \dfrac{kT}{L}$, where L is latent heat of fusion.

Melt rate, R, over the whole catchment $= \displaystyle\int_{Z_s}^{Z_0} \frac{k\pi}{L \tan\theta . \sin\theta} . Tz\mathrm{d}z$

$$= k' \int_{Z_s}^{Z_0} z(T_P - \Gamma z)\mathrm{d}z,$$

where $\Gamma = -\partial T/\partial z$ is assumed to be a uniform lapse rate, T_P is temperature at Pulur and k' is another constant, thus

$$R = k' \left[T_P \frac{z^2}{2} - \Gamma \frac{z^3}{3} \right]_{Z_s}^{Z_0}. \qquad \ldots (1)$$

Two cases of interest arise :

(a) The 0°C level is below the watershed, i.e. $Z_0 < H$, then $Z_0 = T_P/\Gamma$ and equation (1) reduces to :

$$R = \frac{k'}{\Gamma^2}\left[\frac{1}{6} T_P{}^3\right] - k' Z_s{}^2\left[\frac{T_P}{2} - \Gamma\frac{Z_s}{3}\right].$$

(b) The 0°C level is above the watershed, i.e. $Z_0 > H$, then equation (1) reduces to :

$$R = k' \frac{T_P}{2}\left[H^2 - Z_s{}^2\right] - k' \frac{\Gamma}{3}\left[H^3 - Z_s{}^3\right]. \qquad \ldots (2)$$

At the time of the year when major snowmelt floods have occurred (late April to early June), daily maximum temperatures at Pulur are such that case (b) will apply; when temperatures at Pulur are above 10°C, less than 10 per cent of the catchment area will have sub-zero temperatures, if a lapse rate of 9 degC/km is assumed. On potentially critical snowmelt occasions when there is a low snow-line (i.e. Z_s small compared with H), equation (2) indicates that the melt rate over the catchment is linearly dependent on the temperature at Pulur.

Integration of R over the time during which T_P is above zero (i.e. morning to evening) gives the total direct run-off for the day; assumption of a consistent shape of hydrograph enables the *maximum* rate of direct run-off (ΔQ) to be taken as proportional to the *total* direct run-off for the day. A similar assumption about the consistent shape of the diurnal temperature–time curve allows the daily maximum temperature at Pulur to be taken as proportional to the time-integral of T_P. Thus, knowing from equation (2) that the instantaneous snowmelt over the catchment is linearly dependent on T_P, it can be assumed with reasonable confidence that the daily maximum temperature at Pulur provides a good index of the peak rate of snowmelt discharge on occasions when circumstances can be expected to produce 'extreme' run-off.

Observed snowmelt events. Strip-charts showing the variation of river level with time at Pulur are available since 1953, and 24 pure snowmelt flood events could be selected from this record to establish the peak snowmelt run-off/temperature relationships. Rating curves obtained from the Ministry of Water and Power, Tehran, were used to convert river level to river flow, and values of ΔQ and Q_b were extracted for each event. These values are plotted versus T_1 and T_2 in Figure 4. Such plots were attempted for each month of the snowmelt season in an attempt to take into account the variation of 'ripeness' of the snow pack through the season. However, because of the poor quality of a large number of the original river-level charts and the difficulty of obtaining pure snowmelt events (not complicated by additional rainfall run-off), the number of events on each monthly plot was insufficient to give any reasonable indication of Q/T behaviour. Accordingly, all months were combined in Figure 4.

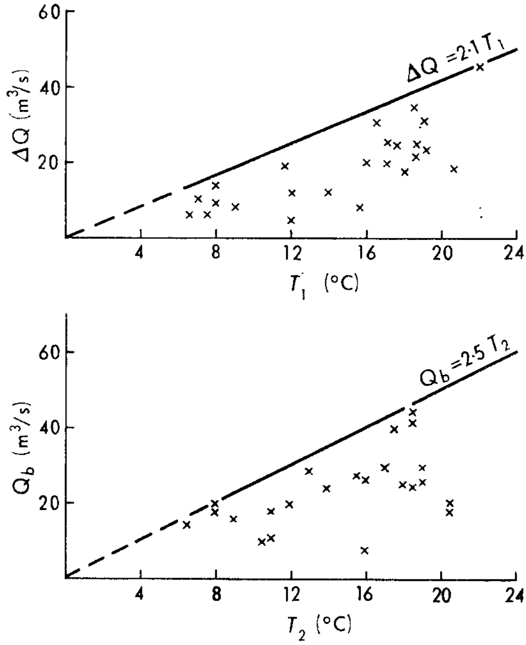

FIGURE 4—RELATIONSHIPS BETWEEN FLOOD FLOW AND PREVIOUS DAILY MAXIMUM TEMPERATURES AT PULUR

The Q/T relationship required is that which will give extreme run-off at a given air temperature when all unmeasured factors such as snow depth, snow water equivalent and height of snow-line combine critically. Such a relationship is provided by a curve drawn to envelop a large number of Q/T observations, and following the argument set out above, there is justification in drawing the envelope as a straight line.

If the assumption of Q/T linearity can be applied over the whole range of observed T values (and there is no real evidence that this is so), then the origin on the Q/T diagram provides a reference point for the enveloping line since, when the daily maximum temperature does not attain 0°C, no snowmelt run-off should be expected.

The lines obtained are :

$$\Delta Q = 2\cdot 1\ T_1 \qquad \ldots (3)$$

$$Q_b = 2\cdot 5\ T_2. \qquad \ldots (4)$$

They indicate that the maximum temperature 2 days before the event has slightly more influence on the magnitude of the peak flow Q_{max} than does the maximum temperature on the day immediately preceding.

Critical temperature sequences. To obtain plausible 'extreme' temperatures for substitution into equations (3)–(4), 20 years' (1950–69) daily maximum temperatures at Pulur were collected and analysed as follows. Starting on 21 January 1950, the daily maxima over an n-day period were scrutinized, and the smallest of these maxima was selected. A similar value for each n-day period commencing 21 January of each other year of record was extracted and then the maximum of these 20 values was displayed. This value is the highest daily maximum which was attained or exceeded on each of the n days following 21 January during the 20 years of record. A simple computer programme enabled the extraction to be repeated for successive n-day periods throughout the snowmelt season and for all values for n from 1 to 6. Figure 5

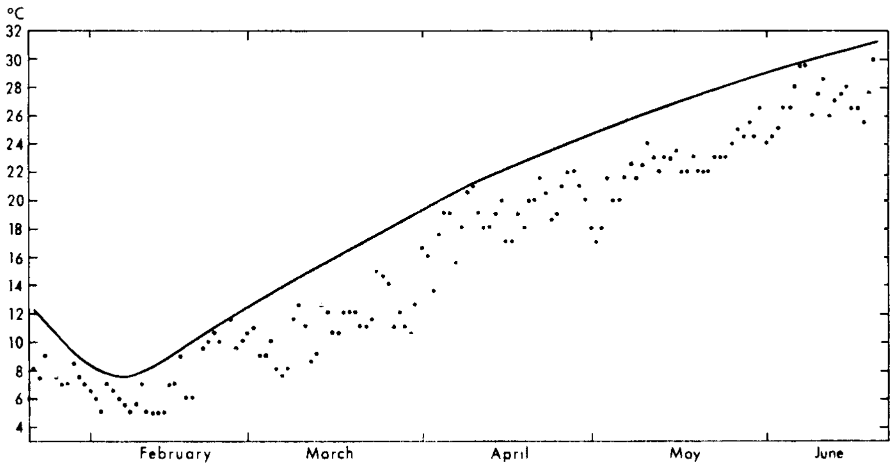

FIGURE 5—CONSTRUCTION OF EXTREME DAILY MAXIMUM TEMPERATURE CURVE FOR PULUR

$n = 2$ days

shows the temperature values obtained for 2-day periods plotted against time of year. The smooth curve drawn to envelop these observed points represents a working approximation to the 'upper limit' of daily maximum temperatures observed over 2 consecutive days. The drawing of the envelope was, of course, subjective, but consistency was achieved by comparison with other *n*-day periods, since the 'upper limit' of temperatures on 2 consecutive days must obviously be greater than or equal to that over 3 consecutive days. Figure 6 shows the 1- to 6-day 'extreme' temperature curves, together with the 20-year-average daily maximum temperature.

Sequences of daily maximum temperatures which are likely to produce extreme snowmelt run-off and yet are not inconsistent with the temperature observations over 20 years may be constructed from Figure 6.

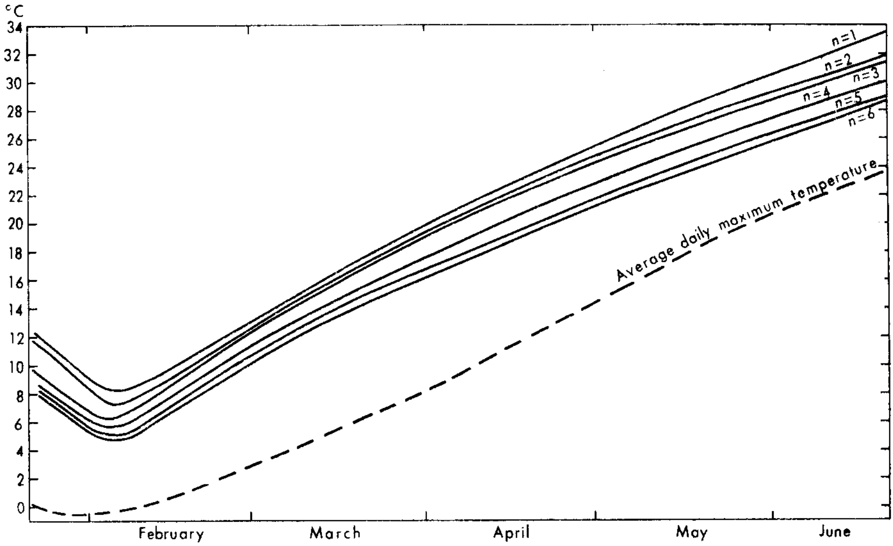

FIGURE 6—EXTREME *n*-DAY DAILY MAXIMUM TEMPERATURE CURVES FOR PULUR

Table I shows two possible sequences for early April, each assuming that 5 April has $T = 21{\cdot}0$°C, and two sequences for late May, assuming $T = 29{\cdot}6$°C on 25 May.

It is difficult to estimate how often these 'extreme' snowmelt run-off values may be attained, since the occurrence of an extreme flood event depends not only on the occurrence of high temperatures but also on the availability of a large amount of snow in the catchment. It might be considered that the early season values of Q_{max} in Table I would be approched more often than the late season values, because of the high probability of snow depletion during the course of the season.

Discussion. The demand for water-storage projects in the developing countries is likely to increase, and engineers will continue to require design figures based on physical considerations of hydrological and meteorological processes. The establishment of new climatological networks is proceeding rapidly in most countries but, until observations have been made over a number of years, the meteorologist must make the best use of the limited data which are available now. A simply based model, perhaps requiring a large number of assumptions and approximations, will often lead to a

TABLE I—EXTREME VALUES OF ΔQ, Q_b AND Q_{max} CALCULATED FROM EQUATIONS (3) AND (4) FOR TWO PERIODS DURING THE SNOWMELT SEASON

	April 2	3	4	5	6	7	8	9	10
Sequence 1									
T(°C)		16·7	17·4	21·0	20·4	20·0	18·6	16·8	
ΔQ(m³/s)			35·0	36·5	44·0	42·7	42·0	39·0	35·3
Q_b(m³/s)				41·7	43·5	52·5	51·0	50·0	46·5
Q_{max}(m³/s)				78·2	87·5	95·4	93·0	89·0	81·8
Sequence 2									
T(°C)	18·0	19·7	20·2	21·0	16·9	16·6			
ΔQ(m³/s)		37·8	41·3	42·4	44·0	35·5	34·8		
Q_b(m³/s)			45·0	49·2	50·4	52·5	42·2		
Q_{max}(m³/s)			86·3	91·6	94·4	88·0	77·0		

	May 22	23	24	25	26	27	28	29
Sequence 1								
T(°C)		24·6	26·6	29·6	28·4	28·0	25·3	
ΔQ(m³/s)			51·7	56·0	62·2	59·8	58·8	53·2
Q_b(m³/s)				61·5	66·5	74·0	71·1	70·0
Q_{max}(m³/s)				117·5	128·7	133·8	129·9	123·2
Sequence 2								
T(°C)	26·2	27·6	28·3	29·6	25·0	24·4		
ΔQ(m³/s)		55·0	58·0	59·2	62·0	52·5	51·2	
Q_b(m³/s)			65·5	69·0	70·9	74·0	62·5	
Q_{max}(m³/s)			123·5	128·2	132·9	126·5	113·7	

quantitative result which is of considerable value to the engineer, who without such guidance might be forced to 'over-design' the system in the interests of safety at considerable additional cost.

Acknowledgement. This work was performed for Sir Alexander Gibb and Partners, London.

REFERENCES

1. SCOTT, K. F., REEVE, W. T. N. and GERMOND, J. P.; Farahnaz Pahlavi Dam at Latiyan. *Proc Inst Civ Eng, London*, **39**, 1968, pp. 353–395.
2. ANDERSON, E. A.; Development and testing of snow pack energy balance equations. *Wat Resour Res, Washington*, **4**, 1968, pp. 19–37.

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DESERT DEPRESSIONS OVER NORTH-EAST AFRICA

By D. E. PEDGLEY
Centre for Overseas Pest Research, London

Summary. Desert depressions crossing north-east Africa during the spring of 1962 are described and a model developed, supported by simple physical and dynamical reasoning. A depression forms or intensifies over southern Tunisia or north-western Libya, within a surface trough extending northwards from the intertropical convergence zone, and ahead of a shallow trough in the upper westerlies where positive vorticity advection is to be expected. It moves eastward to Egypt in a lower tropospheric baroclinic zone parallel to the African coast, baroclinicity apparently being the result of differential heating on two scales — in association with the hemispheric circulation and with the land–sea contrast. It maintains a quasi-steady state and develops a well-marked cold front extending southwards from the centre along the axis of the thermal ridge in the lower troposphere.

Introduction. A characteristic feature of the weather over north-east Africa during the spring, February to June, is the occurrence of spells of southerly winds at a time when climatological charts (e.g. Thompson[1]) show predominant directions are between north and east. These southerlies bring high temperatures and low dew-points, and sometimes they are strong enough to give widespread duststorms. This type of weather, called khamsin in the United Arab Republic (from the Arabic for 'fifty', and applied to the fifty days following the Coptic Easter) and ghibli in Libya (an Arabic word for 'south'), can cause considerable personal discomfort.

With the setting up of a synoptic network over Egypt at the beginning of this century, a relationship was soon discovered[2] between these spells of southerly winds and the approach of depressions from the west, crossing either the Mediterranean or the desert just south of the coast of north Africa. With the accumulation of synoptic analyses over a number of years it was possible to discuss [3,4] the synoptic climatology of these 'khamsin depressions'. About half of them were found to be of the 'desert' or 'Sahara' type, but the fraction was greater in April and May. Desert depressions are not frequent: an average of about six each year can be expected, the latest usually occurring about mid-June. With each depression, khamsin weather lasts a few days, rarely more than four.

Following the development of classical Norwegian ideas on the structure of depressions, frontal structures were given [5–8] to desert depressions over Egypt, but in the absence of data to the west their origin was obscure. When a synoptic network had been established over north-west Africa in the 1920s it became clear that at least some desert depressions had an origin just south of the Atlas Mountains,[9] whilst other, 'Sahara-Sudan', disturbances, developing over the sahel of West Africa south of the Sahara, in the region from Senegal to the Niger Republic, could at times be traced north-eastwards as far as Egypt.[10–12] But the nature of these latter disturbances was also obscure.

An extension of the frontal concept postulated that desert depressions formed along a front separating cool, polar air over the Mediterranean from warm air over north Africa that had come from Arabia and the Red Sea,[13] but it was later pointed out[14] that most khamsin depressions are secondaries to larger depressions over Europe or the northern Mediterranean. However, it was clear that the frontal structure was not always simple because, although the cold front is usually well marked, the warm front is frequently found to be diffuse.[15–17]

At present, although there is general acceptance of a frontal nature of desert depressions,[18–20] their structure, origin and evolution are still poorly understood, no doubt in part a result of the sparseness of data, especially from the middle and upper troposphere. A relation between surface disturbances over north Africa and waves travelling eastwards in the upper westerlies has been pointed out [21–24] and this paper attempts to extend current knowledge of this relationship, and more generally of the nature of desert depressions, by presenting the results of a study of the depressions that crossed north-eastern Africa during the spring of 1962.

Data and analyses. For the period January to June 1962, a vertical time-section was constructed for Tobruk, Libya (32° 05'N 23° 59'E, T in Figure 3), showing winds measured by radar four times each day, and temperatures measured by radiosonde twice each day. This section was used to select days on which troughs seemed to pass overhead at 500 mb, and days on which cyclonic centres seemed to move eastwards to the south of the station. The existence of these disturbances was then checked using the working charts available in the forecast office at RAF El Adem (31° 51′N 23° 55′E), about 30 km south of Tobruk, and also the published charts in the *Daily Weather Report* of the Meteorological Department of the United Arab Republic.

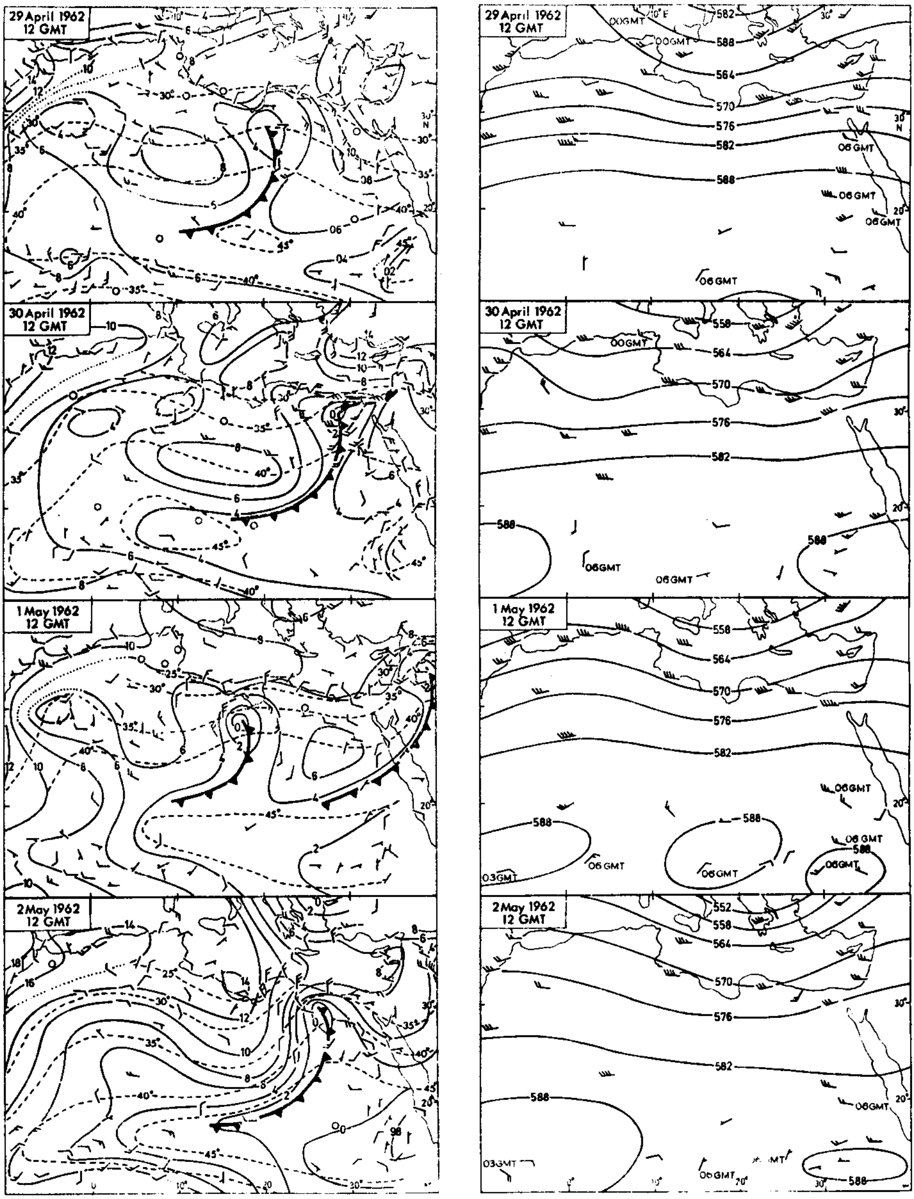
Fourteen desert depressions crossing north-eastern Africa could be discerned from the time-section during the six-month period. To study their structure, daily 12 GMT synoptic analyses were prepared for the surface and for 500 mb on a scale of 1:20 million over Africa north of the equator, the Mediterranean and Europe south of 45°N. Sufficient analyses were constructed to follow the development of each depression as it crossed north-east Africa. For such analyses, because the synoptic network is so sparse, it is desirable to have observations from the same places each day. This was possible where data were available either in published form (*Daily Weather Report* of the United Arab Republic, *Synoptic Bulletin* of the Sudan Meteorological Service, *Overseas Supplement* of the British *Daily Weather Report* and *Northern Hemisphere Data Tabulations* prepared by the National Oceanic and Atmospheric Administration) or from the original registers (in the case of Libya, data were made available by courtesy of the Libyan Meteorological Department). Elsewhere, reliance had to be placed on 12 GMT data routinely available through normal meteorological communications channels.

If only one surface chart each day is used, it is also desirable to have off-time data, at least from stations affected by disturbances, to assist in the location of centres and other synoptic features. Observations at 6-hourly intervals were available for the United Arab Republic and Sudan from the published sources quoted above, and at 3-hourly intervals for Libyan stations, except at El Adem, where hourly observations were available.

On the surface charts, winds were plotted and isobars and isopleths of potential temperature (potential isotherms) drawn. The latter were used to reduce the effects on air temperature of differences in altitude between observing stations. On the 500-mb charts, winds were plotted and contours and potential isotherms drawn. Some data for 00 or 06 GMT previous to the chart time had to be used from some stations where 12 GMT data were not available at 500 mb. This was usually on the periphery of the analysis area and never in the vicinity of a disturbance.

At both levels, disturbances lasting a few days could be tracked over distances of several thousand kilometres without much recourse to interpolation. Despite the sparse network, it was possible to draw consistent analyses on successive days without relying heavily on continuity. This success, contrasting with difficulties often encountered during routine analysis, can be attributed to the use of observation sequences which are often not available routinely.

A pair of desert depressions. Figure 1 shows a chart sequence from 29 April to 2 May 1962. During this period two depressions moved eastwards along remarkably similar tracks near 30°N, starting south of the Atlas Mountains and continuing just south of the African coast. Each had a central pressure around 1000 mb and maximum winds of 20 to 30 kt, sufficient to give spells of rising sand, or duststorms, lasting a few hours. The centres lay



(a) Surface
——— Isobars at 2-mb intervals
– – – Potential temperature (°C)

(b) 500-mb contours
——— Contours (geopotential decametres)

FIGURE 1—SEQUENCES OF 12 GMT CHARTS FOR THE PERIOD 29 APRIL TO 2 MAY 1962
International symbols are used for plotting the winds.

at the northern limits of troughs extending from the intertropical convergence zone. Southerly winds on the eastern sides of these troughs were present as far south as about 15°N. Maximum day-time potential temperatures approached 40°C as far north as 30°N, and with the second depression, maximum potential temperatures reached 45°C at 25°N. Temperatures exceeding 40°C are observed in Cairo on an average of two days in each of the months May and June.[25] Along the coast ahead of each depression temperatures in the easterlies remained mostly in the mid-20s, leading to a strong temperature contrast with the southerlies and the development of a coastal front.

At 500 mb the flow was dominantly westerly with small-amplitude troughs and ridges moving eastwards. On each chart the surface depression was found to lie near or just ahead of a trough axis where it crossed the coast.

To illustrate changes in surface weather near and to the south of the desert depressions, Figure 2 gives 3-hourly sequences of pressure and winds at Gialo and Kufra (G and K in Figure 3). For times other than 12 GMT, pressures have been corrected for diurnal variation by using mean differences between pressures at 12 GMT and at other times. Means for May 1962 were used. At Gialo, the reversal from southerly winds ahead of the first depression to northerlies in its rear is well shown. The backing through east at 12 GMT on the 29th suggests the centre passed south of the station. North to north-

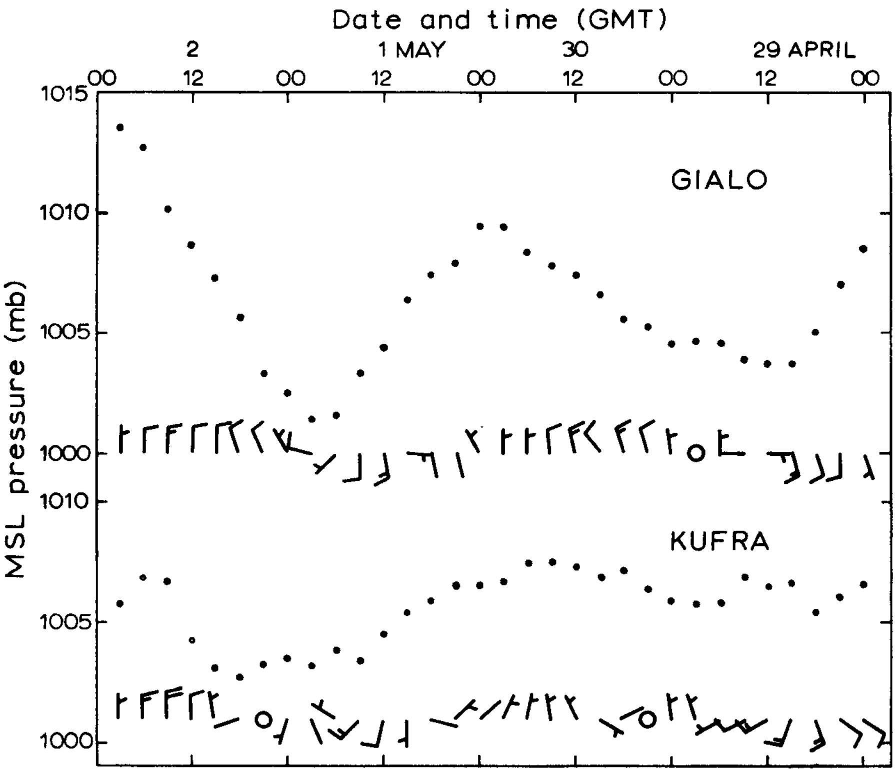


FIGURE 2—SEQUENCES OF 3-HOURLY OBSERVATIONS OF PRESSURE AND WIND AT GIALO AND KUFRA FOR THE PERIOD 29 APRIL TO 2 MAY 1962

● Pressure

west winds are at first light, probably as a result of increased friction following development of the night-time temperature inversion. With the passage of the ridge between the two depressions, winds decreased and then reversed direction to south-easterly before increasing again ahead of the second depression. A veer to north-west late on the 1st suggests the centre passed north of the station.

At Kufra, the pressure trace is more complex. The first dip appears double but this may be unreal because of uncertainties in the corrections for diurnal variation. With both depressions, southerlies are followed by spells with light and variable winds, corresponding to the passage of cols south of the centres. The veer in direction between the northerlies of the 30th and southerlies of the 1st was associated with the eastward passage of an anticyclone north of Kufra. By 12 GMT on the 2nd, good northerlies had set in again with a sudden rise of pressure, showing the passage of a cold front.

To illustrate in more detail the lower tropospheric structure of the second depression, Figure 3 gives the flow patterns at 850 and 700 mb for 12 GMT on 2 May 1962. At 850 mb, a trough extended northwards from the low-latitude easterlies and the centre was still present, but displaced a little north compared with the surface. Southerlies on its eastern side were reported as far south as 10°N. At 700 mb there was little evidence for a closed centre; rather there was a trough in the westerlies just west of Tobruk — in much the same place as the trough at 500 mb, but at 700 mb it was more clearly defined. The trough extending northwards from low latitudes was no longer present, nor were extensive southerlies. Instead, the subtropical anticyclonic belt at about 15°N had two cells, with a col lying above the region of light southerlies at 850 mb. The latitude of the axis of this anticyclonic belt decreased with

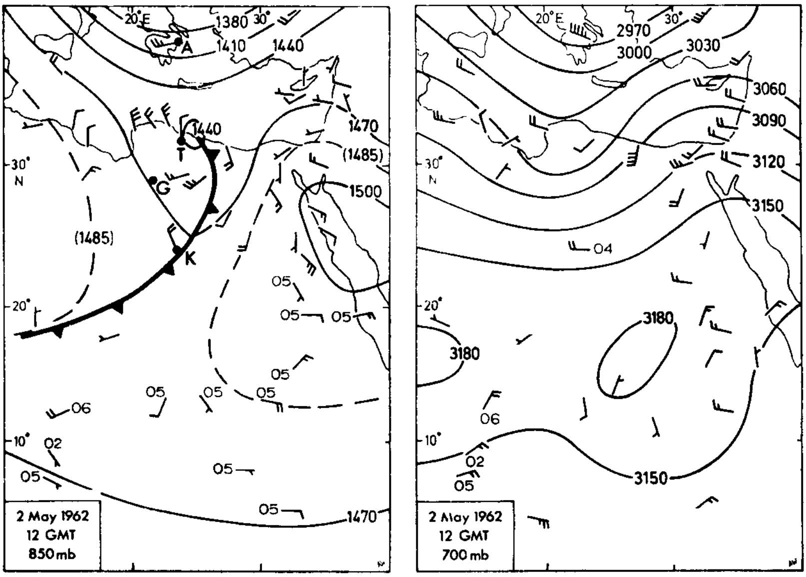


FIGURE 3—CONTOUR CHARTS FOR 12 GMT ON 2 MAY 1962 AT 850 mb AND 700 mb

Letters A, G, K and T indicate positions of Athens, Gialo, Kufra and Tobruk referred to in text. Contours in geopotential metres.

altitude — from over the Mediterranean at the surface, through 30°N at 850 mb, to near 10°N at 500 mb.

Part of the Tobruk time-section is given in Figure 4; it extends from 00 GMT on 29 April to 00 GMT on 3 May and temperatures have been converted

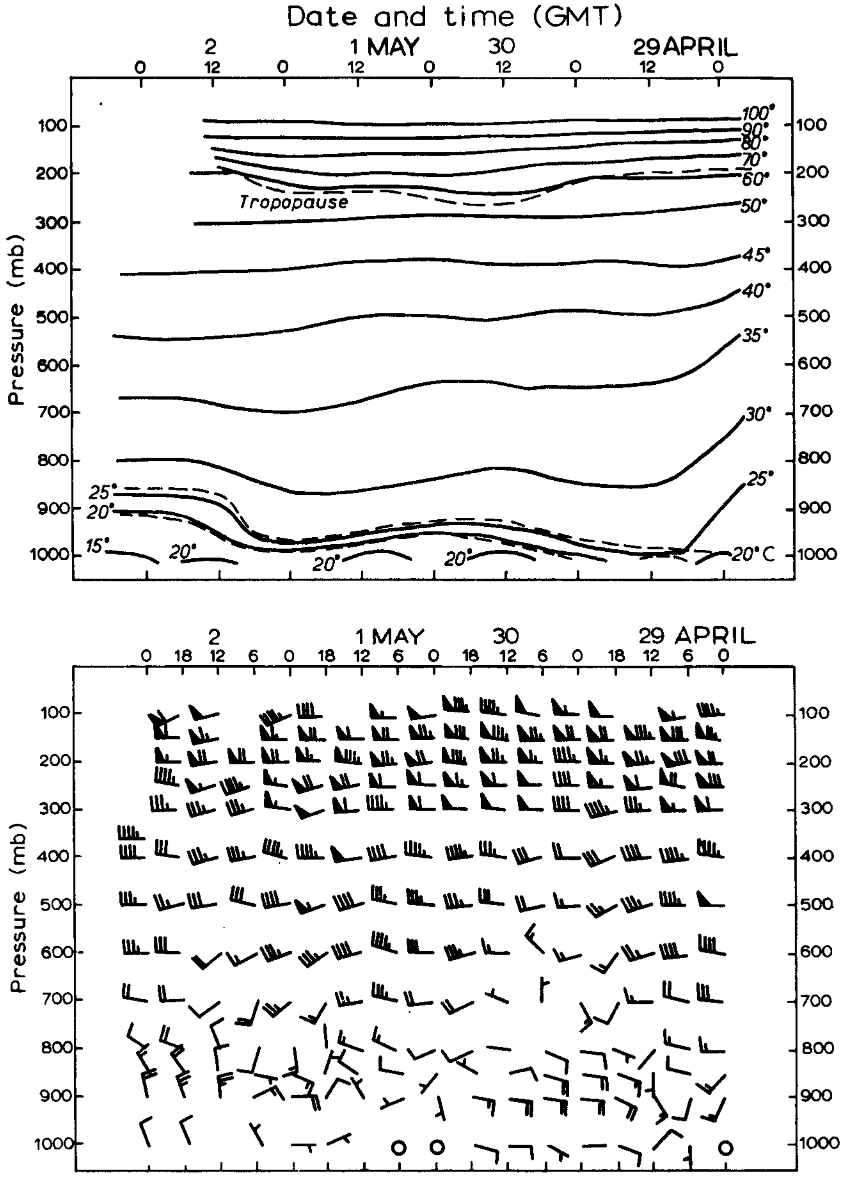


FIGURE 4—VERTICAL TIME-SECTION AT TOBRUK FOR THE PERIOD 00 GMT ON 29 APRIL TO 00 GMT ON 3 MAY 1962 SHOWING POTENTIAL TEMPERATURES BASED ON TEMPERATURES MEASURED BY RADIOSONDE AND WINDS MEASURED BY RADAR

The depth of the inversion near the surface is shown by two pecked lines.

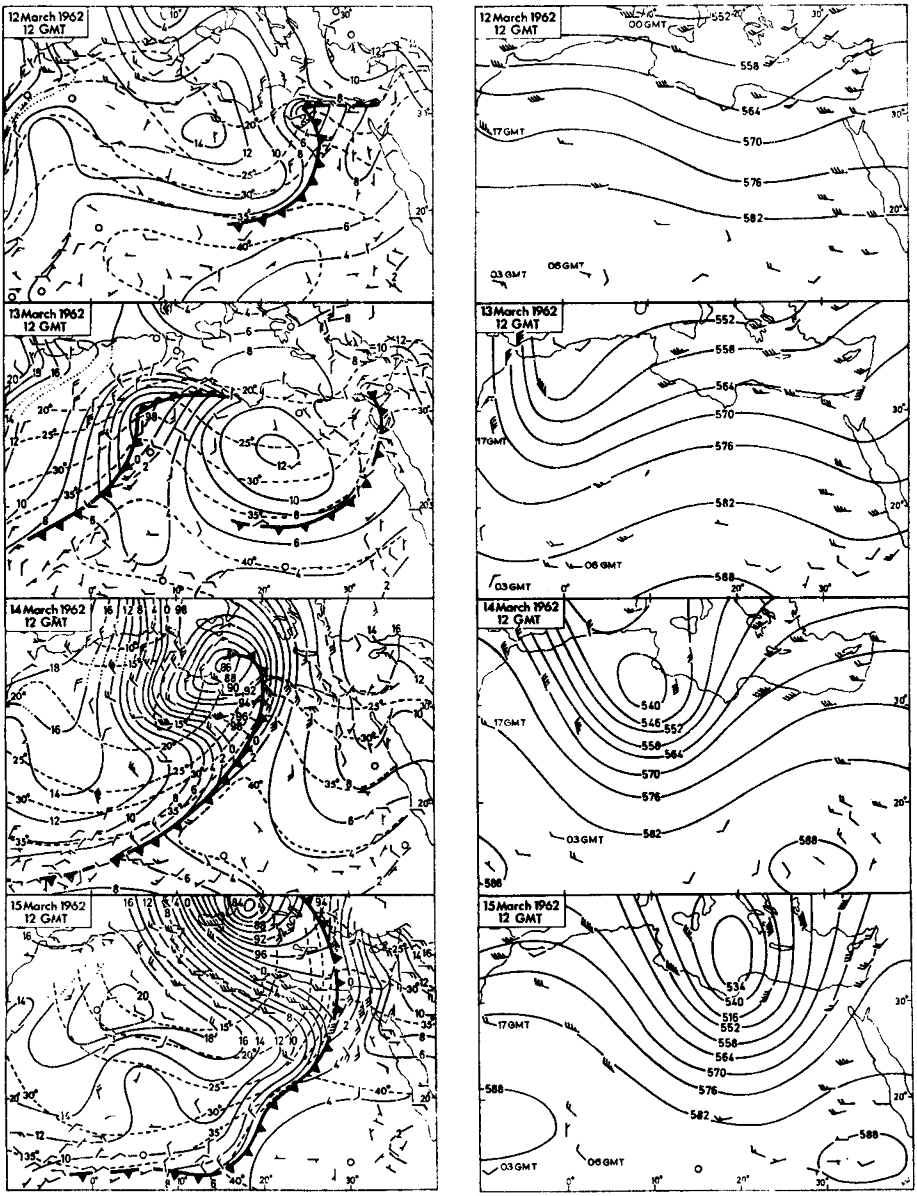
to potential temperatures. A prominent feature is the shallow layer of cool air near the surface, surmounted by an inversion about 50 mb deep. With onset of the north-westerlies, by 00 GMT on the 3rd, the top of the cool layer had risen to near 900 mb. It is the presence of this shallow 'maritime layer' that causes the strong horizontal temperature contrast by day along the coast, leading to the formation of a coastal front separating cool easterlies from warm southerlies. In some respects it resembles a warm front but its position is topographically determined. In addition, the cool layer causes pressures at coastal stations to be higher than would be the case if the layer were absent, thereby leading to difficulties in analysis since many reporting stations are on or near the coast. For example, a layer from 1000 to 950 mb with a potential temperature 25°C gives a pressure increase of about 1·5 mb compared with an occasion when the potential temperature is 35°C.

Below 700 mb there were considerable variations of wind direction throughout the period. Easterlies extended up to about 750 mb with the first depression and to about 850 mb with the second. It is not possible to decide from the section alone whether these are the levels above which there is no closed circulation, or whether they are the levels at which the centres passed overhead. From Figure 3 and similar charts for the first depression, it is clear that the circulations almost certainly did not extend above 700 mb. At higher levels, disturbances in the westerlies were weaker, but the trough passing between 12 and 18 GMT on the 2nd was traceable into the high troposphere.

An example of rapid development. Figure 5 shows a chart sequence from 12 to 15 March 1962. Again there were two disturbances but they had markedly different histories. From 11 to 13 March, a desert depression crossed Libya and the United Arab Republic along a track closely similar to those shown in Figure 1. Furthermore, in general structure and behaviour there was little difference between this depression and the two discussed previously.

A second disturbance developed quickly between 12 and 13 March south of the Atlas Mountains. By the 14th it had moved to the central Mediterranean and deepened to about 980 mb. Its circulation became very vigorous and a broad area of strong southerlies with duststorms was separated from westerlies by a well-marked cold front sweeping rapidly eastwards. Between 12 GMT on the 14th and the same time on the 15th, temperatures fell from 34° to 18°C at Gialo and from 33° to 20°C at Kufra. Figure 6 shows a 3-hourly sequence of observations at these same places to illustrate the sharpness of this front. At Tobruk, southerlies exceeded 50 kt at 900 mb at 18 GMT on the 14th. At El Adem, surface south-south-easterlies at 25 kt blew continuously from 10 GMT onwards with much rising sand or duststorms, visibility often less than 2 km, and dew-points around 0°C. Temperatures remained remarkably steady at between 24 and 27°C but wind speeds increased to 30 kt by 21 GMT with gusts to 44 kt and visibility less than 500 m at times. The front passed at 2320 GMT with a sudden wind veer to westerly, a temporary decrease of speed and a temperature fall of 5 degC in the following hour, but by 10 GMT on the next day wind speeds were again 30 kt or more with visibility below 200 m at times, and the sun was unable to cast shadows until 0830 GMT.

Upper troughs and surface disturbances. Each of the 14 desert depressions crossing north-eastern Africa from January to June 1962 was



(a) Surface
——— Isobars at 2-mb intervals
– Potential temperature (°C)

(b) 500-mb contours
——— Contours (geopotential decametres)

FIGURE 5—SEQUENCES OF 12 GMT CHARTS FOR THE PERIOD 12–15 MARCH 1962

International symbols are used for plotting the winds.

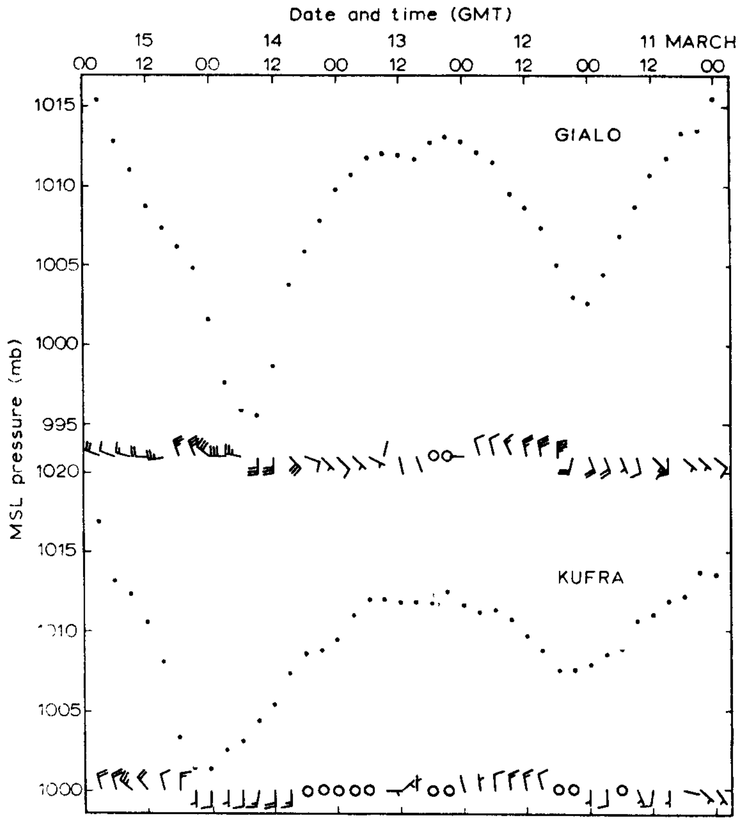


FIGURE 6—SEQUENCES OF 3-HOURLY OBSERVATIONS OF PRESSURE AND WIND AT GIALO AND KUFRA FOR THE PERIOD 11–15 MARCH 1962

● Pressure

associated with a shallow trough in the upper westerlies. For 12 of them the trough axis passed Tobruk on either the same day as, or the day following, the passage of the desert depression; for the remaining 2 the delays were two and three days. During the same six-month period there were 17 further troughs that were not associated with desert depressions. However, 9 of them were preceded by definite surface cold fronts (including the front on 14 March). On 6 of these 9 occasions the trough axis passed Tobruk on either the same day or the day following the passage of the front. For the 3 remaining fronts the delay was two or three days. Of the 8 troughs with which neither a desert depression nor a surface cold front could be identified, 2 occurred in early January and 3 in late June, at times when desert depressions are unlikely to have been present.

Table I shows that the cold fronts unaccompanied by desert depressions were most frequent during the first half of spring. Even though cold fronts could be recognized easily over the land, this was not always so over the sea, particularly when a cool, maritime layer persisted near the surface. This difficulty in analysis tended to increase during the season as the airstreams became potentially warmer than the sea surface. In such a situation a front

TABLE I—NUMBER OF TROUGHS CROSSING TOBRUK AT 500 mb DURING JANUARY TO JUNE 1962, AND THE NUMBERS ASSOCIATED WITH DESERT DEPRESSIONS OR COLD FRONTS

	Desert depressions	Cold fronts	Neither	Total
January	1	1	2	4
February	1	2	1	4
March	3	4	1	8
April	4	1	0	5
May	2	1	1	4
June	3	0	3	6
Total	14	9	8	31

might ride over the maritime layer. On the other hand, there were occasions when the passage of a front was represented by little more than a deepening of the maritime layer in association with the onset of northerly winds. There were also occasions when a front could be traced northwards to a disturbance over the Mediterranean or Europe; this was most likely with a vigorous upper trough preceded by a well-marked front.

The passage of a cold front was often clearly defined as far south as 20°N. At lower latitudes analysis was more difficult, but occasionally fronts could be traced into the intertropical convergence zone which would consequently be displaced southwards, sometimes by five degrees of latitude. By contrast, warm fronts were almost always diffuse except where they were represented by coastal fronts separating, for distances of some hundreds of kilometres ahead of each depression, warm and dry southerlies from cool and moist easterlies.

A cold front seldom appeared to trail westwards into a following depression. Each front marked the leading edge of a new burst of polar air penetrating the tropics. At low latitudes, where the direction of the east to north-east trade winds was often only slightly disturbed by the passage of a desert depression, the arrival of a front was typically associated with an increase in speed and perhaps a slight backing of direction. Changes were more in the nature of pulses in the trade with little or no tendency for southerly components to develop ahead of them.

On 21 March, a wave disturbance moved north-eastwards along a vigorous cold front over Cyrenaica. It was associated with widespread duststorms, the worst of the season at El Adem, where surface winds reached 50 kt in gusts, visibility was reduced to 100 m and the haze top was observed from aircraft to be near 4 km above the ground.

Clouds and rain. Clouds accompanying the desert depressions during 1962 were largely confined to upper levels. Medium clouds were characteristically chaotic, appearing in one or more layers with much altocumulus castellanus. Bases were usually above 600 mb and often above 500 mb. Their horizontal distribution was related to the flow pattern at 500 mb, clouds often appearing in bands or sheets ahead of an upper cold trough and above the surface depression. Sometimes the southern extremity of a medium-cloud system would be at a latitude greater than that of the depression centre, when the approach and passage of a depression would be cloudless, or with only cirrus or cirrostratus. With the larger and more vigorous cold troughs, medium clouds extended as far south as 20°N and sometimes linked with clouds south of 15° or 10° N associated with the intertropical convergence zone.

Development of virga and extensive glaciation typically accompanied medium-cloud masses, but precipitation more intense than 'scattered drops' rarely reached the ground, presumably because evaporation was so effective in the deep layer of dry air between cloud base and the ground. There was circumstantial evidence for such evaporation in the presence of (a) extensive and deep virga not reaching the ground, (b) small-scale, erratic pressure fluctuations of about one millibar, (c) gusty surface winds with variable directions. Sometimes, measurable amounts of rain fell, even with thunder, as at Gialo during the afternoon of 1 May. Such rains were unusual south of 30°N and rare south of 25°N. Apparently complete glaciation of the medium cloud led to either sheets of altrostratus with a variable density or to extensive patches of dense cirrus. The few reports of cloud tops from aircraft were mostly of between 400 and 250 mb, but cirrus or cirrostratus was sometimes present at altitudes, measured or estimated, near 200 mb.

In the maritime layer, there were sometimes some shallow stratocumulus clouds along the coast, but day-time heating dispersed this cloud if it spread inland. Between the surface cold front and the axis of the following upper cold trough, the maritime layer often increased in depth, allowing the development of cumulus, especially over land by day, but such clouds became deep enough for the growth of showers only near the axis of vigorous cold troughs. Even then, showers were usually confined to the coast, and occurred particularly when winds had veered north of west behind the trough axis. Sometimes small cumulus clouds were reported as far south as Kufra. On the few occasions when closed vortices, or cold pools, in the middle and upper troposphere penetrated as far south as 30°N, showers and thunderstorms became heavy and widespread along the coast, and were not confined to daylight hours.

Discussion. The fact that each of the 14 desert depressions lay beneath, or just ahead of, a shallow trough in the westerlies at 500 mb suggests a connection between the two types of disturbance. Tantawy,[24] using composite charts for khamsin days in March of three years, found the surface depression lay farther east, nearer the ridge axis. Petterssen[26] has discussed the relation between positive vorticity advection in advance of upper tropospheric troughs and cyclogenesis in the lower troposphere. Each desert depression lay below part of its associated upper trough where positive vorticity advection is to be expected, suggesting strongly that such advection is a factor in the development of desert depressions. However, cyclonic development at the surface also depends on the thermal field in the lower troposphere. This latter is represented well by the field of surface potential temperature, for when convection extends from the ground through a layer to 850 or 700 mb then the surface potential temperature will be little more than the potential temperature throughout that layer. Such is the situation over north Africa on most occasions at 12 GMT, but not over the sea when a maritime layer of cool air is present at the surface.

Figures 1 and 5 show that the surface potential isotherms form a wavy pattern of cold troughs and warm ridges superimposed on an essentially east–west alignment with colder air to the north. Each desert depression is associated with a warm ridge, and a cold trough extends southward in its rear. The thermal advection field, as represented by these isotherms and by the isobars, favours cyclogenesis ahead of each centre, and anticyclogenesis in its rear, leading to an eastward movement. Moreover, that part of the cyclogenesis associated with positive thermal advection ahead of the centre is likely to be much greater than the cyclogenesis associated with upper vorticity advection. This is because the first part will be large in the region of strong thermal gradients, whereas the latter will be small since wind speeds (and vorticities) will be weak compared with thermal wind speeds. Now, it is observed that a desert depression moves in a quasi-steady state, with little or no intensification and a retention of its configuration of isobars and isotherms, despite persistence in a region favourable to cyclogenesis due to upper positive vorticity advection. It is likely, therefore, that there is a mechanism which prevents the continued distortion of the thermal field that is expected with continued cyclogenesis. Such a mechanism is non-adiabatic heating and convective mixing within the northerly winds behind a depression. It is here that the warming of the lower troposphere as it flows from sea to land will reduce the rate of advection of isotherms, with the result that distortion of the isotherms is less than that which might have been expected from advection alone, and a brake is placed on the rate of development. This brake is applied diurnally, therefore a diurnal oscillation in the rate of development is possible. With only one surface analysis each day, such an oscillation could not be verified in this study.

A likely structure for the maintenance of a desert depression that emerges from these considerations is of a trough in the upper westerlies overlying a region with a strong meridional temperature gradient. This gradient has been associated with the coolness of the Mediterranean in contrast to north Africa, even to the extent of postulating the existence of a 'Mediterranean front'[20] or a 'subtropical front'.[27] But the contrast of surface temperatures is observed to increase to a maximum in late spring, by which time the incidence of desert depressions is decreasing. This increase is illustrated by Table II which gives monthly means of sea surface temperatures in the square

TABLE II—COMPARISON OF MONTHLY MEAN TEMPERATURES AT THE SURFACE

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						degrees	*Celsius*					
Sea surface in square 32–33°N 24–25°E	17	16	16	17	19	22	25	26	25	24	21	19
Daily maximum at Gialo (29° 02′N 21° 34′E 61 m ASL)	20	22	26	30	35	38	37	37	36	33	27	22
Difference	3	6	10	13	16	16	12	11	11	9	6	3

Sea temperatures from the atlas of the Royal Netherlands Meteorological Institute,[28] and Gialo temperature from Fantoli.[29]

32–33°N 24–25°E, and of daily maximum temperature at Gialo, where advective cooling from the sea is almost certainly small. At higher levels, there are no observations in the desert south of Tobruk, but it is instructive to consider temperature differences between Tobruk and Athens (A in Figure 3), about 700 km apart and close to the 24°E meridian. Table III shows monthly means for 850 and 750 mb. For the period February to June, the difference for both levels is greater than about 4 degC; November is the only other month with a comparable difference. Considering 850 mb, the seasonal variation in this temperature difference suggests the north–south movement of a latitudinal belt of maximum meridional gradient across the

TABLE III—COMPARISON OF MONTHLY MEAN TEMPERATURES AT 850 mb AND 700 mb

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						degrees	*Celsius*					
850 mb												
Athens	0·9	1·8	2·5	6·2	11·1	14·5	16·4	17·2	13·1	9·9	5·6	2·4
Difference	3·5	4·1	4·7	5·3	3·9	4·3	2·7	2·2	3·8	3·8	4·3	3·5
Tobruk	4·4	5·9	7·2	11·5	15·0	18·8	19·1	19·4	16·9	13·7	9·9	5·9
Difference	1·3	1·9	4·1	4·3	5·6	4·5	3·7	3·5	4·7	4·9	2·7	1·5
Gialo (estimated)	5·7	7·8	11·3	15·8	20·6	23·3	22·8	22·9	21·6	18·5	12·6	7·4
700 mb												
Athens	−7·4	−6·2	−5·9	−3·0	−0·7	4·1	6·5	7·1	4·3	1·4	−2·6	−5·4
Difference	3·9	3·8	4·5	4·9	5·4	4·1	3·6	3·2	3·1	2·5	3·8	3·9
Tobruk	−3·5	−2·4	−1·4	1·9	4·7	8·2	10·1	10·3	7·4	3·9	1·2	−1·5

Data from tabulations of the World Meteorological Organization;[30] Gialo estimates based on surface data,[29] assuming a constant altitude of 1·50 km for the 850-mb level — probably correct to within 0·02 km.[1]

eastern Mediterranean — northwards in spring and southwards in autumn — and this suggestion is supported by the patterns of 850-mb isotherms over north-east Africa in January, April and July given by Thompson,[1] even though these latter are based on scanty data from the Nile valley and from north-west Africa. Such a seasonal movement of the isotherms is to be expected in association with the well-known seasonal changes of hemispheric circulation patterns, and must be considered to be partly of dynamic origin. Maximum meridional gradients over the Mediterranean are therefore observed in April and November. In April and following months, the meridional gradient over north-east Africa, being south of the Mediterranean, will be less than the maximum. By contrast, in March, and possibly also in February, the belt of maximum gradient should be over north-east Africa. Thus, in so far as seasonal changes of the hemispheric circulation control the meridional temperature gradient over north-east Africa, desert depressions would be expected to be most frequent in March.

There is still the more local effect of differential heating of land and sea to be considered. In the absence of temperature soundings south of Tobruk, an estimate of 850-mb temperatures can be made using afternoon maximum air temperatures near the ground, and assuming a dry adiabatic lapse rate from the ground to 850 mb. At Gialo, for example, this is almost certainly a reasonable assumption in all months, except perhaps January. Table III gives temperatures at 850 mb over Gialo estimated in this way, from which it is seen that the difference between Gialo estimates and Tobruk measurements increases to a maximum in May. This displacement of the timing of the maximum by two months can be ascribed to an increasing differential heating from March to May over-compensating the reduction in gradient caused by the northward movement away from north-east Africa of the belt of maximum gradient associated with changes in the hemispheric circulation. From January to March, the rapid increase of gradient over north-east Africa is attributable to the two processes working together. That differential heating between land and sea plays a part in the development of desert depressions is further supported by the similar depths of the layers in which cyclonic circulation and overland convection occur. Moreover, the baroclinicity in April has been shown[31] to lie mostly below 850 mb.

Tables II and III show that substantial gradients persist into the summer at both the surface and 850 mb, although temperature contrasts at the surface are greatly increased by the presence of the shallow maritime layer over the sea. The almost complete absence of desert depressions in that season is therefore likely to be related to a reduction in the frequency of occurrence of areas of positive vorticity advection aloft. During the summer, upper troughs do not extend southwards as far as in the spring, an occurrence related to the seasonal northward migration of the axis of subtropical anticyclones at 500 mb — from near 10°N in January to near 25°N in July.[1,32] This northward movement is likely to be most rapid in late May or early June when there is a correspondingly rapid movement of the subtropical jet near 200 mb to about 40°N.[33,34]

Desert depressions are often observed to form over southern Tunisia or north-western Libya, or to intensify in the same region having previously moved eastwards as diffuse centres or open troughs close to the southern side of the Atlas Mountains. Surface pressure falls in this region have been shown[24] to accompany cyclonic vorticity at 500 mb. It is in this region of formation or intensification that lower tropospheric air can first stream southwards in the rear of a disturbance. Farther west, the Atlas Mountains are a barrier to such flow and they probably restrict the advective distortion of the thermal field which is observed to occur more freely to the east.

A model desert depression. The considerable similarities of structure and movement shown by the desert depressions of spring 1962 make it possible to construct a model that can be supported by qualitative physical and dynamical arguments (Figure 7). Ahead of a shallow upper cold trough in the westerlies, positive vorticity advection induces cyclogenesis at the surface,

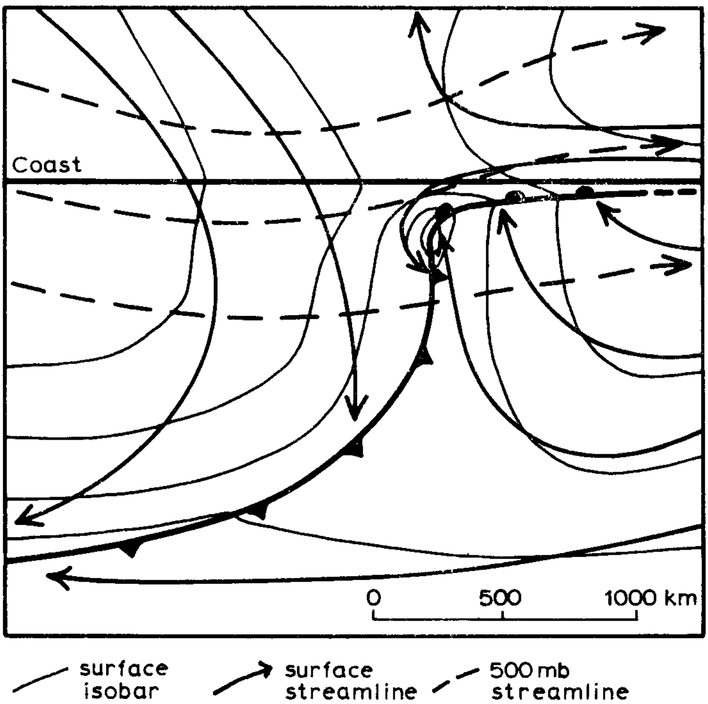


FIGURE 7—MODEL OF A DESERT DEPRESSION SHOWING SCHEMATIC STREAMLINES AT SURFACE AND 500 mb, AND SURFACE ISOBARS AND FRONTS

leading to a northward-pointing trough in the trades, moving eastwards with the upper trough, i.e. against the surface wind. The resulting distortion of the lower tropospheric thermal field leads to increased development and the appearance of a cyclonic centre at the tip of the warm ridge, especially when the coastal temperature contrast is strong. This centre moves eastwards across the desert, along a track some hundreds of kilometres south of the coast, in a direction normal to the broad-scale temperature gradient. It maintains a steady state, perhaps because non-adiabatic effects resulting from differential heating counterbalance advective distortion of the thermal field, and the field of thermal advection remains essentially symmetrical about the axis of the warm ridge. Continued intensification is likely if there is increased positive vorticity advection aloft ahead of a developing upper trough; a turning of the track to the left, to cross the Mediterranean, is then likely. A cold front extends southwards from the centre, and it can sometimes be tracked into the intertropical convergence zone. Its northern part is usually well defined and on occasions can be identified as a southern extension of the cold front associated with a disturbance at higher latitudes. There is no warm front, although a strong coastal front is present ahead of the cyclonic centre, especially in the warmer months. In so far as subjective analyses allow, it is found that the cold front often coincides with the axis of the warm ridge in the surface potential isotherms — warm advection occurs ahead of it, and cold advection in its rear. The front is a particular form of the 'advection discontinuity' discussed by Kirk.[21,22] Moreover, with the dominance of thermal advection in controlling cyclogenesis, it is likely that the direction of vertical motion is closely related to the sign of thermal advection, i.e. upward motion will occur ahead of the front, and downward in its rear. This vertical motion must be expected to change the vorticity at higher levels, but it remains unresolved to what extent the trough at 500 mb, as observed near a steady-state desert depression, is a product of, or the originator of, the circulation.

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REFERENCES

1. THOMPSON, B. W.; The climate of Africa. London, Oxford University Press, 1965.
2. CRAIG, J. I.; Types of weather in Egypt. *Cairo Scient J, Cairo*, **3**, 1909, pp. 70–72.
3. CRAIG, J. I.; Diagrams of storm tracks and thermo-isopleths. Cairo, Ministry of Finance, Survey Department, Met Rep, 1910, Pt. II.
4. SUTTON, L. J.; A barometric depression of the khamsin type. *Phys Dep Pap, Cairo*, No. 10, 1923.
5. DURWARD, J.; Pressure, temperature and wind variations at Heliopolis, Egypt, associated with the warm and cold sectors of a depression. *Met Mag, London*, **63**, 1928, pp. 57–61.
6. TWIST, T. F.; Relatively low temperature during khamsin conditions, Ismailia, Egypt, *Met Mag, London*, **71**, 1936, pp. 214–215.
7. FLOWER, W. D.; A note on the influx of cold air into Egypt and the Northern Sudan during the period 18th to 23rd April, 1930. *Q J R Met Soc, London*, **66**, 1940, pp. 216–222.
8. BIRTWISTLE, A.; A khamsin in northern Egypt. *Geography, London*, **31**, 1946, pp. 59–62.
9. HARE, F. K.; Atlas lee-depressions and their significance for Scirocco. London, Meteorological Office, 1943. (Unpublished, copy available in the Meteorological Office Library, Bracknell.)

10. DUBIEF, J. and QUENEY, P.; Les grands traits du climat du Sahara algérien. *La Mét, Paris*, **11**, 1935, pp. 80–91.
11. QUENEY, P.; Classification aérologiques des types de temps du Sahara français. *Trav Inst Rech Sah, Algiers*, **3**, 1945.
12. QUENEY, P.; Quelques données nouvelles de la météorologie nord-africaine: perturbations tropicales, fronts tropicaux, circulation cellulaire. *Annls Géophys, Paris*, **2**, 1946, pp. 309–314.
13. ELFANDY, M. G.; The formation of depressions of the khamsin type. *Q J R Met Soc, London*, **66**, 1940, pp. 323–335.
14. SAYED AHMED, M. M.; Khamsin and khamsin conditions. *Met Dep Pap, Cairo*, No. 1, 1949.
15. London, Meteorological Office. Aviation meteorology of the route Castel Benito–Cairo. *Met Rep, London*, No. 5, 1950.
16. LUNSON, E. A.; Sandstorms on the northern coast of Libya and Egypt. *Prof Notes, Met Off, London*, No. 102, 1950.
17. SIVALL, T.; Sirocco in the Levant. *Geogr Annlr, Stockholm*, **39**, 1957, pp. 114–142.
18. DHONNEUR, M.; Étude climatologique des routes aériennes aboutissant à Fort Lamy. *Monogrs Mét Natn, Paris*, No. 2, 1957.
19. BERENGER, M.; Quelques remarques sur les perturbations intéressant le Sahara. *La Mét, Paris*, **4**, 1960, pp. 325–334.
20. London, Meteorological Office. Weather in the Mediterranean (second edition), Vol. I. London, HMSO, 1962. Chap. 3.
21. KIRK, T. H.; Discontinuities with reference to Mediterranean and North African meteorology. *Tech Notes, Wld Met Org, Geneva*, No. 64, 1964, pp. 35–48.
22. KIRK, T. H.; Some aspects of the theory of fronts and frontal analysis. *Q J R Met Soc, London*, **92**, 1966, pp. 374–381.
23. TANTAWY, A. H. I.; The role of the jet stream in the formation of desert depressions in the Middle East. *Tech Notes, Wld Met Org, Geneva*, No. 64, 1964, pp. 159–163.
24. TANTAWY, A. H. I.; On the genesis and structure of spring desert depressions in subtropical Africa. *Met Res Bull, Cairo*, **1**, 1969, pp. 69–106.
25. SOLIMAN, K. H.; Heat waves over Egypt. *Proc Math Phys Soc, Egypt, Cairo*, **5**, No. 1, 1953, pp. 91–101.
26. PETTERSSEN, S.; Weather analysis and forecasting. New York, McGraw-Hill, 1956, Chapter 16.
27. SOLIMAN, K. H.; On the intertropical front and intertropical convergence zone over Africa and adjacent oceans. Symposium on Monsoons of the World, New Delhi, 1958. Delhi, Manager of Publications, 1960, pp. 135–142.
28. De Bilt, Royal Netherlands Meteorological Institute. The Mediterranean. Oceanographic and meteorological data, 1957.
29. FANTOLI, A.; Contributo alla climatologia della Cirenaica. Rome, Ministero degli Affari Esteri, 1968.
30. Geneva, World Meteorological Organization. Short-period averages for 1951–60 and provisional average values for CLIMAT TEMP and CLIMAT TEMP SHIP stations. WMO No. 170, Geneva, 1965.
31. HASSAN, A. A.; Seasonal distribution of the horizontal baroclinicity component over subtropical Africa and Mediterranean. *Met Res Bull, Cairo*, **2**, 1970, pp. 171–188.
32. JACKSON, S. P.; Climatological atlas of Africa. Lagos, Commission for Technical Cooperation in Africa South of the Sahara, Joint Project No. 1. 1961.
33. WICKHAM, P. G.; 200 mb mean winds on the route El Adem to Aden derived from aircraft reports. *Met Mag, London*, **90**, 1961, pp. 255–260.
34. ABANDAH, A. I.; The winter jet-stream in the Middle East. (Unpublished thesis, 1966, available in University of London Library.)

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A NOTE ON THE COMBINATION OF OBSERVATIONS OF UNEQUAL ACCURACY

By B. R. MAY and K. H. STEWART

Summary. The combination of observations of a variable made with instruments of differing accuracy is considered and it is argued that when the instrumental accuracy is much greater or much less than the natural variability, standard textbook results are applicable. The less familiar case, when the instrumental accuracy and the natural variability are comparable is discussed and an iterative procedure for calculating the best estimate of the mean and its variance in these circumstances is given.

If we make several observations of a quantity, they are not usually all the same, either because there are errors in the measurements or because the quantity itself is not constant, or both. The simplest method of combining the observations is to take their arithmetic mean, and in many cases this gives the best possible estimate of the quantity that can be made from the observations. If, however, some of the observations are known to be more accurate than others because they were made by better observers or with better instruments, for example, it is obvious that they should be given greater weight; it is shown in textbooks on statistics that the appropriate weighting factor is $1/V_j$, where V_j is the variance of the jth observation (the square of the standard error).

It is not usually emphasized that the V_j to be used in these weighting factors are the variances of the *observations* not the variances of the *measurements*, that is to say they are the sums of the variances due to instrumental (or observer) error, V_i, and the variance due to the natural variability of the quantity being observed, V_0. In laboratory physics it is common for V_0 to be very small compared with the V_i so that $V_j \approx V_i$ and weighting of observations according to $1/V_i$ is appropriate, but in outdoor physics the variability of the phenomenon, measured by V_0, is often much greater than the error of the measurements, the V_i. In this case the use of $1/V_i$ as weighting factors (instead of the correct values $1/V_j = 1/(V_i + V_0)$) can give absurd results. For example if we were finding a monthly mean temperature from a set of daily readings and the readings on one day happened to be taken on a precision laboratory thermometer with an accuracy of 0·001 degC it would be absurd to give those readings 10^4 times the weight of the readings on the other days, taken with a thermometer accurate to, say, 0·1 degC. In cases where the natural variability (V_0) is much greater than the instrumental errors (V_i) it is far better to give all observations equal weight.

We can summarize the two extreme cases as follows :

Case 1. Natural variation large, all instrument errors small, $V_0 \gg V_i$.

$$\text{Weighting factor } \frac{1}{V_i + V_0} \approx \frac{1}{V_0} \text{ (equal weights).}$$

Case 2. Natural variation small, instrument errors large, $V_0 \ll V_i$.

$$\text{Weighting factor } \frac{1}{V_i + V_0} \approx \frac{1}{V_i}$$

We have recently had to deal with some observations which fell into an intermediate category. The accuracy of individual observations (which could be estimated from internal evidence) covered quite a wide range and the natural variability of the quantity being studied lay in the same range. We could find no discussion of how to handle this type of data in the textbooks and would like to report on the method we have developed.

We assume we have a set of observations $x_1, x_2, x_3, \ldots x_i, \ldots x_n$ and that the 'instrumental' accuracy of each observation is known and is expressed by the variance V_i (that is, V_i is the variance that would be obtained for a series of observations made with the ith instrument on an unchanging quantity x). We wish to make the best estimate we can (M_e) of the mean value (M)

of the quantity x, recognizing that x may have a natural variability expressed by its variance, V_0, whose value is not known. There is no difficulty in writing down the value of M_c; it is the weighted mean

$$M_c = \frac{\sum\limits_{n} \dfrac{x_i}{V_i + V_0}}{\sum\limits_{n} \dfrac{1}{V_i + V_0}}. \qquad \ldots (1)$$

The difficulty is to find a value of V_0 to use in this expression. If we assume for the moment that the true mean value of x, M, is known, then it can be shown that the best estimate (V_0') of V_0 is given by

$$V_0' = \frac{\sum\limits_{n} \dfrac{(x_i - M)^2 - V_i}{(V_i + V_0)^2}}{\sum\limits_{n} \dfrac{1}{(V_i + V_0)^2}}. \qquad \ldots (2)$$

(This expression can be derived either by maximizing the probability of obtaining the set of observations $x_1, x_2, \ldots x_n$ with respect to V_0, or by considering that each observation provides an estimate of V_0 and combining these estimates with appropriate weights.)

We have not been able to solve equations (1) and (2) except by an iterative computer process, but the programme needed is simple and converges rapidly. It is assumed initially that $V_0 = 0$, and equation (1) is used to evaluate M_c. This value of M_c is used as an estimate of M in equation (2) (still with $V_0 = 0$ on the right-hand side of the equation) to evaluate a value of V_0, which is then used as a better approximation to V_0 in equation (1) to start a new iteration. The process stops when successive values of M_c and V_0 differ by an acceptably small amount, and these values are taken as the best estimates of the mean value and the natural variance of x. The only difficulty in the operation of the programme is that it may produce negative values of V_0, which are physically unacceptable. This is to be expected if V_0 is small (if $V_0 = 0$, then equation (2) will yield negative values as often as not, through the statistical distribution of the instrumental errors) and in fact if equation (2) yields a negative value then the best estimate that can be made of V_0 is that it is zero.

The accuracy of the final estimate of M, M_c, is measured by its statistical standard deviation S_c, which can be shown to be given by

$$S_c = \left[\sum_{n}(V_0 + V_i)^{-1}\right]^{-\frac{1}{2}}$$

This, of course, reduces to the usual expression $S = (V/n)^{\frac{1}{2}}$ if all observations have the same variance, V.

The methods given here for estimating the mean value of x can fairly easily be extended if it is required to find the best regression equation between x

and some other variable, assuming that the instrumental errors, V_i, are known and that some reasonable assumption can be made about the way in which the natural variability, V_0, varies with x.

The programme just outlined has been used to calculate means (and their standard deviations) and the 'natural' variance for groups of observations of molecular oxygen densities in the thermosphere made by the Meteorological Office equipment in the ARIEL 3 satellite. The results seem reasonable, but the question may be asked whether they are any better than results obtained by taking simple arithmetic means or, if instrumental errors are thought to be large, means weighted according to the method of Case 2. It has been shown by considering limiting cases and by computer simulations that, on average, results by the method described here will be closer to true values than results by the other two methods, but in general the improvement will not be very great. The maximum gain over the better of the two simple methods is only about 15 per cent (that is, a 15 per cent reduction in the spread of estimates of M that would be obtained if the sets of observations were repeated many times), but in practice it is not always easy to see which of the two simple methods is appropriate and, if the wrong one is chosen, worse errors will result. The procedure described here avoids the need for this choice, and is worth using in any doubtful cases as well as in other cases when it is deemed necessary to squeeze the last drop of accuracy from the measurements.

REVIEWS

Numerical weather prediction, by G. J. Haltiner. 233 mm × 160 mm, pp. xvi + 317, *illus.*, John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex, 1971. Price: £5.

Now that numerical weather prediction is no longer an esoteric research project but is an operational routine which in mid-latitudes at least is a basic forecasting tool, it has become part of the general education of meteorologists and some account of it must appear in any reasonably advanced meteorological syllabus. We might expect a number of textbooks to be available for students, and their elders, written by those who give courses, but so far there have been very few, probably more in Russian than in English, and fewer still of any quality. Professor Haltiner has written a book aimed particularly at students and scientists who need to have a general view of the basic ideas, and it is sure of a welcome as a pioneer effort offering a connected account.

The author has many problems to overcome. Perhaps the first is that the subject matter — numerical weather prediction — of necessity requires the use of a lot of mathematics and it would be very easy to allow the mathematics to dominate so that the reader becomes more involved in following a mathematical argument than considering the physical processes of meteorology. There are, of course, parts of the book devoted to mathematical problems, those of computational stability and methods, but in the main development the author has managed to keep the meteorology well in focus, so that this is not essentially a mathematical book although there is an abundance of equations.

The second main problem is what to include. There is a vast literature dating from the late 1940s and it would be impossible to attempt to pay attention to it all. The earlier work was mainly concerned with vorticity models which have pedagogic attraction because there is a clear physical picture associated with the spin about a vertical axis and it is possible to argue qualitatively and then supply the quantitative analysis. There is probably now little or no research going on anywhere concerned with vorticity models and although routine predictions based on them are still made in a number of countries these models are obsolescent. More recent research and more recently developed models for routine forecasting have used the primitive equations, that is a slight modification of the Navier–Stokes equations and equations relating to supply and distribution of energy. How much space should be allotted to out-of-date methods? Professor Haltiner chooses to devote nearly half of his book to the foundations and the development of vorticity ideas, and this may be right for the student reader although it looks rather a lot in retrospect.

There has been a rapid increase in the number of published papers over the last decade, as more countries have developed expertise in numerical prediction and most of them have been devoted to primitive equation models. The author thus has a problem of selection from all this material for the second half of his book. It is an unenviable problem and the solution is bound to invite criticism. Mine is that the choice does not seem to have been dictated by a pattern which can be clearly seen, and that it tends to be parochial; of course the latter is understandable since the book is probably the outcome of a series of lectures prepared for students at Monterey.

The book has considerable solid merits. Professor Haltiner is known from his previous writings to be extremely clear and lucid and these qualities are apparent throughout. The first half of the book covers the development of the equations, the linearized versions and the possible wave-motions, the elimination of the unwanted motions by filtering and the development of vorticity models. There is a surprising amount of additional information about such subjects as the ancillary mathematics, map projection, integral constraints, etc. The second half contains some material relating to most of the relevant aspects that have to be taken into account in trying to develop realistic atmospheric models. There are accounts of the introduction of physical effects, such as the hydrological cycle, radiation, cumulus convection, of mathematical techniques and of preparing the data on which the predictions are to be made. No particular aspect is dealt with in detail but enough is given to make the problem clear and to indicate one way of dealing with it. Some of the models currently in use in the U.S.A. are also briefly described.

Professor Haltiner's book does not at this time have a serious rival for its intended purpose and it is sure to be popular with students who will readily understand this crisp writing, and by others who have to design and give courses in numerical weather prediction.

E. KNIGHTING

The blizzard of '91, by Clive Carter. 225 mm × 145 mm, pp. 204, *illus.*, David and Charles (Publishers) Limited, South Devon House, Newton Abbot, Devon, 1971. Price: £2·75.

On 10 March 1891 a depression from the south-west deepened rapidly near the Brest Peninsula and moved along the north coast of France. The resulting blizzard affected most of southern England but hit Devon and

Cornwall with especial ferocity, causing much loss of life, damage and disruption of communications. The author has given a detailed reconstruction of the impact on the community, with many contemporary accounts and well illustrated by photographs and some attractive drawings. Two aspects have received particular attention: the casualties in the storm at sea and the stranding of trains in snowdrifts around Dartmoor.

The emphasis is on 'human interest': on efforts to save the shipwrecked (some of whom survived for a time only to succumb to exposure to the severe gales at near-freezing temperatures, within sight of the would-be rescuers); on the trials of stranded passengers (the 'Zulu' express which had left Bristol at 6 p.m. on Monday 10 March did not reach its destination of Plymouth until 8.30 p.m. on Friday 14 March); and on the isolation of farm, hamlet and town. There is some occasional hyperbole in the account, as when winds are described as of hurricane force, but a useful record is provided of the tragedy, destruction and disruption caused by this famous blizzard and will give a basis of comparison with more recent blizzards.

The meteorologist will be glad to find a sequence of weather charts reconstructed from the contemporary British *Daily Weather Reports* in terms of frontal analysis by Mr F. Singleton of the Meteorological Office. These charts show well the frontal contrast between mild south-westerlies over France and the cold north-easterly gales over Devon and Cornwall at the time when the blizzard was developing. On the map on page 192 there are some errors in the values of the central isobars of the depression.

J. E. ATKINS

Satellite and computer applications to synoptic meteorology. Lectures presented during the scientific discussions at the fifth session of the Commission for Synoptic Meteorology (Geneva, 15 June–3 July 1970). 275 mm × 213 mm, pp. xiv + 88, *illus.*, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1971. Price: Sw. Fr. 15.

This WMO publication reproduces three lectures presented during the scientific discussions at the fifth session of the Commission for Synoptic Meteorology (Geneva 15 June–3 July 1970). The first, available in both Russian and English versions, is 'The use of satellite information for weather analysis and forecast' by A. I. Burtsev and A. D. Čistjakov. Apart from a few unconventional expressions and ambiguities, the English text presents a competent account of the use of satellite data in an operational context. There is evidence throughout the paper of the great importance given to satellite information in the U.S.S.R. and of its influence on the activities of the weather service.

In the operational application of satellite data to synoptic analysis, emphasis is placed on the combined use of television, infra-red and actinometric information to elucidate the three-dimensional structure of cloud formations. In routine applications for the estimation of various meteorological parameters, objective methods are described, these being based for the most part on statistical rules derived from painstaking comparisons over large areas. Some of these data are given in Tables 1 to 4. The authors stress that there is an urgent need for the development of objective methods for the decoding of satellite information by computer and briefly refer to current picture-processing techniques.

Applications to forecasting include the now conventional methods based on the identification of cloud systems and their typical evolution as well as the direct input of derived information into numerical forecasting schemes. No reference however is made to Satellite Infra-Red Spectrometer (SIRS) type data. The paper ends, surprisingly, with an account of an experiment on routine weather forecasting without using data on visual cloud and weather phenomena but using satellite and radar information instead. It is of course more orthodox to regard both satellite and radar information as supplementing rather than replacing conventional types of observations. Yet we read: 'In connexion with the complex automation carried out in the Hydrometeorological Service of the U.S.S.R. the existing network of meteorological stations will be replaced by automatic stations, which will not be able to provide information on the amount and forms of clouds as well as on weather phenomena'.

For those wanting a brief account of the recent U.S. development in the application of satellite data to numerical forecasting, the second paper 'Operational use of SIRS data' by William L. Smith and Edwin B. Fawcett can be warmly recommended for its practical approach. The SIRS was carried on the NIMBUS spacecraft and briefly provides measures of the radiation emitted by the earth and atmosphere in seven narrow spectral intervals of the 15-micrometre carbon-dioxide band and one narrow spectral interval of the 11-micrometre window region. The radiation measured in the various spectral intervals corresponds to a vertically weighted mean temperature of different atmospheric layers. The practical problem is to use the observed radiances to deduce the vertical temperature profile. This paper describes the regression method of doing this, in which use is made of conventional temperature data gathered over a short period of time and updated every few days. These derived temperature profiles can then be used as input for routine numerical forecasting operations. The importance of this development is at once evident and interest immediately centres on the reliability of the method. Accordingly, much of the paper is taken up with a consideration of the advantages and limitations of these data in an operational context.

The last paper, 'An operational system for numerical weather prediction' by L. Bengtsson and L. Moen is an interesting one for all forecasters and can serve as a model for the integrated research/operations activity that should be a feature of all meteorological services. The authors have been successful in giving a well-balanced account of a relatively simple filtered model and its exploitation to best advantage in an operational organization. Of particular interest is the account of a grid-telescoping technique and its advantages in meeting operational requirements. Some pertinent remarks on the relative advantages and disadvantages of filtered and primitive-equation models in operational use will be of interest to most readers.

T. H. KIRK

Meteorological factors in air pollution, WMO Technical Note No. 114, by A. G. Forsdyke. 275 mm × 213 mm, pp. iv + 32, *illus.*, Secretariat of the World Meteorological Organization, Geneva, Switzerland, 1970. Price: Sw. Fr. 10.

This WMO *Technical Note* is described in the foreword as designed specifically for the non-specialist who will from time to time be required to solve problems or provide advice on matters relating to air pollution. Dr Forsdyke admirably fulfils his aim of producing a simple text, and it will serve as an excellent introduction to the subject for the ordinary meteorologist and non-meteorologist alike.

The note deals with the dispersion of pollutants in the atmosphere and is largely concerned with pollution at the ground over fairly short distances. After a brief opening section in which the main pollutants are mentioned, the author describes the meteorological factors involved (wind, turbulence and stability) in very simple terms for the non-meteorologist. Typical shapes which a plume from a chimney may assume in different stability conditions are illustrated. In the next, and most important, section Dr Forsdyke develops the standard formula for the concentration at a point downwind of pollutant from a single continuous source. There is no pretence that the derivation is rigorous, but the author very cleverly succeeds in taking the veriest novice through the essential steps. If a minor criticism may be made it is that many users of the book will find the elementary derivation of the Gaussian from the binomial distribution unnecessary. Pasquill's* method of deducing stability from wind speed and cloud cover is described, and tables and a worked example are included in an appendix. Enough information is thus included in the note to enable simple queries to be answered. Advice is given on the need for making allowances for sampling time, plume rise due to buoyancy, multiple sources, sloping ground, rough terrain, valleys and sea-breezes; and dependence of stability on air mass and anticyclonic inversions is also discussed. Most of these matters can be dealt with only in a rough subjective manner and the reader should begin to realize that in spite of Dr Forsdyke's extremely simple presentation, the subject is in fact a most complex one. Nevertheless, as an introduction for the non-expert the note can be thoroughly recommended.

M. H. FREEMAN

Meteorological conditions in the Arctic during IQSY. Arctic and Antarctic Research Institute, Transactions, Volume 274, edited by I. M. Dolgin and L. A. Gavrilova. 240 mm × 165 mm, pp. vi + 145, *illus.* (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), Keter Press Ltd, 15 Provost Road, London NW3 4ST, 1971. Price: £4·20.

This book consists mainly of papers giving the results of the investigations carried out in the Soviet Arctic during the IQSY (International Quiet Sun Year). To meteorologists specifically interested in the Arctic the diagrams and tables may be of interest, but the text is mainly narrative, boring and uncritical. The book is evidently written for internal circulation as of the 80 references (excluding the last chapter) only three are to non-Soviet sources, there is neither a map nor a gazetteer giving the position of the observing stations referred to, and several terms used in the text are not defined. The translation is poor and at times wrong and in the opposite sense of what the author must have written. I would not recommend this book to meteorologists for general interest.

R. A. HAMILTON

* PASQUILL, F.; The estimation of the dispersion of windborne material. *Met Mag, London*, **90**, 1961, pp. 33–49.

OBITUARY

It is with regret that we record the death on 14 May 1972 of Mr N. C. Helliwell, Principal Scientific Officer, Met. O. 3.

AWARD

We note with pleasure that the seventeenth International Meteorological Organization Prize for outstanding work in meteorology and in international collaboration has been awarded for this year to Academician Viktor Antonovich Bugaev, Director of the Central Institute of Prognoses in Moscow, by the Executive Committee of the World Meteorological Organization.

CORRECTIONS

Meteorological Magazine, April 1972, p. 107, Table VI, Rule No. 17, Critical anomaly : for '> -6' read '< -6'.
Meteorological Magazine, April 1972, p. 108, Table VII, Period (c) November : for '$N_c - N_m = 0$ or 1' read '$N_c - N_m = 0$'.

OFFICIAL PUBLICATION

The following publication has recently been issued :
Meteorological glossary. Fifth edition. (London, HMSO. Price: £2·75)

This glossary has been revised and enlarged to include a number of new entries and revisions stemming from recent advances made, for example, in numerical prediction and satellite meteorology. Units of the Système International (SI) have been used, though in some cases the traditional British or metric units have been included as well for the convenience of user interests during the period before the complete adoption of SI units.

The new edition is about 10 per cent larger than the fourth edition and includes most of the terms and concepts which are in everyday use in meteorology and many others which are in less common use. In addition, relevant information from mathematics, statistics, physics and geophysics is included.

THE METEOROLOGICAL MAGAZINE

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NOTICES

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PREDICTION OF SUMMER RAINFALL AND TEMPERATURE FOR ENGLAND AND WALES FROM ANOMALOUS ATMOSPHERIC CIRCULATION IN SPRING

By R. MURRAY

Summary. From an analysis of 97 years of monthly mean pressure anomaly data for March, April and May, simple indices of anomalous circulation in key areas of the northern hemisphere are related to the subsequent general rainfall and mean temperature in the summer over England and Wales. Useful predictors are shown to be in evidence on about 50 per cent of occasions in early spring. On the basis of anomalous circulation in March, April and May, objective predictors can be applied on most occasions with considerable success.

Introduction. This paper presents objective procedures for predicting summer rainfall and mean temperature, derived from analysing mean monthly pressure anomalies over the northern hemisphere in March, April and May. The general method of attacking the seasonal prediction problem has been given in some detail in a recent paper by Murray[1] dealing with winter. In the present paper the general rainfall over England and Wales and Manley's[2] central-England mean temperature are employed. The percentile boundaries used for rainfall and temperature have already been published by Murray.[3,4]

It is convenient here to repeat briefly some of the discussion on procedure which is given in the earlier paper by Murray.[1] For each class of summer, as specified by the quintile of mean temperature in central England, the mean pressure anomaly maps in March, April and May preceding the specified summers were computed. These composite mean pressure anomaly maps in the spring months generally show areas where the pressure anomalies are apparently significantly different from zero (at the 5 per cent level), as indicated by the *t*-test. For example, Figure 1 shows the composite mean pressure anomaly map for Mays before very cool (T_1 or quintile 1) summers. It appears that mean pressure anomalies are significantly positive in the polar region and over north Africa. Incidentally, a composite map for Mays before very warm (T_5 or quintile 5) summers shows apparently significant negative pressure anomalies over the Arctic of western Canada and also over south Spain and Morocco. In other words for the opposite type of summer the significant mean pressure anomalies in May have different signs but are located in roughly the same areas as shown in Figure 1. Composite maps like Figure 1 suggest that the circulation in certain areas in March, April

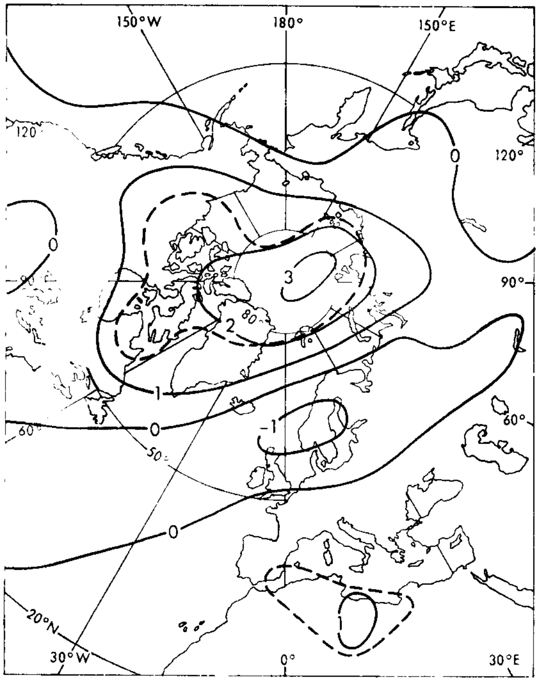

FIGURE 1—COMPOSITE MEAN PRESSURE ANOMALY PATTERN FOR MAY PRECEDING VERY COOL (QUINTILE 1) SUMMERS OVER CENTRAL ENGLAND

Pressure anomalies (1-mb intervals) from 1873–1968 average. Broken lines enclose areas where anomalies are significantly different from zero at the 5 per cent level according to *t*-test.

and May might well be associated in a complex way with the development of characteristic temperature quintiles in the following summer. To explore this further the mean monthly pressure anomalies at one or occasionally more than one grid point within areas where the mean anomalies on the composite maps were apparently significant were then computed for the particular spring month in question for each month from 1873. These monthly mean pressure anomalies were ranked and related to the temperature quintiles of the summers following. In many cases the difference between monthly mean pressure anomalies at two grid points was computed and ranked when it was thought from examining the composite mean pressure anomaly map that the anomaly in the pressure gradient might be a more relevant indicator of abnormal circulation. In a few cases grid points were taken where the composite mean pressure anomaly was not significant at the 5 per cent level, particularly when pressure anomaly gradients seemed likely to be informative. The broad association between monthly mean pressure anomaly data and summer temperature (quintiles) was readily seen from contingency tables. The significance of such tables cannot be obtained by merely computing the chi-square statistic since the number of degrees of freedom is uncertain in these cases. However, the chi-square statistic still indicates roughly the relative importance of the associations. As indicated in the earlier paper, it was found best to examine the ranked pressure anomaly data and to classify objectively according to the following criteria :

(a) The class must contain at least 15 years.

(b) If both ends of the distribution of pressure data appear to have an association with summer temperature then the Sutcliffe score *(SS)* for each class must be equal to or greater than 1·2.

(c) If only one end of the distribution of pressure data appears to have an association with summer temperature then $SS \geqslant 1{\cdot}4$.

(d) The pressure class was taken so that the critical pressure anomaly boundary was a whole number (e.g. pressure anomaly > 3·0 mb) provided also that (a) and either (b) or (c) were also satisfied.

Details concerning the Sutcliffe score are given in the earlier paper by Murray.[1]

The same general procedure was carried out in searching for predictors of summer rainfall except that terciles of rainfall were employed and also the upper and lower ten-percentiles.

In cases when pressure anomalies (or differences) were at nearby places and clearly represented the same features of the large-scale anomaly of circulation, one was usually selected. As far as can be seen little difference would have resulted in the conclusions if other choices had been made in such cases.

Forecasting summer rainfall. Predictive indications given by simple indices of anomalous monthly mean circulation in the three spring months are summarized in Table I, in which latitude/longitude positions are abbreviated (e.g. 55 10 is 55°N 10°W and 55 10E is 55°N 10°E).

TABLE I—PRESSURE ANOMALIES AND PRESSURE ANOMALY DIFFERENCE AT KEY AREAS IN MARCH, APRIL AND MAY RELATED TO SUMMER RAINFALL IN ENGLAND AND WALES

Rule No.	Pressure anomaly (PA) or difference	Normal	Critical anomaly	Rainfall (terciles) 1	2	3
		millibars				
(a) March						
1	PA(70 100E) − PA(60 170E)	1018·0 − 1011·4	< 0·0	5	19	19
2	PA(70 100E) − PA(60 170E)	1018·0 − 1011·4	> 3·0	25	6	10
3	PA(50 110) − PA(60 170E)	1017·6 − 1011·4	> 6·0	10	5	3
4	PA(55 170E)	1007·3	< −1·0	25	10	10
5	PA(55 170E)	1007·3	> 2·0	2	14	12
6	PA(65 30E) − PA(75 100E)	1011·0 − 1017·0	> 7·0	13	4	5
7	PA(70 60) − PA(65 90E)	1011·8 − 1018·7	< −7·0	8	5	2
(b) April						
8	PA(40 20E) − PA(60 20)	1012·9 − 1009·1	< −4·0	5	5	14
9	PA(40 20E) − PA(60 20)	1012·9 − 1009·1	> 3·0	12	8	2
10	PA(55 70) − PA(60 150)	1014·8 − 1009·4	< −5·0	2	8	8
11	PA(55 70) − PA(60 150)	1014·8 − 1009·4	> 4·0	12	4	4
12	PA(80 00)	1017·2	> 5·0	2	5	10
13	PA(55 20E)	1013·5	< −2·0	3	5	12
14	PA(80 00) − PA(55 20E)	1017·2 − 1013·5	< −7·0	8	5	3
15	PA(80 00) − PA(55 20E)	1017·2 − 1013·5	> 4·0	6	7	15
(c) May						
16	PA(70 60E) − PA(60 00)	1014·0 − 1014·6	> 6·0	10	4	2
17	PA(70 80)	1018·0	≥ 3·0	3	4	10
18	PA(70 80) − PA(55 180)	1018·0 − 1008·9	> 4·0	4	3	12

Normal monthly pressure or pressure difference refers to the period 1873 to 1968.

Note : Tercile boundaries, based on period 1874 to 1963, are: $R_1 < 193$ mm; $193 < R_2 < 254$ mm; $R_3 > 254$ mm.

For convenience the positions of PA and PA differences employed in Table I are shown in Figures 2, 3 and 4 for each month. In Figure 2 it is clear that anomalously high or low pressure in the Bering Sea and near the Taymyr Peninsula in northern Siberia are especially important as predictors in March. Figure 3 shows that abnormal pressure differences from the Gulf of Alaska to eastern Canada, from off north-east Greenland to the southern Baltic and from south of Iceland to near the west coast of Greece are likely to be useful as predictors in April. Judging by the number of predictors shown in Table I it appears that the circulation in May is less important than in March and April in setting the stage for the rainfall in summer.

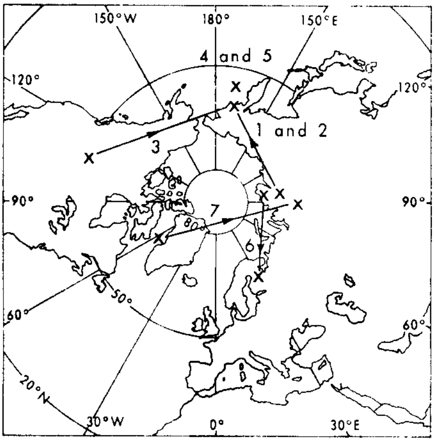

FIGURE 2 — POSITIONS OF SUMMER RAINFALL PREDICTORS BASED ON MARCH MEAN PRESSURE ANOMALIES GIVEN IN TABLE I (a)

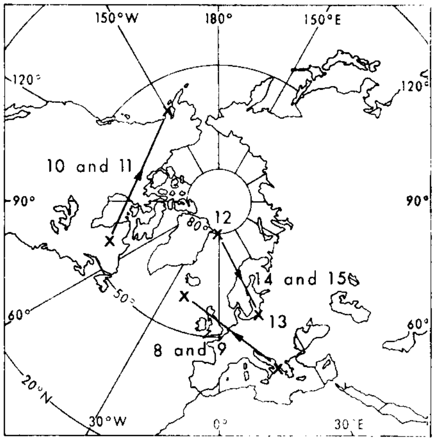

FIGURE 3 — POSITIONS OF SUMMER RAINFALL PREDICTORS BASED ON APRIL MEAN PRESSURE ANOMALIES GIVEN IN TABLE I (b)

Positions used in PA differences are joined by arrows.

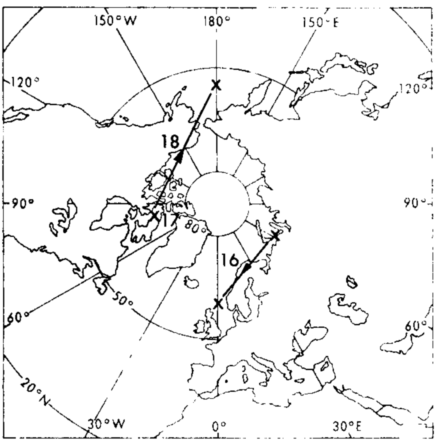

FIGURE 4—POSITIONS OF SUMMER RAINFALL PREDICTORS BASED ON MAY MEAN PRESSURE ANOMALIES GIVEN IN TABLE I (c)

Positions used in PA differences are joined by arrows.

The individual rules given in Table I are not all satisfied in general in a particular year, nor do they always indicate the same type of summer rainfall when the pressure criteria are satisfied. In the paper on predicting winter rainfall several possible discriminant procedures were mentioned but a very simple method of combining the individual rules was adopted with considerable success. The same simple procedure is employed in the present paper. Equal weight was given to each of the basic rules listed in Table I and simple, common-sense relationships between the number of individual rules which predict dry (N_d) and wet (N_w) summers and the occurrence of different classes of summer were developed as shown in Table II.

TABLE II—LAG ASSOCIATIONS BETWEEN VARIOUS COMBINATIONS OF RULES BASED ON MONTHLY PRESSURE ANOMALIES IN MARCH, APRIL AND MAY OVER THE NORTHERN HEMISPHERE AND SUMMER RAINFALL OVER ENGLAND AND WALES

Period		Predictor $N_d - N_w$	Winter rainfall (terciles) 1	2	3	Totals	*SS*
(a) March		≥ 3	16	3	2	21	2·6
		≤ -1	2	11	15	28	1·8
(b) April		≥ 1	17	11	3	31	1·8
		≤ -3	1	6	13	20	2·4
(c) May		≥ 0	10	4	1	15	2·4
		≤ -1	4	4	16	24	2·0
(d) March + April		≥ 1	28	9	7	44	1·9
		(≥ 3)	(17)	(2)	(1)	(20)	(3·2)
		≤ -1	6	16	23	43	1·7
		(≤ -3)	(0)	(4)	(11)	(15)	(2·9)
(e) March + April + May	1	≥ 2	23	5	3	31	2·6
		(≥ 4)	(15)	(0)	(1)	(16)	(3·5)
	2	1, 0 or -1	9	16	8	33	0·9
	3	≤ -2	2	10	21	33	2·3
		(≤ -4)	(0)	(4)	(12)	(16)	(3·0)

N_d and N_w are the number of individual rules (see Table I) which indicate dry (tercile 1) and wet (tercile 3) summers respectively. *SS* is the mean Sutcliffe score. Tercile boundaries are given in Table I.

Note : For a predictor value in brackets, the tercile distribution is shown in brackets.

Table II contains predictive relationships based on the various individual monthly rules. Two useful predictors are available at the end of March but these are applicable on only about 50 per cent of occasions. When the April pressure anomaly information becomes available rules based on April only or on March and April together can be applied. The combined March and April predictors are likely to be usable on over 85 per cent of occasions and should generally take precedence over the March indications when there is a difference in their predictions. May adds further useful information on occasions. By the end of May, rules (e)1 to (e)3 based on the three spring months come into operation; these rules cover all cases, but (e)1 and (e)3 are more significant than (e)2. When more stringent conditions are set, as shown in brackets in Table II, very strong predictive relationships are in evidence. For instance, in rule (e)1 when $N_d - N_w \geq 4$ in March, April and May then only one wet summer occurred in 16 years; in rule (e)3 when $N_d - N_w \leq -4$ no dry summer occurred in 16 years. It is interesting to see in Figure 5 the composite mean pressure anomaly pattern in summer for the group of years in which the predictor in spring satisfied the criterion $N_d - N_w \geq 4$ (Table II, rule (e)1). The mean pressure in Figure 5 is

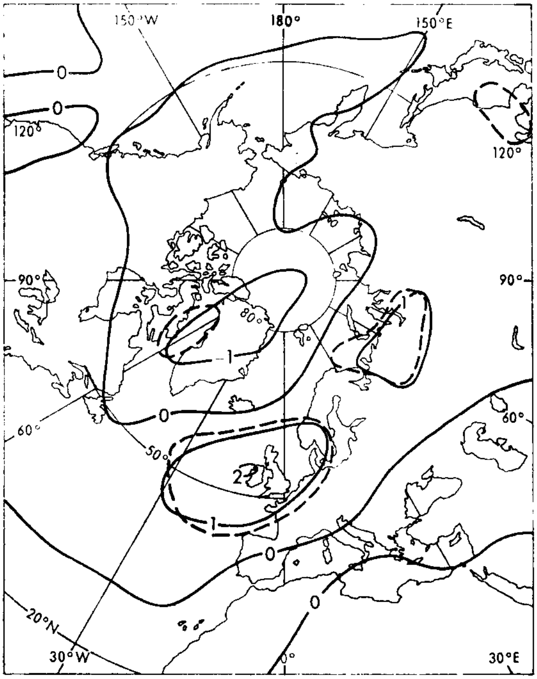

FIGURE 5—COMPOSITE MEAN PRESSURE ANOMALY PATTERN IN SUMMERS FOLLOWING SPRINGS SATISFYING RAINFALL PREDICTOR $N_d - N_w \geqslant 4$ GIVEN IN TABLE II (e)1

See notes under Figure 1.

significantly (at the 5 per cent level) above average over and near the British Isles and also in north Russia, and below average in west Greenland. For the less restrictive criterion $N_d - N_w \geqslant 2$ the composite map (not shown) is a weaker version of Figure 5. In the case of the group of summers associated with the predictor $N_d - N_w \leqslant -4$ (Table II, rule (e)3), the mean pressure anomaly over and near the British Isles is significantly (at the 5 per cent level) below average and it is not surprising that most of these summers are wet. In this case the mean pressure is also significantly above average in central Asia at about 45°N 80°E and almost significantly above average in the Canadian Arctic. The composite map for the $N_d - N_w \leqslant -4$ case depicts patterns which are quite similar to those in Figure 5 (case $N_d - N_w \geqslant 4$) but with the signs of the pressure anomalies reversed.

It is believed that the relationships shown in Table II, based on circulation patterns during nearly a century in which several major secular changes have taken place, will prove stable. This point was tested by breaking down the 97 years into the so-called 'westerly' epoch (1896–1939) and the 'blocked' epochs before 1896 and after 1939. Considering the principal rules of Table II(e), when $N_d - N_w \geqslant 2$ the summer rainfall distribution turned out to be 12, 1, 0 in the 'westerly' epoch and 11, 4, 3 in the 'blocked' epoch; when $N_d - N_w \leqslant -2$ the distribution was 2, 5, 8 in the 'westerly' epoch and 0, 5, 13 in the 'blocked' epoch. The accuracy of predictions of dry summers was likely to have been somewhat greater in the 'westerly' than in the 'blocked' epochs, whilst predictions of wet summers were probably better in the 'blocked' than in the 'westerly' epochs. Nevertheless, there does not appear to be any great difference between the distributions in the two epochs. In the 1960s the general standard was well maintained. The three wet summers (1960, 1966 and 1968) and the three dry summers (1961, 1962 and 1967) had spring pre-conditions which satisfied rules (e)3 and (e)1 respectively. Indeed for the decade 1960–69 the high value of 2·6 was achieved for the mean Sutcliffe score. The recent two summers 1970 and 1971 were not considered in deriving the rules. In fact the rules in Table II correctly predicted summer 1970 but not summer 1971. The predictor for a dry summer was satisfied in March 1971. No prediction was possible from the April pressure anomalies, but the May pressure anomaly rule suggested that the summer would be wet. The overall rule based on the three spring months gave $N_d - N_w = 2$ and so the overall predictor for a dry summer was just satisfied. Evidently the circulation in March, April and May was somewhat conflicting, although the overall rule was satisfied. In the event the June to August period of 1971 was wetter than usual (rainfall just above the tercile 3 boundary), largely as a result of a very wet June. Summer 1971 was in fact peculiar. There were other indications that a good summer was likely in 1971, including those mentioned in a statement by Sir Graham Sutton.[5] Moreover, Murray[6] has drawn attention to the fact that it was only the conventional summer (i.e. June to August) that was on the wet side. Indeed any other period of 3, 4 or 5 consecutive months from June to October 1971 was drier than usual.

Forecasting summer temperature. The individual indicators based on monthly mean pressure anomalies are given in Table III.

The positions where the rules of Table III apply are conveniently indicated in Figures 6, 7 and 8.

The individual rules were next combined in the manner employed to derive predictors for summer rainfall. The temperature predictors are summarized in Table IV.

From Table IV it is seen that very useful predictive relationships exist as early as March but on rather less than 50 per cent of occasions. The mean circulation in April can give useful predictions on over 50 per cent of occasions. However, the anomalous mean monthly circulations in key areas in March and April can be combined to produce three predictors which cover virtually all cases (one year is not included since $N_c = N_w = 0$). At the end of April positive predictions can thus be made and the success is likely to be high. If the more stringent criteria given in brackets are required to be satisfied the success of the predictions appears likely to be very high.

The circulation in May is important on less than 45 per cent of occasions. Nevertheless, the inclusion of this month's mean pressure anomaly rules with the predictors available in March and April means that three predictors emerge, as shown in (e) of Table IV. In this case only one year is omitted owing to the fact that $N_c = N_w = 0$. The predictions of cool, average and warm summers based on the criteria laid down in Table IV(e) will give negative Sutcliffe scores (i.e. failures) on just over 12 per cent of occasions. When the more stringent criteria given in brackets are insisted upon then predictions can be made on only 29 occasions (about 30 per cent), but only one was seriously in error (i.e. $SS < 0$) — a remarkable result in the field of

TABLE III—PRESSURE ANOMALIES AND PRESSURE ANOMALY DIFFERENCES AT KEY AREAS IN MARCH, APRIL AND MAY RELATED TO SUMMER MEAN TEMPERATURE IN CENTRAL ENGLAND

Rule No.	Pressure anomaly (PA) or difference	Normal	Critical anomaly	Temperature (quintiles) 1	2	3	4	5
		millibars						
(a) March								
1	PA(30 10E)	1015·7	$\geqslant 2$	4	9	2	2	2
2	PA(50 80)	1016·7	> 3	7	5	3	2	0
3	PA(55 170E)	1007·3	< -4	2	1	2	10	6
4	PA(70 80E) −PA(55 170E)	1014·6−1007·3	< -1	9	13	8	2	4
5	PA(70 80E) −PA(55 170E)	1014·6−1007·3	> 7	2	0	3	7	4
6	PA(45 170)	1011·3	> 6	5	6	4	1	0
(b) April								
7	PA(45 20E)	1013·0	$\leqslant -2$	9	5	6	0	2
8	PA(45 20E)	1013·0	> 2	0	1	5	7	4
9	PA(80 60E)	1015·5	< -4	0	1	5	7	3
10	PA(80 60E)	1015·5	> 4	9	2	4	2	1
11	PA(45 20E) −PA(80 60E)	1013·0−1015·5	< -5	11	4	3	1	2
12	PA(45 20E) −PA(80 60E)	1013·0−1015·5	> 5	1	2	7	6	4
13	PA(40 80E) −PA(80 60E)	1015·2−1015·5	< -5	9	2	5	0	3
14	PA(40 80E) −PA(80 60E)	1015·2−1015·5	> 4	2	3	5	8	4
15	PA(70 140)	1018·8	> 3	9	2	2	3	1
16	PA(60 50) −PA(70 140)	1009·3−1018·8	< -5	7	2	5	2	1
17	PA(60 50) −PA(70 140)	1009·3−1018·8	> 3	3	5	7	4	13
18	PA(35 160) −PA(70 140)	1020·9−1018·8	< -4	8	4	2	5	0
(c) May								
19	PA(70 120)	1019·6	> 2	9	8	8	6	0
20	PA(60 70)	1014·4	> 3	7	3	3	2	1
21	PA(30 10E) −PA(60 00)	1012·9−1014·6	< -4	0	3	6	6	7
22	PA(80 20E)	1018·1	> 4	8	5	1	2	1
23	PA(65 170E)−PA(80 20E)	1013·6−1018·1	$\leqslant -5$	7	7	1	1	3
24	PA(65 170E)−PA(80 20E)	1013·6−1018·1	> 5	1	3	2	6	6

Normal monthly pressure or pressure difference refers to the period 1873 to 1968.

Note : Quintile boundaries, based on period 1874 to 1963, are : $T_1 \leqslant 14{\cdot}5$; $14{\cdot}5 < T_2 \leqslant 15{\cdot}0$; $15{\cdot}0 < T_3 \leqslant 15{\cdot}4$; $15{\cdot}4 < T_4 \leqslant 15{\cdot}7$; $T_5 > 15{\cdot}7$°C.

TABLE IV—LAG ASSOCIATIONS BETWEEN VARIOUS COMBINATIONS OF RULES BASED ON MONTHLY PRESSURE ANOMALIES IN MARCH, APRIL AND MAY OVER THE NORTHERN HEMISPHERE AND SUMMER MEAN TEMPERATURE IN CENTRAL ENGLAND

Period	Predictor $N_c - N_w$	Summer temperature (quintiles) 1	2	3	4	5	Totals	*SS*
(a) March	$\geqslant 2$	9	10	4	0	0	23	2·4
	$\leqslant -1$	2	0	3	11	7	23	2·0
(b) April	$\geqslant 2$	13	6	3	3	1	26	2·0
	$\leqslant -2$	1	3	4	10	7	25	1·6
(c) May	$\geqslant 2$	10	7	1	1	1	20	2·4
	$\leqslant -1$	1	2	5	5	9	22	1·7
(d) March + April	$\geqslant 2$	14	14	4	2	2	36	2·0
	($\geqslant 5$)	(9)	(3)	(1)	(0)	(0)	(13)	(3·2)
	1	1	0	8	1	2	12	1·7
	$\leqslant 0$	2	5	10	14	15	48	1·4
	($\leqslant -2$)	(1)	(2)	(3)	(13)	(7)	(26)	(2·0)
(e) March + April + May	1 $\geqslant 3$	14	12	2	1	0	29	2·7
	($\geqslant 6$)	(9)	(5)	(0)	(0)	(0)	(14)	(3·2)
	2 1 or 2	3	4	10	3	4	24	1·1
	3 $\leqslant 0$	1	3	10	14	15	43	1·8
	($\leqslant -3$)	(1)	(0)	(1)	(8)	(5)	(15)	(2·2)

N_c and N_w are the number of individual rules (Table III) which indicate cool (quintiles 1 or 2) and warm (quintiles 4 or 5) summers respectively. *SS* is the mean Sutcliffe score.

Note : For a predictor value in brackets, the tercile distribution is shown in brackets.

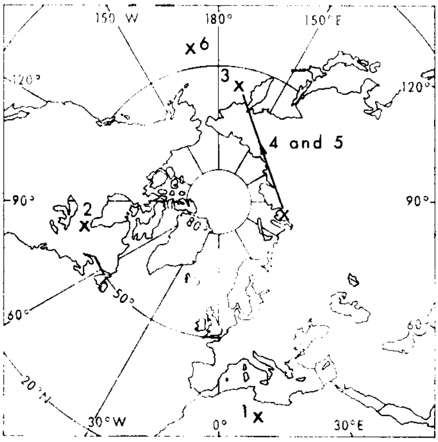

FIGURE 6 — POSITIONS OF SUMMER TEMPERATURE PREDICTORS BASED ON MARCH MEAN PRESSURE ANOMALIES GIVEN IN TABLE III (a)

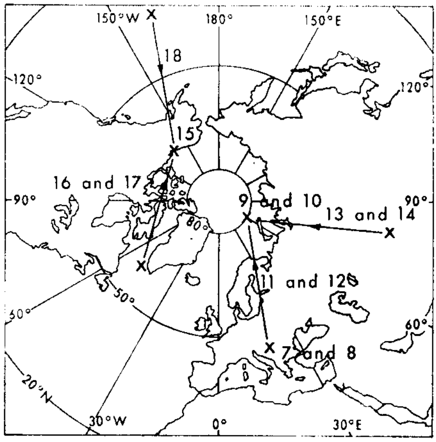

FIGURE 7 — POSITIONS OF SUMMER TEMPERATURE PREDICTORS BASED ON APRIL MEAN PRESSURE ANOMALIES GIVEN IN TABLE III (b)

Positions used in PA differences are joined by arrows.

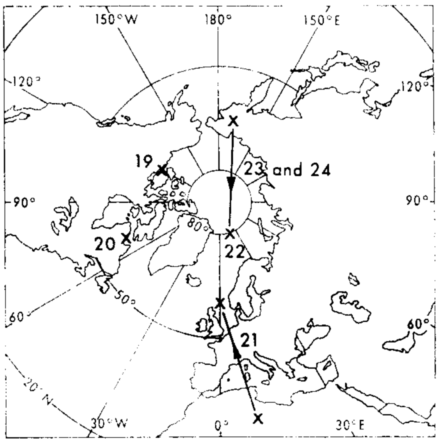

FIGURE 8—POSITIONS OF SUMMER TEMPERATURE PREDICTORS BASED ON MAY MEAN PRESSURE ANOMALIES GIVEN IN TABLE III (c)

Positions used in PA differences are joined by arrows.

seasonal forecasting. The composite summer mean pressure anomaly map for the cases satisfying the criterion $N_c - N_w \geqslant 6$ (Table IV, (e) 1) is shown in Figure 9. It is seen that negative pressure anomalies (significant at the 5 per cent level) occur over Scandinavia and in the Gulf of Alaska and significant positive pressure anomalies over central and north Canada and also over Asia centred at about 50°N 100°E. The less restrictive case $N_c - N_w \geqslant 3$ has a summer pressure anomaly pattern similar to but slightly weaker than that shown in Figure 9. The criterion $N_c - N_w \leqslant -3$, associated with warm summers, results in the composite map given in Figure 10 in which the mean pressure is significantly above average from the British Isles to

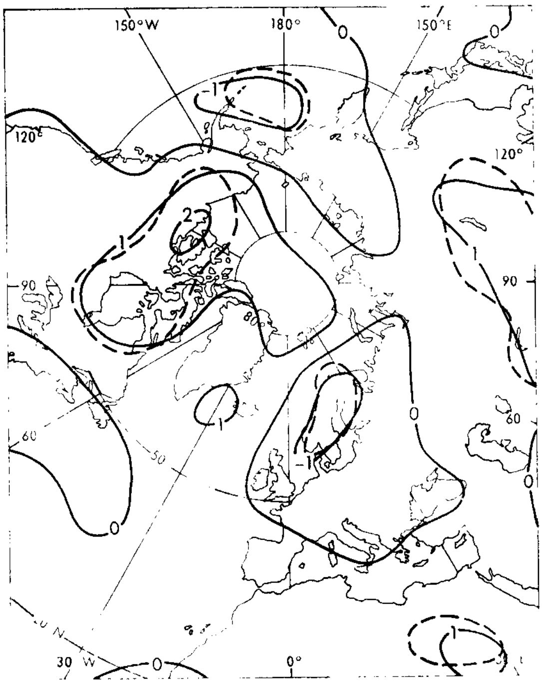

FIGURE 9—COMPOSITE MEAN PRESSURE ANOMALY PATTERN IN SUMMERS FOLLOWING SPRINGS SATISFYING THE TEMPERATURE PREDICTOR $N_c - N_w \geqslant 6$ GIVEN IN TABLE IV (e)1

See notes under Figure 1.

Scandinavia and below average in north-east Canada and north Greenland. The less restrictive criterion $N_c - N_w \leqslant 0$ gives a composite map rather like Figure 10.

The whole period was next subdivided into the 'westerly' and 'blocked' epochs, as was done for rainfall. For the main rule (e)1 of Table IV, when $N_c - N_w \geqslant 3$ the summer temperature distribution was 7, 7, 1, 1, 0 in the 'westerly' epoch and 7, 5, 1, 0, 0 in the 'blocked' epoch; for rule (e)3 when $N_c - N_w \leqslant 0$ the distribution was 0, 2, 5, 4, 7 in the 'westerly' epoch and 1, 1, 5, 10, 8 in the 'blocked' epoch. Again there seems little difference between the distributions in the two epochs.

In the recent decade 1960–69 the summers were generally in accord with the relevant predictors, except 1962. Actually, summer 1962 was fairly unusual in that it was very cool and dry. Although the temperature in summer 1962 was not in agreement with expectations from the predictors, the rainfall was well indicated by the predictive rules, as mentioned in the previous section. Data for summers 1970 and 1971 were not employed in deriving the rules in Table IV. The circulation parameters in spring 1970 correctly indicated a warm summer in 1970. The predictors in spring 1971 also suggested that summer 1971 would be warm (quintile 4 or 5) but in the event the mean temperature for June to August was only quintile 3, mainly because of the very cool June. However, as already mentioned in connection

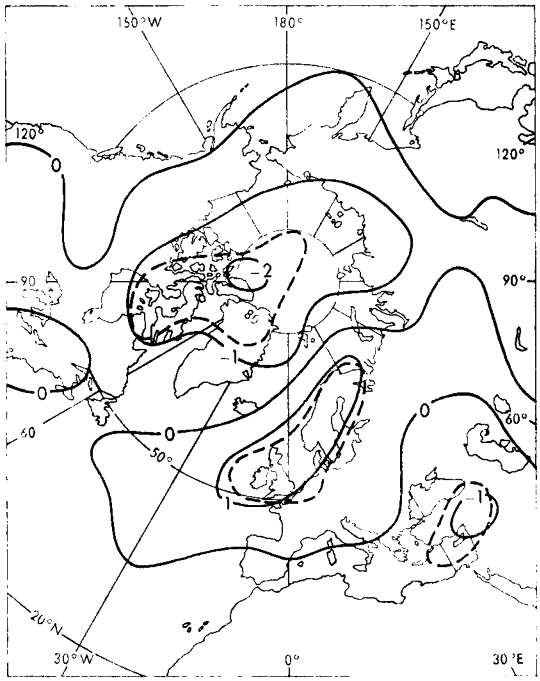

FIGURE 10—COMPOSITE MEAN PRESSURE ANOMALY PATTERN IN SUMMERS FOLLOWING SPRINGS SATISFYING THE TEMPERATURE PREDICTOR $N_c - N_w \leqslant -3$ GIVEN IN TABLE IV (e)3

See notes under Figure 1.

with rainfall in 1971, the summer was unusual. Any period of 3, 4 or 5 consecutive months from June to October 1971 except the conventional summer (June to August) was warmer than usual.

Conclusions. The predictive rules in this paper have been derived from an extensive analysis of monthly mean pressure anomaly data over the northern hemisphere since 1873. The general argument for the use of such data was given in an earlier paper.[1] Briefly, there is a complex interaction between atmospheric circulation and the physical processes operating within and at the lower boundary of the atmosphere (radiation, heat exchange from oceans, etc.). The detailed physical processes cannot be unravelled at present but they seem likely to be traced out in time as a result of highly sophisticated numerical research on the general circulation. Large-scale anomalous circulation, which is linked closely to these physical processes and to the rainfall and temperature which result from their interaction, can be represented to a first approximation by large-scale mean pressure anomalies.

The analysis of the long series of monthly mean pressure anomalies in March, April and May has brought to light several relationships, which are given in Tables II and IV. The main rules at (e) in these two tables can be applied on the great majority of occasions with considerable success. Whenever more stringent criteria are laid down, as indicated in brackets in these two tables, remarkably accurate predictions of summer rainfall and mean temperature can be made on a smaller number of occasions. It must of course be remembered that the method has been developed for the prediction of seasonal rainfall and temperature over a fairly large area. Predictions for a smaller space-scale (e.g. south-east England) and for a smaller time-scale (e.g. particular weeks or months) within the summer are not attempted. However, the broad procedure outlined in this paper has fairly general applications to regions other than England and Wales and to time-scales other than the summer season.

Acknowledgement. The writer wishes to thank colleagues in the Synoptic Climatology Branch, especially Mr M. J. Weller and Mr P. Collison, for their help in the data processing.

REFERENCES

1. MURRAY, R.; An objective method of foreshadowing winter rainfall and temperature for England and Wales. *Met Mag, London*, **101**, 1972, pp. 97–110.
2. MANLEY, G.; The mean temperature of central England 1698–1952. *Q J R Met Soc, London*, **79**, 1953, pp. 242–261.
3. MURRAY, R.; Some predictive relationships concerning seasonal rainfall over England and Wales and seasonal temperature in central England. *Met Mag, London*, **97**, 1968, pp. 303–310.
4. MURRAY, R.; A note on central England temperatures in quintiles. *Met Mag, London*, **99**, 1970, pp. 292–294.
5. SUTTON, O. G.; Prospects for this summer. *Weather, London*, **26**, 1971, pp. 180–181.
6. MURRAY, R.; A simple summer index with an illustration for summer 1971. *Weather, London*, **27**, 1972, pp. 161–169.

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FORECASTING TEMPERATURE FOR THE GAS AND ELECTRICITY INDUSTRIES*

By G. E. PARREY

Summary. The meteorological requirements of the gas and electricity industries are outlined and the procedure adopted at the Watnall Meteorological Office in forecasting temperatures for the East Midlands Gas Board is described in detail. The accuracy of the temperature forecasts supplied in November and December 1971 is discussed.

Meteorological requirements of the gas and electricity industries. The gas and electricity industries are among the most weather-sensitive industries there are in this country. Both, therefore, require regular weather forecasts so that they can estimate, accurately for up to 24 hours ahead and at least approximately for a further two or three days, what the demand for their product will be. The Central Electricity Generating Board (CEGB) must have the generating capacity available and the area Gas Boards must have the gas, whether manufactured or natural, in the right place at the right time, to meet that demand. In periods of reduced demand, in summer for example, both industries must have quite a high proportion of their plant out of commission for repair and maintenance, and the sudden onset of cold weather must not find them with insufficient equipment at operational readiness.

Each gas and electricity area grid control centre requires from its associated regional forecast office, frequent forecasts of temperature, cloud amount,

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height and thickness, visibility, precipitation, and wind speed and direction. A thick cloud layer and poor visibility, particularly fog, will result in an increased demand for day-time illumination; moderate or heavy precipitation and strong winds give rise to increased demand for heating — as do winds from certain directions; in the Midlands and south-east England, for example, north-easterly winds are said to have a greater chilling effect than winds of the same speed from other directions. But it will be obvious that temperature is the most important factor in determining the demand for both gas and electricity, and it is to the forecasting of temperatures for the grid control centres that this article will be confined.

Requirements for temperature forecasts. At the public service office at Watnall, near Nottingham, the principal forecasts of the day are issued in the early afternoon and the routine which is followed, between 13 and 15 hours (GMT in winter, GMT + 1 in summer) each day, will be described in detail. The office at Watnall is responsible for providing forecasts to the CEGB Grid Control Centres at Birmingham and Nottingham and to the East Midlands Gas Board Grid Control Centre at Leicester. The task which confronts the afternoon forecaster is illustrated in Table I. The CEGB grid

TABLE I—FORECAST TEMPERATURES REQUIRED FOR ISSUE AT 14–15 HOURS

CEGB	East Midlands Gas Board
Mean 06–09 h next day ($D+1$)	Every 2 hours from 17 h on current day (D) until 05 h on $D+2$
09–12	
...	Maximum for current day D and for $D+1$, $D+2$, and $D+3$
18–21	
	Minimum for $D+1$, $D+2$, $D+3$ and $D+4$

controls have a relatively simple requirement for 3-hourly mean temperatures covering most of the following day. On the other hand it will be seen that the Gas Board presents a much more formidable problem; forecast temperatures are required at 2-hourly intervals for the remainder of the current day, D, throughout the next day, $D + 1$, and up to 05 hours on the day after that, $D + 2$. In addition, maximum temperatures are required for the four days D to $D + 3$ and minimum temperatures for $D + 1$ to $D + 4$. The procedure adopted in meeting the requirement of the Gas Board will now be described.

Forecasting maximum and minimum temperatures. The East Midlands Gas Board area includes the heavily populated areas of Sheffield, Nottingham, Derby, Leicester and Northampton; it extends to the Lincolnshire coast to take in Grimsby and Cleethorpes and the boundary follows the Humber to include Goole, Scunthorpe and Doncaster before turning south-west to just north of Sheffield. The forecaster is not required to produce a mean temperature for the whole of that area, or temperatures at more than one place within the area; what he is required to do is to forecast for one reference point — in this case Watnall. Any wide differences expected within the Board's area are merely expressed in general terms, for example : 'three to five degrees colder near the east coast'.

By 13 hours the forecaster has a very good idea what the maximum temperature on the current day will be. His first major problem is, therefore, the minimum temperature during the following night, for the forecasting of which there are a number of well-known methods. The one in common use at Watnall is based on that due to Craddock and Pritchard[1] who considered data for 16 widely separated stations in England, all of them more than 10 miles (or 15 km) inland. The formula used is :

$$T_{min} = [0{\cdot}316T_{12} + 0{\cdot}548T_{d12} - 1{\cdot}24] + K,$$

where T_{12} and T_{d12} are the 12 GMT screen dry-bulb and dew-point temperatures (degrees Celsius) respectively, in the air mass which is expected to be over the station during the night. A diagram (Figure 1) can be constructed to give:

$$X = 0{\cdot}316T_{12} + 0{\cdot}548T_{d12} - 1{\cdot}24,$$

where $T_{min} = X + K$, from T_{12} and T_{d12}. The additional correction term K can be obtained from Table II according to the predicted overnight mean cloud amount and mean geostrophic wind speed.

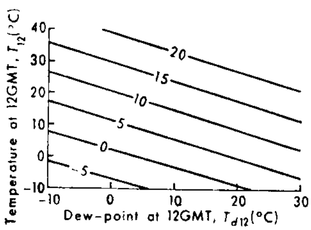

FIGURE 1—DIAGRAM FOR FINDING X IN EQUATION $T_{min} = X + K$

K is given in Table II.

TABLE II—CORRECTION K TO BE ADDED TO X TO OBTAIN FINAL ESTIMATE OF NIGHT MINIMUM TEMPERATURE

Mean geostrophic wind speed *knots*	Mean cloud amount (oktas) 0 to 2	2+ to 4	4+ to 6	6+ to 8
		degrees Celsius		
0–12	−2	−2	−1	0
13–25	−1	0	+1	+1
26–38	−1	0	+1	+1
39–51	+1	+2	+3	

X is given in Figure 1.

The Craddock and Pritchard method gives good results at Watnall in most circumstances, an exception being when there is an anticyclone centred over the area with clear skies and with no wind overnight. In this situation the method gives values which are generally too high and better results have been obtained by using a formula based on that due to Gold:[2]

$$T_{15} - T_{min} = 5{\cdot}7 + 0{\cdot}15T_{15} + 0{\cdot}4(T_{15} - T_{d15}),$$

where T_{15} and T_{d15} are the 15 GMT dry-bulb and dew-point temperatures (degrees Celsius) respectively. In this case, as there is likely to be little movement of air mass during the afternoon and following night, the 15 GMT temperatures at the station itself could be used. But as the forecast has to be ready for despatch by 15 hours, it is necessary to estimate the 15 GMT temperature by making a small adjustment to the latest available temperature (14 GMT in winter, 13 GMT in summer).

The next problem is the maximum temperature for the following day. When forecasting maximum temperatures for the current day it is usual to consider a suitable upper-air ascent plotted on a tephigram, make an adjustment to the lower layer for the maximum possible incoming solar radiation at the time of year, assuming clear skies, and then arrive at a forecast maximum temperature by making a further subjective modification according to the cloud amount and thickness, and perhaps also wind speed, expected during the day. This method cannot very well be used for the following and succeeding days and recourse is made to a method based upon an idea by Boyden,[3] who, bearing in mind that the vertical thickness in the atmosphere between the 1000- and 500-millibar levels is one of the easier meteorological quantities to forecast, related this thickness, and the season, to daily mean surface temperature. Later Boyden[4] extended the work to include wind direction and maximum surface temperature. At Watnall the 1000–500-mb thickness, geostrophic wind direction and month of the year have been related to both maximum and minimum surface temperatures. Five years of data (1964–68) have been analysed to give a series of eight diagrams, four in which the 1000–500-mb thickness at midnight is related to minimum temperature and time of year (one diagram for the wind from each of the quadrants north-east, south-east, south-west and north-west), and another four in which the midday 1000–500-mb thickness is related to maximum temperature, time of year and winds from each of the four quadrants. From these it is a simple matter to read off maximum and minimum temperatures for as many days ahead as one has forecasts of 1000–500-mb thickness and surface isobars. A sample diagram is shown in Figure 2. The diagrams have,

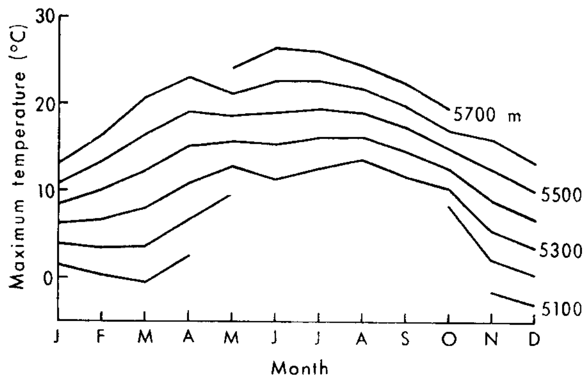

FIGURE 2—MAXIMUM TEMPERATURE RELATED TO 1000–500-mb THICKNESS FOR GEOSTROPHIC WINDS IN THE NORTH-WEST QUADRANT FOR EACH MONTH OF THE YEAR

of course, to be used with some discretion; for example, if the forecast surface chart indicates strong surface winds, one would obviously take a somewhat higher minimum temperature than that indicated on the diagram. As an aid in this respect, monthly extreme values of both maximum and minimum temperatures which occurred with given thicknesses during the five-year period in which data were collected, have been tabulated.

Forecast charts are issued from the Central Forecasting Office (CFO) at Bracknell by about 1230 GMT each day, showing isopleths of the 1000–500-mb thickness values and also the surface isobars and fronts for intervals up to midnight on $D + 3$. Thus, by the methods described, maximum and minimum temperatures can be forecast up to and including the minimum on $D + 3$. This still leaves the maximum on $D + 3$ and the minimum on $D + 4$. To derive these one or other of a number of regression formulae is used. For example :

$$T_{\max(D+3)} = \tfrac{1}{2}(T_{\max(D+2)} + T'_{\max}) ,$$

where $T_{\max(D+2)}$ is the maximum already forecast for $D + 2$ and $T'_{\max}$ is either the 5- or 10-day mean maximum for the station. At Watnall, 10-day means for the period 1941–70 are used. Minimum temperatures can be derived from similar equations, using $T'_{\min}$ as a mean minimum for the station, and proceeding as far as $D + 4$ with the equation :

$$T_{\min(D+4)} = \tfrac{1}{2}(T_{\min(D+3)} + T'_{\min}) .$$

When the situation is particularly difficult, an equation of the type :

$$T_{\max(D+3)} = \tfrac{1}{3}(T_{\max(D+1)} + 2T'_{\max})$$

gives the maximum on $D + 3$ from the maximum temperature forecast for $D + 1$ and the 10-day mean, but in this case with more weight given to the mean.

Forecasting temperatures for 2-hourly intervals. The final task is to forecast temperatures for 2-hourly intervals during the first 38 hours of the forecast period. A useful aid has been found in another series of diagrams which show the mean hourly temperatures at Watnall in each month of the year, constructed from 1961–70 data. Figure 3 shows the curves for January

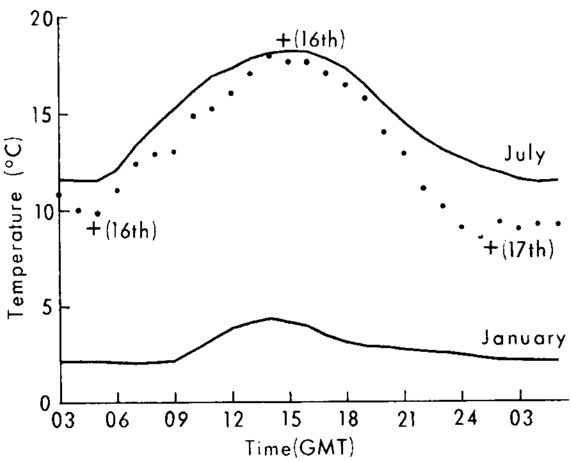

FIGURE 3—HOURLY TEMPERATURES FOR JANUARY AND JULY AT WATNALL

——— Mean hourly temperatures 1961–70
. . . Hourly temperatures from 03 GMT on 16 July 1971 to 05 GMT on 17th
\+ Maximum and minimum temperatures 16–17 July 1971

and July. The curve for the current month is placed behind a transparent sheet and the procedure is to mark the forecast maximum and minimum temperatures for the 38-hour period at the times one expects them to occur and then, using the mean curve as a guide, draw in a forecast curve, bearing in mind such possibilities as the development of convection cloud, shower activity, clearance of cloud in the evening, increase in frontal cloud, or even the passage of a front. The CFO forecast charts give guidance as to the likelihood of any of these occurrences. As an example, Figure 3 also shows the actual hourly temperatures recorded during a period taken at random from July 1971. These follow the shape of the mean curve for July fairly well until 09 GMT when convection cloud first developed and the rise of temperature was temporarily checked. The curve of falling temperature in the late afternoon was almost parallel to the mean until 19 GMT when the cloud dispersed and the fall became much more rapid. Between 01 and 02 GMT a layer of stratocumulus spread over, followed by a slight rise of temperature. It is not of course pretended that *all* these variations can be correctly forecast or even attempted. The three crosses in the figure show the recorded maximum and two minimum temperatures. The fact that they all lie outside the curve of hourly temperatures illustrates the fact that maxima and minima rarely occur precisely on the hour and therefore hourly, or 2-hourly forecast temperatures need not necessarily include the forecast extremes.

The task is now complete, but it remains to be said that although the next full forecast, as described, will not be issued until 24 hours hence, the forecast temperatures are kept constantly under review and are either amended or confirmed in routine messages to the grid control centres at approximately 4-hourly intervals.

Accuracy of forecasts. The programme described has only been in operation for the East Midlands Gas Board since 1 November 1971 and it is too early to make a conclusive assessment of the accuracy of the temperature forecasts made. However, forecasts issued in November and December 1971 have been checked and the results are shown in Tables III and IV. Before it became the practice to issue routine reassessments at 4-hourly intervals, it was a Gas Board (and CEGB) requirement that amendments be issued whenever it was evident that the forecast temperatures were likely to be more than 2 degC in error. It is reasonable, therefore, to regard 'successful' forecasts as those in which the error was within ± 2 degC. Errors in this range are grouped together in the tables. The few very large errors which occurred

TABLE III—PERCENTAGE FREQUENCY OF VARIOUS RANGES OF ERRORS IN TWO-HOURLY TEMPERATURE FORCASTS FOR D, $D + 1$ AND $D + 2$, ISSUED BY WATNALL AT 15 HOURS DURING NOVEMBER AND DECEMBER 1971

Error	*D*				*D* + 1												*D* + 2			
	17	19	21	23	01	03	05	07	09	11	13	15	17	19	21	23	01	03	05 hours
degC									*percentage*										
0–2	100	97	87	82	79	70	69	66	73	77	79	79	71	74	71	74	66	61	59
3		3	11	13	13	18	13	13	10	10	12	10	20	13	18	13	18	18	19
4			2	3		3	8	11	8	7	5	8	2	10	7	7	8	11	7
5				2	7	5	7	5	5	3	2	3	6	2	3	2	3	3	8
6								2	1	2	1		1	1		3		2	2
7					1	2			3	1	1						2		
8								2							1	1	3	3	2
9						2	3	1											3
10																		2	

TABLE IV—PERCENTAGE FREQUENCY OF VARIOUS RANGES OF ERRORS IN MAXIMUM AND MINIMUM TEMPERATURE FORECASTS FOR $D + 1$ TO $D + 4$, ISSUED BY WATNALL AT 15 HOURS DURING NOVEMBER AND DECEMBER 1971

	$D + 1$		$D + 2$						$D + 3$						$D + 4$		
Error	Min.	Max.	Minimum			Maximum			Minimum			Maximum			Minimum		
				M	P		M	P		M	P		M	P		M	P
degC								*percentage*									
0–2	82	84	74	36	51	74	44	49	64	46	57	64	46	46	54	39	48
3	13	8	7	18	17	12	18	18	18	16	5	15	18	16	17	17	10
4	5	2	10	20	15	8	26	8	10	16	3	7	21	10	19	20	10
5		5	2	13	8	3	7	7	3	11	20	6	7	3	3	11	7
6			3	8	3		3	5	2	7	2	3	5	10	2	8	13
7			3	3	3	3	1	5		3	7	5	2	7	3	3	8
8		1	1		2		1	7	3		2		1	3	2		1
9				2	1			1		1	3			5		2	
10											1						3

M Using 10-day means P 'Persistence', using maximum or minimum on day *D*.

were due to such causes as the mistiming of fronts, etc. and would undoubtedly have been corrected in subsequent amending messages. From Table III it will be seen that there is a marked decline in the successful percentage during the early morning of $D + 1$ with a recovery in the afternoon. The cause for this will have to be investigated but as most of the very large errors on $D + 1$ occurred during the early morning, and as Table IV shows that the minimum temperatures on $D + 1$ were quite well forecast, the reason may be the wrong *timing* of the latter due, in turn, to bad timing of fronts, changes in cloud amount, etc.

To illustrate how the forecasts compared with (a) the corresponding mean temperatures and (b) persistence, Table IV also shows the errors which would have resulted if the mean or persistence had been used for maximum and minimum temperatures on $D + 2$ and $D + 3$ and for the minimum on $D + 4$. The 'mean' was taken as the appropriate 10-day mean and for 'persistence' the minimum and maximum temperatures on the day of issue were used.

REFERENCES

1. CRADDOCK, J. M. and PRITCHARD, D.; Forecasting the formation of radiation fog — a preliminary approach. London, Meteorological Office, 1951. (Unpublished, copy available in the Meteorological Office Library, Bracknell.)
2. GOLD, E.; Prediction of minimum temperatures at Larkhill. *Met Mag, London*, **69**, 1934, pp. 88–90.
3. BOYDEN, C. J.; The forecasting of daily mean surface temperature from 1000–500-millibar thickness lines. *Met Mag, London*, **87**, 1958, pp. 98–105.
4. BOYDEN, C. J.; Forecasting of maximum surface temperature from 1000–500-millibar thickness lines. *Met Mag, London*, **91**, 1962, pp. 242–246.

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INVESTIGATION OF A UNITED STATES MIDWEST TORNADO

By E. C. W. GOLDIE and J. M. HEIGHES

Summary. A major tornado outbreak occurred in the United States Midwest on Palm Sunday, 11 April 1965. This outbreak is considered in relation to the aerological situation, and one of the 37 reported tornadoes is selected for investigation. The tornado in question passed within about half a mile of an anemometer, and winds of up to 150 miles/h were recorded. A geometrical method for analysing tornado wind records is discussed, which makes use of the concept of the irrotational vortex. A computerized version of this method was used to analyse the wind record of the Palm Sunday tornado, and useful results were obtained.

Introduction. The United States Midwest is the most tornado-prone region in the world. The highest frequency of tornadoes occurs in Kansas and Oklahoma; both of these states have one tornado per year per 35-mile square on average. However, the frequency of tornadoes is high from the southern shores of the Great Lakes, down the western side of the Mississippi valley as far as north-east Texas. Every spring tornado outbreaks occur in this region, killing and injuring people, and causing serious property damage.

On Palm Sunday, 11 April 1965, no less than 37 tornadoes were reported over six of the northern states in the United States Midwest. The death toll in these tornadoes was 258, over 3000 people were injured, and property damage was estimated at around 250 million dollars. This was one of the worst tornado disasters ever known anywhere in the world.

Autographic records showing the passage of a tornado are seldom obtained. Wind information is especially valuable, since the manner in which the tornado circulation is formed within the larger circulation of the parent thunderstorm is not well understood at present. Fortunately, two of the Palm Sunday tornadoes passed close to an anemometer without damaging it, and useful records were obtained. The passages of both tornadoes were actually recorded by the same anemometer, which was located near Tecumseh, Michigan (42°N 84°W). The tornadoes passed by the anemometer at 1907 and 2004 CST, respectively (CST is 6 hours behind GMT). The first one resulted in a maximum gust of 150 miles/h* being recorded by the anemometer. This is the tornado which is the subject of the present investigation.

The tornado situation of 11 April 1965. On 11 April 1965, a deep depression moved quickly east-north-eastwards over the Great Lakes region. The depression had a well-marked warm sector, in which warm moist air flowed north-north-eastwards at low levels on the south-east flank of the depression. This warm moist air originated over the Gulf of Mexico on the 9th/10th. A warm front extended eastwards from the depression, with much colder air to the north of it. This front made only slow progress northwards. At the same time, cool dry air was advected rapidly eastwards on the south flank of the depression, behind a dry cold front.

A detailed aerial survey of the damage tracks of the Palm Sunday tornadoes was carried out a few days after the outbreak, and the results were published (Fujita *et alii*[1]). Figure 1 of the present paper is based on Figure 48 of the paper by Fujita. Figure 1 shows the tracks of the storms or storm groups which produced tornadoes. The positions of the storms at hourly intervals (CST) are marked. Continuous lines denote lengths of storm track along which tornadoes occurred. It can be seen that tornadic activity commenced in eastern Iowa at 1230 CST and ended in central Ohio shortly after 23 CST. The positions of Flint, Dayton, Peoria and Green Bay are shown, these being the four upper-air stations nearest to the tornado area.

Figures 2 and 3 show upper-air temperatures and winds, respectively. These are based on the 1800 CST soundings made at Flint and Dayton, using data on microfilm (U.S. Department of Commerce[2]). Wind data were not available for Dayton between 475 and 65 mb, but winds between these levels were estimated in order that Figure 3 could be constructed. Figure 1 shows that an ascent intermediate between those for Flint and Dayton should be representative of the area which was just ahead of the tornadoes at 1800 CST.

* 1 mile/h ≈ 0·45 m/s

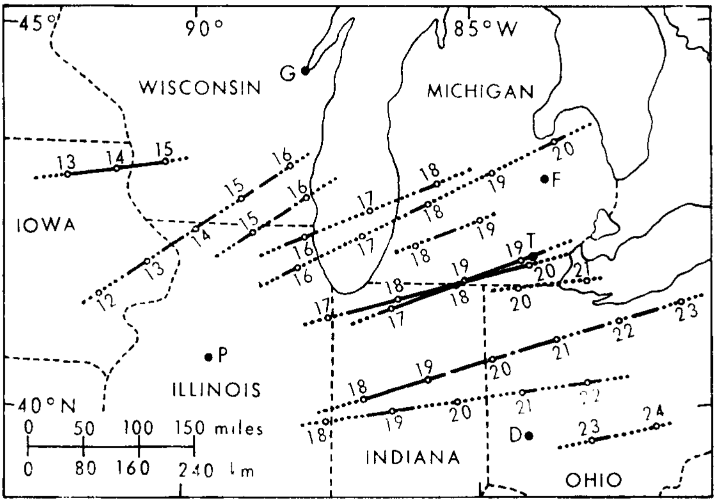

FIGURE 1—TRACKS OF THUNDERSTORMS PRODUCING TORNADOES ON 11 APRIL 1965 (after Fujita *et alii*,[1] Figure 48)

Continuous lines denote occurrence of tornadoes. Positions of storms are at hourly *(CST)* intervals.

F = Flint D = Dayton P = Peoria G = Green Bay T = Tecumseh

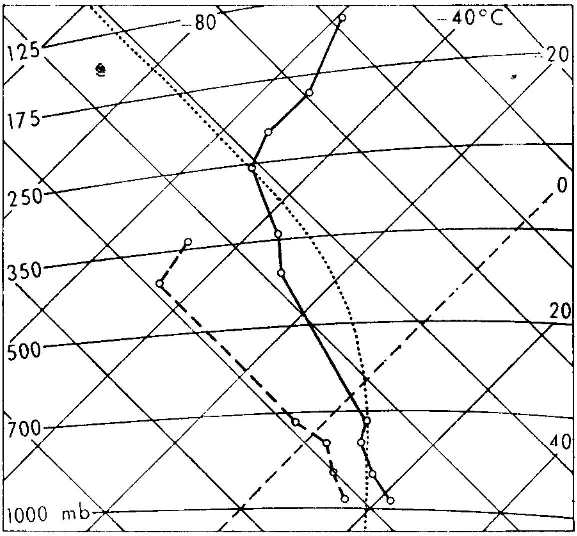

FIGURE 2—TEMPERATURE SOUNDING FOR 18 CST ON 11 APRIL 1965 (MEAN OF FLINT AND DAYTON)

——— Dry-bulb temperature – – – Dew-point temperature
...... Saturated adiabatic for wet-bulb potential temperature = 19°C

The important features to note on Figures 2 and 3 are (a) the warm moist air at low levels, (b) the stable layer near 750 mb, (c) the deep layer of dry air above the stable layer, (d) the steep lapse rate in the moist low-level air, and in the dry air above the stable layer, (e) the strong vertical wind shear in the lower and middle troposphere, and (f) the marked wind veer with height, especially at lower levels, indicating geostrophic warm advection. The upper-air structure as revealed in Figures 2 and 3 is fairly typical of a severe-storm situation (e.g. Fawbush and Miller[3]).

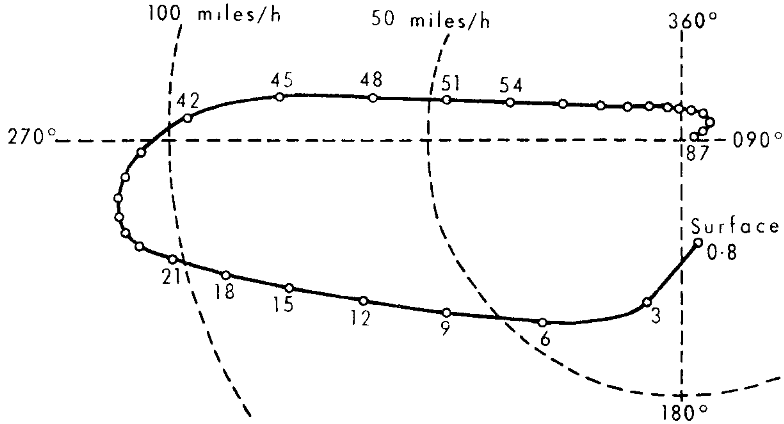

FIGURE 3—UPPER WINDS FOR 18 CST ON 11 APRIL 1965 (MEAN OF FLINT AND DAYTON)

Heights (above MSL) are at intervals of 3000 ft and in thousands of feet.
Based on tabulations by the U.S. Department of Commerce.[2]

All the tornadoes occurred in the warm sector of the depression, just ahead of the dry cold front. Flint and Dayton were both in the warm sector at 1800 CST, while Peoria was in the cool dry air behind the cold front and Green Bay was in the cold moist air to the north of the depression. Tornadoes are a by-product of the intense convective activity which takes place within severe thunderstorms. The upper-air ascent shown in Figure 2 is potentially very unstable, but the stable layer near 750 mb allowed only shallow convection to occur in most of the warm sector. Convective cells penetrated the stable layer west of Flint and Dayton (at 18 CST); this was presumably because of a combination of low-level convergence ahead of the dry cold front and moister air being advected in from the south. In the absence of forced upward motion, the wet-bulb potential temperature of the low-level air would need to be at least 19°C before this air was sufficiently buoyant to penetrate the stable layer. The temperature in the storm updraughts is therefore assumed to have followed the dotted curve shown in Figure 2, i.e. the saturated adiabatic corresponding to a wet-bulb potential temperature of 19°C. Once the stable layer was penetrated, convection proceeded explosively, leading to the development of a number of severe storms. If the temperature curves shown in Figure 2 are correct, they indicate maximum vertical velocities in the storm updraughts of 107 miles/h, and storm tops at 167 mb. In fact, storm tops at 45 000 feet ($\approx$ 150 mb) were actually reported (Weather Bureau Survey Team[4]).

In addition to the exceptional number of tornadoes on Palm Sunday, there were reports of torrential rain, large hailstones, (2·5 cm or more across), intense electrical activity, and severe thunderstorm gusts not associated with tornadoes. Severe thunderstorm gusts are normally associated with high surface temperatures; day maximum temperatures were around 23°C over most of the area affected by the severe storms. Applying the formula originated by Fawbush and Miller[5] to the upper-air ascent (Figure 2), maximum gusts of 60 miles/h would be predicted. However, gusts of up to 80 miles/h were actually reported (Weather Bureau Survey Team[4]). It should be noted here that the severe storms (and their accompanying tornadoes) advanced at speeds ranging from 40 to 60 miles/h.

Analysis of the Tecumseh wind record. Table I gives wind data covering the period of the first of the two Tecumseh tornadoes. The winds tabulated are derived from the Tecumseh anemometer record, and represent gust averages over a minute, centred on the time given.

TABLE I—ANEMOMETER READINGS AT TECUMSEH ON 11 APRIL 1965

Time	Wind		Time	Wind		Time	Wind	
CST	*deg*	*miles/h*	*CST*	*deg*	*miles/h*	*CST*	*deg*	*miles/h*
1846	150	26	1902	132	54	1910½	231	48
1847	150	22	1903	129	66	1911	228	43
1848	152	24	1903½	133	65	1911½	216	29
1849	148	23	1904	136	73	1912	201	22
1850	138	36	1904½	156	60	1913	202	30
1851	139	33	1905	240	51 (1)	1914	211	20
1852	144	31	1905½	242	78 (2)	1915	227	15
1853	142	38	1906	239	83 (3)	1916	225	15
1854	138	36	1906½	235	67 (4)	1917	225	28
1855	140	38	1907	238	122 (5)	1918	226	19
1856	139	38	1907½	264	149 (6)	1919	245	18
1857	139	40	1908	283	109 (7)	1920	244	22
1858	139	36	1908½	284	89 (8)	1921	257	28
1859	139	47	1909	286	74 (9)	1922	210	26
1900	135	42	1909½	271	64 (10)	1923	199	10
1901	133	41	1910	228	64	1924	202	21

Note : 1 mile/h ≈ 0·45 m/s, Values (1) to (10) were used in the construction of Figure 6.

This wind information is based on that contained in the paper by Fujita.[1] According to Fujita, the tornado travelled in an almost straight line on a bearing towards 073°, its forward speed was 60 miles/h, and at the time of closest approach (given as 1907·4 CST) the centre was 1·2 miles north of the anemometer. Fujita also states that the winds are consistent with an irrotational vortex, i.e. one in which Vr = constant, where V = velocity of air particle relative to tornado and r = radial distance of air particle from centre. The constant for the first Tecumseh tornado is given as 90 miles^2/h, this constant being valid for radii between 0·5 and 2·5 miles.

It is likely that tornadoes in general are approximately irrotational at low levels, in other words the inflow results in angular momentum being conserved. However, this does not apply in the cores of tornadoes, in which solid rotation is believed to occur. Considerable use may be made of the concept of the irrotational vortex in the analysis of tornado wind records. Provided that the tornado is irrotational, is in a steady state, and is travelling in a straight line at a constant speed, it can be proved that if the winds in such a tornado were recorded by an anemometer, the hodograph plot of these winds would trace out a circle which started and finished at the point representing the undisturbed wind. The undisturbed wind in this case refers to the undisturbed wind velocity in the air mass in which the tornado is assumed to be embedded. It should be emphasized here that for an irrotational tornado, its own forward velocity and that of the undisturbed wind must be assumed to be equal.

Figure 4 shows a plan view of a theoretical tornado track in relation to an anemometer, *A*. The angle of inflow of the relative winds, ε, is assumed to be constant for any particular tornado. Figure 5 shows the hodograph plot

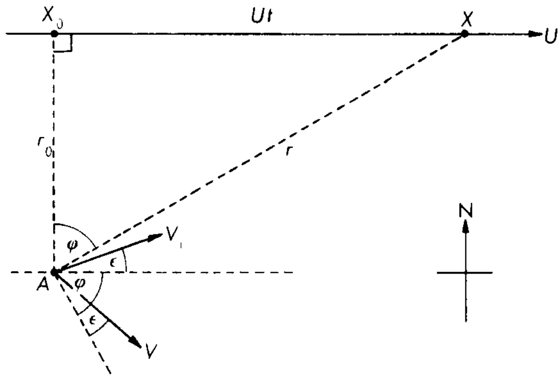

FIGURE 4—PLAN VIEW SHOWING TORNADO TRAVELLING EASTWARDS AT SPEED *U* ON A TRACK WHICH LIES TO THE NORTH OF AN ANEMOMETER *A*

X_0 Position of centre at time of closest approach T_0
X Position of centre at time $T_0 + t$

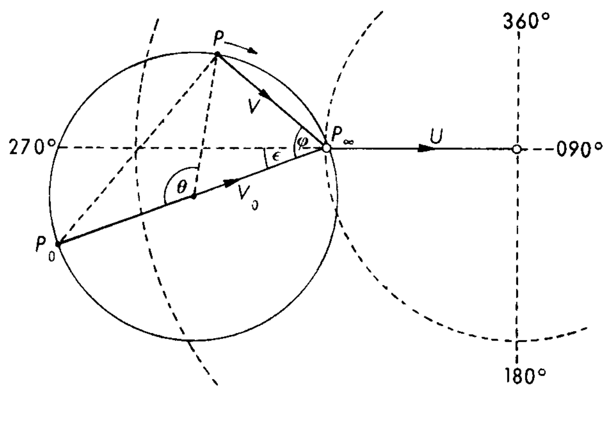

FIGURE 5—THEORETICAL CIRCULAR PATH, *P*, TRACED OUT BY WINDS (AS IN FIGURE 4) ON HODOGRAPH

The path starts and ends at P_∞. $P_0P_\infty = V_0$ = wind component due to tornado at time T_0. Since $(V\cos\varepsilon)r = (V_0\cos\varepsilon)r_0$ and $r = r_0/\cos\varphi$, $V = V_0\cos\varphi$, and thus the locus of P is a circle of diameter P_0P_∞.

of the winds corresponding to the tornado track depicted in Figure 4. Two very useful relationships emerge from Figures 4 and 5. From Figure 4 it can be seen that

$$\varphi = \tan^{-1}\left(\frac{Ut}{r_0}\right)$$

while from Figure 5 it can be seen that $\theta = 2\varphi$. Note that t is the time interval between closest approach and actual position, and that U and r_0 are constant for any particular tornado.

A casual inspection of the winds (see Table I) suggested that those from 1905 to 1909½ CST inclusive might describe an approximate circle if plotted on a hodograph. These winds were therefore plotted and analysed. The purpose of the analysis was to obtain the best possible fit between the 10 winds as estimated in Table I and their 10 theoretical counterparts, as defined by the relationship $\theta = 2\tan^{-1}(Ut/r_0)$ and thereby obtain values for six constants connected with the tornado, namely α, U, V_0, T_0, r_0 and ε, where α is the direction from which the tornado has come, U is the speed of travel of the tornado, V_0 is the relative wind speed at closest approach, T_0 is the time of closest approach, r_0 is the distance of the centre of the tornado from the anemometer at time T_0, and ε is the angle of inflow of the relative winds.

The analysis was carried out in two stages. The first stage consisted of geometrical construction, from which provisional values for the constants were obtained. The second stage consisted of a computerized version of the first stage; a computer programme was written, by means of which equations based on the geometry of Figures 4 and 5 were solved a large number of times, starting with the provisional values for the constants obtained in the first stage, and using these to obtain a minimum variance between observed and calculated wind velocities at half-minute intervals. The final values obtained for α, U, V_0, T_0, r_0 and ε were 261°, 59 miles/h, 91 miles/h, 1907·43 CST, 0·48 miles and + 4°, respectively. However, it should be emphasized here that the basic data do not really justify the degree of accuracy implied in the above results.

Using the values for the constants given above, it is possible to deduce the theoretical wind at any time. Figure 6 shows a simple method for deducing these winds at specific times. Values of θ were obtained at half-minute intervals from 1905 to 1909½ CST by substituting appropriate values of U, r_0 and t in the equation $\theta = 2\tan^{-1}(Ut/r_0)$ where t is measured from T_0 = 1907·43 CST. The angles θ were marked as radial intersections on the circle, as shown in Figure 6. These radial intersections give the ends of the theoretical wind vectors at specific times at half-minute intervals, and these may be compared directly with the wind data (dots, numbered from 1 to 10). Fairly good overall agreement will be noted between the two sets of winds.

There is one point worth mentioning in connection with the value obtained for α. The value obtained above was 261°, whereas the value given by Fujita[1] was 253°. This value of 253° was obtained from measurements of the track of the storm which gave the first Tecumseh tornado, as recorded on radar film. The damage track of the tornado itself was many miles in length, and measurements of this confirmed the value of 253°, which may therefore be taken as reasonably reliable. A possible explanation for the discrepancy

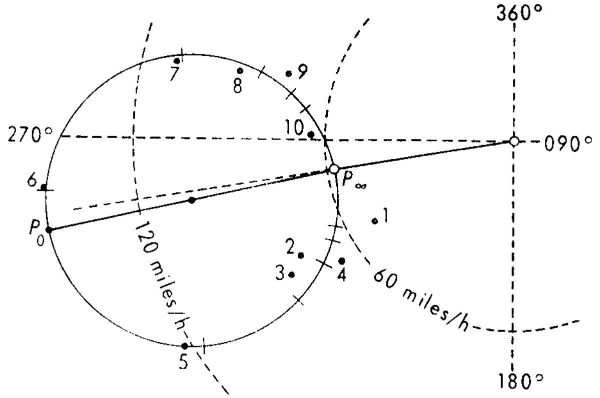

FIGURE 6—CIRCLE OF BEST FIT (AS DEDUCED BY COMPUTER) TO WINDS FROM 1905 TO 1909½ CST

. Values 1 to 10 were obtained from Table I (1) to (10).
Radial intersections give theoretical winds at the same times.

of 8° is that the wind directions recorded by the anemometer were systematically too veered. Had 8° been subtracted from all the directions at the start, this would have resulted in a value for α of 253°.

Finally, it is worth considering the probable position of the tornado in relation to the larger circulation of the parent thunderstorm. Figure 7 shows the winds from Table I plotted with respect to time. It is suggested here that the major direction discontinuity at 1905 CST was caused by the passage of a vigorous gust front. If this is so, it means that the tornado was embedded in the cool outflow air, about 2½ miles behind the gust front. However, at 1907½ CST the tornado was nearing the end of its lifetime, and it seems quite possible that it actually formed slightly ahead of the gust front, and subsequently became engulfed in the cool air without losing its circulation. A temperature discontinuity of perhaps 8 degC existed at the top of the cool

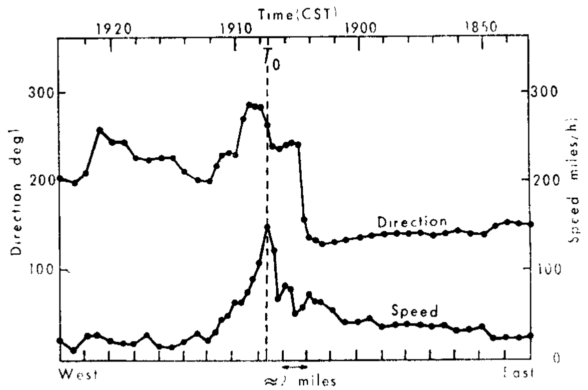

FIGURE 7—PLOT OF WINDS FROM TABLE I

An equivalent distance scale is given based on the tornado's forward speed of 1 mile/minute. T_0 is time of closest approach of tornado.

air, about 3000 feet above the surface; this suggests that in its later stages the tornado circulation may have been limited to the lowest 3000 feet of the atmosphere.

REFERENCES

1. FUJITA, T. T., BRADBURY, D. L. and VAN THULLENAR, C. F.; Palm Sunday tornadoes of April 11, 1965. *Mon Weath Rev, Washington*, **98**, 1970, pp. 29–69.
2. Washington, U.S. Department of Commerce, Weather Bureau. Daily Series, Synoptic Weather Maps, Part II Northern Hemisphere Data Tabulations. Washington, 1965.
3. FAWBUSH, E. J. and MILLER, R. C.; The types of airmasses in which North American tornadoes form. *Bull Amer Met Soc, Lancaster, Pa*, **35**, 1954, pp. 154–165.
4. Washington, U.S. Weather Bureau, Weather Bureau Survey Team. Report of Palm Sunday tornadoes of 1965. Washington, 1965.
5. FAWBUSH, E. J. and MILLER, R. C.; A basis for forecasting peak wind gusts in non-frontal thunderstorms. *Bull Amer Met Soc, Lancaster, Pa*, **35**, 1954, pp. 14–19.

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AN INTERESTING WEATHER PHENOMENON IN AN ICELANDIC FIORD

By R. BOJDYS

The weather reported in this note was experienced by the author when he was the meteorologist aboard M.V. *Miranda*, 1460 tons, the support ship to the British fishing fleet in waters around Iceland.

Description. Stormy weather had persisted in the region of the Denmark Strait for a number of days. On the morning of 30 December 1971 most of the fishing fleet moved to more sheltered fishing grounds to the north and north-east of Iceland, and at 10 GMT *Miranda* took shelter in Dyrafjörður, a long narrow fiord on the north-west coast of Iceland. *Miranda* had experienced moderate to heavy rain continuously since midnight. Dyrafjörður (Figure 1), some 35 km long and 4 km wide, is well sheltered on three sides by ranges

FIGURE 1—MAP OF NORTH-WEST ICELAND

X Position of M.V. *Miranda* in Dyrafjörður on 30 December 1971
Keflavík is about 120 n.miles to south-south-east.

of snow-covered mountains which in parts rise steeply to heights of 600–900 m (2000–3000 ft) within a horizontal distance of 2 km from the shore.

On the sea at the foot of the mountains there appeared long shallow ribbons of white sea spray which looked like fine veils. These ribbons were 7–10 m high; frequently they extended to the height of *Miranda's* bridge. They formed on all three sides of the fiord. Usually their length was between 30 and 100 m, though occasionally one was as long as 200 m. Each veil moved rapidly in a twisted pattern towards the axis of the fiord. Individual recognizable elements lasted for about 10 seconds, often merging with other veils; meanwhile new veils formed almost immediately at the foot of the mountains. None of the veils reached *Miranda*, whose shortest distance to the coast was between 2 and 3 km, but some approached to within an estimated distance of 100 to 50 m before dissipating. It is estimated that visibility inside the veils would be reduced below 100 m.

Comment. At 12 GMT on 30 December 1971 a depression with central pressure 972 mb was centred at 64°N 40°W and the gradient wind over the fiord was 200°, 50 kt. When the veils were observed, surface wind in the fiord was 130°, 45–50 kt with gusts to 90 kt, air temperature was 7°C and sea surface temperature (measured by the bucket method) was 3°C. The tephigram from Keflavík at 00 GMT on 30 December 1971 (Figure 2) showed

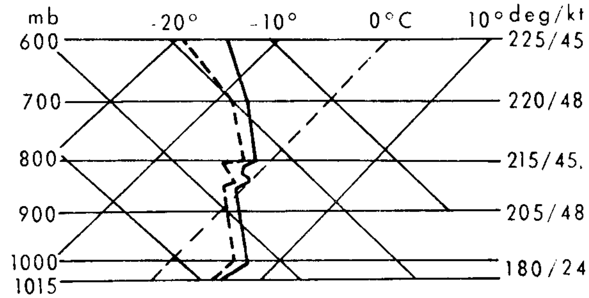

FIGURE 2—TEPHIGRAM FROM KEFLAVIK AT 0000 GMT ON 30 DECEMBER 1971

——— Temperature – – – Dew-point

moist air to 5000 m and winds changing little with height — on average 220°, 45 kt, i.e. across the fiord. There was an inversion with base 865 mb, and it is estimated that lifting over the mountains on the south side of the fiord would cause this to rise to about 800 mb. The tephigram from Keflavík at 12 GMT (Figure 3) showed moist air to 1500 m, dry air from 1500 m to 4000 m, then moist air to 8000 m. Wind structure was similar to that at 00 GMT, the average value being 200°, 55 kt. The inversion with base 865 mb was more marked, and lifting over the mountains would again cause this to rise to about 800 mb.

With an inversion just above the tops of the mountains, the air presumably travels along the length of the fiord as though it is trapped in a tunnel between the mountains, the inversion and the sea surface, and the angle at which the surface wind is inclined to the gradient wind (in this case about 70 degrees) is determined solely by the direction in which the fiord lies. As winds do not increase with height, conditions are not suitable for the formation of lee waves.

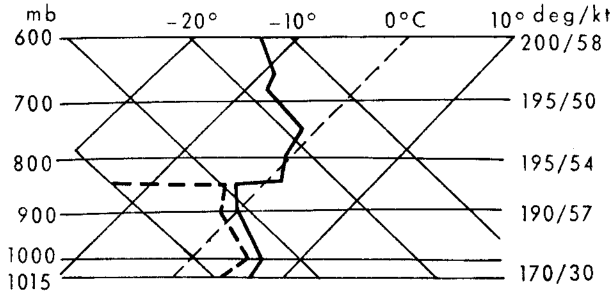

FIGURE 3—TEPHIGRAM FROM KEFLAVIK AT 1200 GMT ON 30 DECEMBER 1971

——— Temperature — — Dew-point

It may be that turbulent rollers are produced in the fiord with their axes parallel to the mountains and rotating with their undersides moving towards the sides of the fiord. The upcurrents at the sides of the fiord would produce the veils which then move to the middle of the fiord on the top sides of the rollers and dissipate in the downcurrents.

REVIEWS

The changing climate, by H. H. Lamb. 233 mm × 154 mm, pp. xi + 236, *illus.*, Methuen and Co. Ltd, 11 New Fetter Lane, London, EC4, 1972 (Paperback edition). Price: £1·10.

This book is a collection of eight papers by H. H. Lamb which originally appeared in various journals between 1959 and 1964. The collection was first published by Methuen in 1966 and is now reissued virtually without change as a University paperback.

The book is well produced and the diagrams are reasonably clear and the whole will form useful first reading for university and other students. The main criticism must inevitably be that the book is out of date. There can be few scientific fields in which progress has been slow over the last eight years and although there may not have been startling progress in the study of climate, advances have been made in this field too. Since 1966 Lamb himself has published several major works, notably his study of 'Volcanic dust in the atmosphere'[1] and also his major paper on 'Climates and circulation regimes developed over the northern hemisphere during and since the last ice age'.[2]

In 1972 a book on the changing climate should refer to current progress in developing a satisfactory numerical model for use in climate change studies (much work on this subject has been done in America by the Smagorinsky group). The book should also refer to the possibility that man himself has now reached the stage where he may be affecting the global climate by means of carbon dioxide or other effluents, by increasing the dust content of the atmosphere or even by the production of heat in industrial conurbations.

In short the book is concerned almost entirely with climatic history and gives little indication of the pitfalls which threaten extrapolation of past trends into the future. It is hoped that the author will bring out a more complete and up-to-date book, remedying these omissions, in the near future.

R. A. S. RATCLIFFE

REFERENCES

1. LAMB, H. H.; Volcanic dust in the atmosphere; with a chronology and assessment of its meteorological significance. *Philos Trans R Soc, London*, A, **266**, No. 1178, 1970.
2. LAMB, H. H.; Climates and circulation regimes developed over the northern hemisphere during and since the last ice age. *Palaeogeogr, Palaeoclim, Palaeoecol, Amsterdam*, **10**, 1971, pp. 125–162.

Climate: Present, past and future, Volume 1, Fundamentals and climate now, by H. H. Lamb. 255 mm × 195 mm, pp. xxxi + 613, *illus.*, Methuen and Co. Ltd, 11 New Fetter Lane, London, EC4, 1972. Price: £11.

Twenty or so years ago one knew what to expect in a book on climate. Its theme would be the averages of temperature, rainfall, cloudiness and so on, and their seasonal and geographical variations. A rather prosaic but useful recital of facts enlivened by only a limited rather general discussion of the causes of climatic differences from place to place. However, in the last decade climatologists have developed their subject in several directions; synoptic climatology and dynamical climatology have appeared, and with the development of numerical methods of simulating climate by dynamical models we can expect future climatologies of the earth to take a highly mathematical and theoretical approach.

Mr Lamb's book however follows none of these lines. It is a highly personal account of an aspect of weather and climate to which Mr Lamb has devoted much of his interest and study over two decades. It deals with variations of weather on all time-scales from a few days to centuries and millenia. The emphasis throughout is upon the way in which the longer-term climatic variations are built up from the anomalies of weather behaviour over shorter periods. The climatic anomaly of a century, or even an ice-age, is to be thought of not as a change in the average level of temperature, but in terms of the reorientation of the tracks of depressions and anticyclones with all that leads to in terms of changed sequences of weather.

Such a theme provides a fascinating book, full of intriguing facts about past climate and weather: that the earlier explorers of Canada walked over ice on the Great Lakes in June in the early 17th century or that the strength of the north-east trade winds in the Atlantic is correlated with later European temperatures. However, such facts are not easy to explain. Plausible chains of cause and effect can be postulated and Mr Lamb's book contains descriptive accounts of many such. However, until the relationships can be put into quantitative form and tested against numerical data, it is difficult to have any confidence in the significance of the processes to which the climatic effects are attributed. To put the theories of long-term weather variation to the quantitative test will be the task of future generations of dynamical climatologists and Mr Lamb's book will give them much material for investigations.

From the beginning to the end of his book Mr Lamb beguiles the reader with interesting aspects of weather variations. This makes for stimulating reading by the informed meteorologist, but the newcomer to the subject will find a lack of systematic development of climatology as a subject. The book is organized into chapters on radiation, atmospheric motions, the oceans, the water cycle, etc., and is provided with a comprehensive index, but the reader needs a fairly complete understanding of meteorological and climatological principles before embarking even on the early chapters.

The book will stand for a long time as a unique reference work on the subject of long-term weather variations. The access it provides to the literature through its references will be invaluable and not the least value will be in the appendices which collect together miscellaneous, useful, and often elusive information including data on past solar variations and world climate.

J. S. SAWYER

An investigation of heat exchange, International Indian Ocean Expedition Monographs No. 5, by D. J. Portman and E. Ryznar. 283 mm × 225 mm, pp. 78, *illus.*, East–West Center Press, Honolulu, Hawaii, 1971. Price: $7.50.

This is one of the series of meteorological monographs to be prepared in connection with the International Indian Ocean Expedition (IIOE). Both authors are at the University of Michigan and the main purpose of the investigation which they describe was to set up a network of radiation stations and hence to help in determining the heat exchange at the air–sea surface over the Indian Ocean.

Fourteen stations were initially set up on islands and coasts, each being equipped with a pyranometer, a total hemispherical radiometer and a special twin recorder/integrator system designed to operate on a 50-Hz mains supply. Many records were missed because of equipment failures and unreliable electrical power but usable data were obtained from 12 stations, of which 10 were in the western half of the Indian Ocean between 40° and 80°E, extending from Karachi in the north to Fort Dauphin, Madagascar, in the south, the remaining two being Port Blair, Andaman Islands, and Christmas Island. Measurements relate to the period between the setting up of the stations, between March and December 1963, and the end of 1965.

The work is in two parts, the first an introduction giving background information, a description of the instruments used and site details, with photographs, and the second presenting and analysing the data. There are two appendices, one concerning the calculation of precipitable water from radiosonde data, the other presenting the measurements in the form of tables of daily values of solar radiation and total hemispherical radiation.

In analysing the data, daily totals of incident radiation on cloudless days were first determined and curves of the annual variation at 8 stations between 13°N and 25°S are presented. The curves agree quite well with computed curves, based on values for the outer limit of the earth's atmosphere and appropriate values for precipitable water and fractional dust depletion, except for Mahé Island in the Seychelles where the measured values were usually large. Because the Mahé values were also much larger than those for Mombasa which is in about the same latitude, and the differences could not be completely accounted for, the Mahé values were assumed to be in error and were excluded. Otherwise longitudinal variations were small and this is held to justify the presentation of a latitudinal distribution of average daily total incident solar radiation throughout the year, covering latitudes 25°S to 25°N with isolines at intervals of 25 langleys/day. The fact that the values are generally lower than those published by Budyko is partly explained as being due to attenuation by volcanic dust from the Mount Agung, Bali, eruption of March 1963.

Information on observed cloudiness over the Indian Ocean, in the form of maps of average monthly cloud amount in each 5-degree square, is used to compute the distribution of solar radiation for each month of 1963 and 1964, using an empirical relationship due to Beryland, the results being presented on 24 maps. Values of reflected solar radiation are computed using an empirical relationship between the albedo for a water surface and solar altitude and a linear relationship is found between average diurnal albedo and daily sums of incident solar radiation. Using this result a latitudinal distribution of reflected solar radiation for cloudless days through the year is obtained. Daily sums of atmospheric radiation, obtained from differences between corresponding hemispherical radiometer and pyranometer measurements, ranged from about 720 to 830 ly for cloudless and cloudy conditions, respectively, but because data were insufficient to provide reliable estimates of seasonal and latitudinal variations a representative average value of 790 ly/day is adopted for the Indian Ocean. Using maps of average sea surface temperature for each month of 1963 and 1964 and the Stefan-Boltzmann law, average daily sums of long-wave radiation emitted by the sea surface were computed for each 5-degree square. Hence the distributions of net radiation exchange were computed for each month of 1963 and 1964, and these also are presented on 24 maps. The distributions of areas of high and low values for the same months in both years are similar but actual values in some months are quite different.

Among the assumptions made by the authors are that the effects of roughness and turbidity may be ignored when computing the solar radiation reflected from a sea surface, that the average diurnal albedo for a water surface is independent of cloudiness and that a single value for the atmospheric radiation can be used for all months and seasons. Already mentioned are the assumption that the longitudinal variation in solar radiation is negligible and the rejection of the Mahé measurements for reasons which are not entirely convincing.

A good number of inconsistencies were noted especially in the first part of the book. For example, photographs of the two installations from which no records were obtained are included while photographs for four stations whose records were used are omitted. There are a number of discrepancies between the numbers of cloudless days for which data are listed in Table 3 and the numbers given in the text on p. 16. Also the values in Table 5 are not always in agreement with those indicated in Figure 9 from which they are said to be derived.

The work is well presented and clearly printed and will be of special interest to meteorologists and other scientists who require information about radiation over the Indian Ocean north of 25°S.

H. C. SHELLARD

NOTES AND NEWS

Retirement of Mr R. A. Hamilton, O.B.E., F.R.S.E.

On 7 July 1972 Richard Hamilton retired from the Meteorological Office in which, for the past four years, he held the post of Assistant Director in charge of the High Atmosphere Research Group. His enthusiasm for practical meteorology, preferably outdoors, was evidenced early in his career and before he joined the Meteorological Office. In 1935, having graduated at Oxford, he was researching with Professor Townsend when he had the opportunity to join the Oxford Expedition to Nordaustlandet (North-east Spitsbergen) as physicist. This was clearly an interesting and challenging experience for in the following year he joined, as Assistant Surveyor, the British Arctic Expedition to North-west Greenland and Ellesmere Island and it was at Thule, not as famous a place then as it is now, that he first met Musse, his wife. Faced now with the responsibilities of married life he entered the Meteorological Office in 1939 only to leave very quickly to join the West African Meteorological Service, working mostly at Lagos. In 1942 he was seconded to the Meteorological Office and finally joined us on returning from Lagos in 1944. A brief spell at Dunstable was followed by about seven years at Prestwick when once more the call of the Arctic proved too strong and he was released in 1952 to become the Chief Scientist to the British North Greenland Expedition and also second in command. He was clearly well suited to this post because of his endearing personality, rugged endurance and powers of leadership, qualities which earned him the Polar Medal and Bar as well as his appointment to the Order of the British Empire. Returning in 1955 he was first at Prestwick and then went to Lerwick where he was a most successful Superintendent until 1966. Two years at Kew Observatory preceded the appointment from which he has just retired. Papers and articles in many journals and a Pelican book *Venture to the Arctic,* testify to his scientific ability, an ability which he habitually tended to underrate.

He will be sorely missed by his colleagues and not least by the younger members for he retains a youthful and energetic approach to life which belies his years. Having very recently recovered from a quite serious operation he continues to play badminton and squash and in the recent Sports Meeting finished a very close second in the veterans 100 metres. We shall miss his fearsome cries in the Scottish dances which he insisted must form a part of the Annual Dinner and Dance. We have no doubt that he will enjoy his retirement in his new home near Edinburgh and wish him and his wife many years of happy activity.

R.F.J.

OBITUARY

It is with regret that we have to record the death of Mr W. E. James, Higher Scientific Officer, Birmingham Airport, on 19 May 1972.


66,000 FT.

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NOTICES

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THE METEOROLOGICAL MAGAZINE

Vol. 101, No. 1203, October 1972

RETIREMENT OF MR R. H. CLEMENTS

Mr R. H. Clements, Deputy Director of the Meteorological Office responsible for the communications and computing organization, retired on 31 July 1972, after 34 years' service. He read mathematics at Oxford University and after taking his degree was a schoolmaster for a few years before joining the Meteorological Office in 1938. The first 14 years of his new career were spent on forecasting duties, first at a variety of outstations and then from 1942 at the Central Forecasting Office at Dunstable. In his 10 years at CFO, Mr Clements became one of the best-known Senior Forecasters and he is still well remembered as one of the Office's 'ace' forecasters.

In 1952 he left Dunstable for a 3-year tour as Chief Meteorological Officer with the Royal Air Force in Germany and on returning home was engaged for some years in forecasting research. In 1958 he transferred to climatology and shortly afterwards became the Assistant Director responsible for Climatological Services. During the next 8 years he initiated many important developments in the applications of climatology to a wide range of activities and also played a prominent part in the international field, notably with the World Meteorological Organization Technical Commissions for Climatology and for Hydrology. In 1966 Mr Clements was promoted to Deputy Director with overall responsibility for applied climatology, including hydrometeorology and argicultural meteorology, and for observational systems and for data processing. Subsequently, with the acquisition of a very powerful new computer and with the modernization of the telecommunications organization, Mr Clements took charge of a new Deputy Directorate responsible for the operation and systems development of these advanced facilities.

Thus Mr Clements's career occupied three main phases — forecasting, climatology, and data acquisition and processing. In each phase he was highly successful and of international reputation. Doubtless he will count among the major milestones of his career the years of planning, studying and assessing that culminated in the purchase, installation and rapid progress to full operational use of the Office's giant computer.

'Clem' was widely known in the Office and most popular. Never one to look on the dark side, his cheerfulness and optimism were infectious. For him retirement from the Office will merely mark a new beginning in other activities and we wish him and Mrs Clements many years of happiness and good health.

P. J. MEADE

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THE MEASUREMENT OF ATMOSPHERIC TURBULENCE FROM A CAPTIVE BALLOON

By C. J. READINGS and H. E. BUTLER

Summary. This paper describes an instrument which has been designed to measure wind and temperature fluctuations from the flying cable of a tethered kite balloon. Its performance has been evaluated from measurements close to the ground with the probe mounted on a fixed support. These enable both its reproducibility and its performance relative to a sonic anemometer to be assessed.

Some preliminary studies of the effect of the balloon motion were carried out using a reference instrument mounted on a 43-metre tower. These showed that though variances were not much affected, quite serious errors may be introduced into the flux measurements but that these might be reduced by adequate vertical separation of the instrument and the balloon. A more comprehensive series of measurements is required to establish these features.

Introduction. Although the structure and properties of the constant-stress layer are now quite well understood, the relative inaccessibility of the rest of the earth's boundary layer means that quite the converse is true of this part of the atmosphere, despite its obvious relevance to the energetics of the troposphere. Furthermore, this situation cannot be remedied just by studying the structural details revealed by applying some of the recent developments in the field of remote probing (e.g. frequency-modulated-continuous-wave radar, see Gossard *et alii*[1]); direct measurements are essential if the effects of the fine structure are to be correctly interpreted and the terms in the various balance equations evaluated.

Though aircraft and tall towers have been extensively used in studying these lower regions of the atmosphere, neither of them provides the perfect 'platform' from which to make measurements. A less familiar technique is to mount the instruments on the flying cable of a tethered balloon. This paper describes a turbulence probe which has been designed to operate in such a fashion (it does not discuss the use of tethered balloons in general for scientific studies — for which the reader may care to consult another article[2]).

The paper is divided into three main parts — first the probe is described, then its performance on a fixed support is assessed and finally the complications introduced by the balloon's movement are considered.

Description of the probe. An article by Jones and Butler[3] describes the first instrument used to study in detail the vertical component of turbulence from the flying cable of a tethered kite balloon. The present instrument (see Figure 1) is a development from this and is designed to measure with adequate response the fluctuations required for evaluating heat and momentum fluxes:

(a) *Temperature.* The sensor consists of 180 cm of platinum wire (25 μm in diameter) wound non-inductively on a plastic former. It is connected to an amplifier (mounted in the vane) which gives a linear output of 0·5 volt/degC over a range of ± 10 degC; the three switches at the bottom of the vane enable the centre zero to be adjusted in 3-degC steps between − 3°C and + 18°C.

(b) *Total wind speed.* As the vane is free to rotate about the flying cable, the probe is kept facing into wind and the anemometer measures the instantaneous values of the total wind speed. The anemometer is

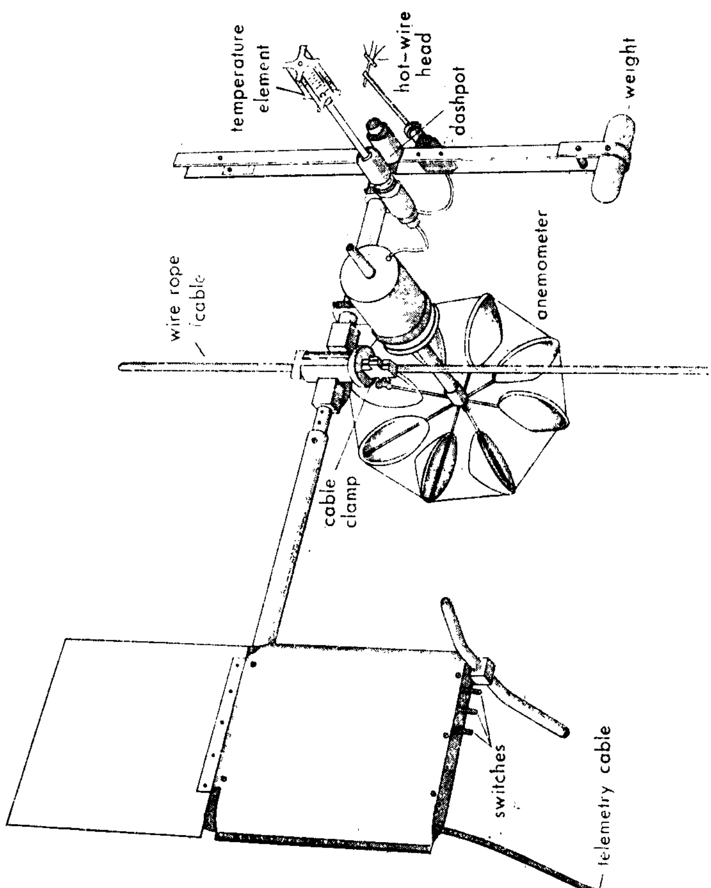


FIGURE 1—THE CARDINGTON PROBE

fitted with an 8-cup polystyrene rotor,[4] the pulses from which are converted to an analogue voltage by a ratemeter located in the laboratory — 120 pulses being produced per revolution.

(c) *The inclination of the wind to the horizontal.* A hot-wire yawmeter consisting of two V-shaped platinum wires (of diameter 13 μm and each containing an angle of 120°) making an angle of 80° (Jones[5]) is attached to the vertical upright pivoted at the front of the probe. This is kept vertical despite any tilting of the balloon cable, by the combination of the weight at its lower end and an oil dashpot which damps oscillations, hence enabling the yawmeter to measure the instantaneous inclination of the wind relative to some fixed reference which is near the vertical (see later). The yawmeter is connected to a bridge situated inside the vane which gives a sensitivity of 0·5 volts/radian. Its output is linear over ± 40° and it will accept lateral flow variations of ± 30° (with respect to the vane) without any errors being introduced.

A battery box is attached to the flying cable just below the probe. This provides the stabilized voltage necessary to operate the two bridges and also acts as a link from which the signals are relayed to the ground by cable (a radio system is being tested at present). There they are sampled once a second by a data-logger whose output is recorded on paper tape. This logger has a resolution of one part in a thousand which corresponds to 0·01 degC, 2 cm/s or 0·02 radians. The higher-frequency fluctuations of inclination and temperature are studied with the aid of a series of band-pass filter units.[6]

Although at present the probe does not measure the instantaneous direction of the wind in the horizontal, it is hoped to remedy this in the near future by the addition of a second yawmeter and a magnetic flux-gate device providing an azimuth reference. Furthermore, by early 1973 it is planned to record all the information on magnetic tape, hence eliminating the sampling restriction referred to above.

The electrical and mechanical parts of the system were subject to certain tests in both the laboratory and the wind-tunnel. However, in view of the complexity of the system and of the environment in which it has to operate, it was necessary to carry out a series of field trials to establish that the atmospheric variables were being measured properly.

The performance of the probe on a fixed support.

Comparison of probes. As a first step in this evaluation, two of these probes were mounted on fixed vertical rods so that they were 2 m apart at a height of about 8·5 m at the Cardington, Bedfordshire, field station — a suitably flat and unobstructed site for low-level work. A series of one-hour runs were carried out with the horizontal boom to which the rods were attached approximately perpendicular to the mean wind direction during each run. Thirty-three runs were carried out under various stability conditions; z/L at 8·5 m varied between 0 and − 2·0 (z being the height above the ground and L the Monin-Obukhov length).

Unfortunately many of the quantities of interest are sensitive to slight rotations of the frame of reference;[7] so, as the axes of these probes cannot be determined with sufficient accuracy using only instrumental techniques, it was decided to fix them by assuming that the value of the mean vertical wind speed, $\overline{W}$, was zero during each run. This produced an axial reference reproducible to within 0·3 degrees and even this uncertainty may well be atmospheric in origin as the mean inclinations of the flow derived from the two probes invariably agreed to within 0·1 degrees.

Although some slight troubles were experienced with the cup anemometers and their associated circuitry, these were not serious and it would be fair to conclude that normally the mean winds would be expected to agree within a few centimetres per second. It was also found that the 20-minute temperature differences were consistent to ± 0·02 degC after correcting for the difference in the resistances of the two temperature elements at 0°C.

The degree of agreement between the other variables was assessed by plotting the cumulative differences on probability paper — a Gaussian distribution would produce a straight line. Some examples of the sort of results obtained are shown in Figure 2 (a) and (b) for the 20-minute values.

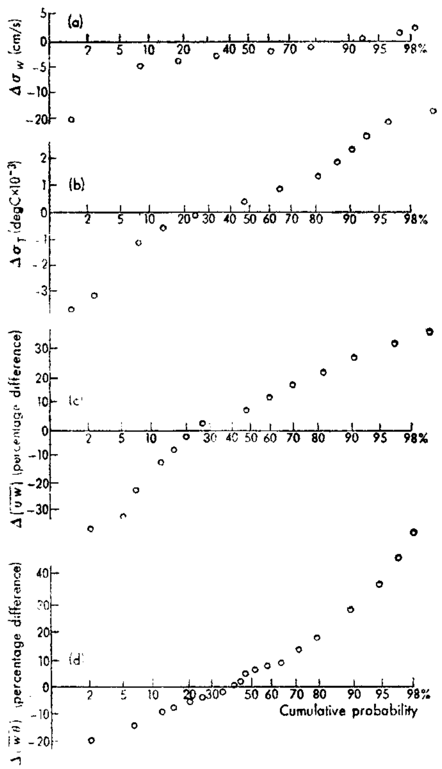


FIGURE 2—COMPARISON OF THE PERFORMANCE OF TWO INSTRUMENTS ON FIXED SUPPORTS AT A HEIGHT OF 8·5 METRES AND 2 METRES APART (20-MINUTE SAMPLES)

See Table I for definitions of symbols.

Although the spread in the differences between the standard deviations (or between the mean vertical winds) is larger than would have been expected from the preliminary laboratory and wind-tunnel tests, the complexities of the full operating system in the natural airflow mean that it would be

TABLE I—THE ACCURACIES IMPLIED BY THE COMPARATIVE RUNS ON FIXED SUPPORTS (USING 20-MINUTE VALUES)

Quantity	Mean difference ± standard error
Mean vertical wind, $\overline{W}$ (cm/s)	0·0 ± 0·3
Standard deviation of temperature fluctuations, σ_T (degC)	0·006 ± 0·001
Standard deviation of horizontal wind fluctuations, σ_u (cm/s)	0·0 ± 0·3
Standard deviation of vertical wind fluctuations, σ_w (cm/s)	− 1·7 ± 0·3
Momentum flux, $\overline{uw}$ (per cent)	9 ± 2
Heat flux, $\overline{w\theta}$ (per cent)	8 ± 2

unsafe to conclude that the discrepancies are purely atmospheric in origin. However, it seems fair to state that these quantities can be measured *at least* to the statistical accuracies implied by these comparisons (see Table I).

With the two vertical fluxes the situation is complicated by their dependence on the frame of reference used and the large variations in their absolute values. This makes it more sensible to compare the percentage differences as is done in Figure 2 (c) and (d). Though it is well known that the two vertical fluxes vary considerably in both space and time,[8] the additional uncertainty introduced by the frame of reference makes it even more unwise to state that the spread merely reflects atmospheric variability; though it is relevant to note that the more extreme differences vanish when 'hour' as opposed to '20-minute' values are compared. However, it does seem reasonable to conclude that statistically the individual fluxes may be determined to within 10 per cent *or better* (see Table I). These conclusions may be considered to be quite general as during the course of these tests a whole series of sensors and circuit elements were used, thus making them a comparison of a series of probes.

Comparison with profile estimates of the friction velocity. During some of these comparative runs a vertical wind profile was available from three single-slot photo-electric anemometers mounted 4·3, 8·5 and 17·1 m above the ground, ordinary Sheppard anemometers with metal cups being used. Estimates of the friction velocity, u_*, were obtained by applying the method described by Webb[9] to the hourly means, and in Figure 3 these results are compared with those derived from one of the probes (i.e. $\sqrt{-(\overline{uw})}$ where $\overline{uw}$ is the momentum flux), the comparison being restricted to occasions when z/L at 8·5 m was greater than −0·10. The agreement is very encouraging and it is interesting to note that the scatter of the differences between the estimates is not much different from that found when two probes are compared.

A similar exercise was carried out by applying the formulation discussed by Dyer and Hicks[10] to the results — the profile winds being used in conjunction with the z/L values from one of the probes (no temperature profile being available at that time). These estimates also agreed very well with the probe values.

Comparison with a sonic anemometer. During October 1969 one of these probes was compared in Boston, U.S.A., with the Air Force Cambridge Research Laboratories' three-component sonic anemometers which have been described by Haugen.[8] These tests were carried out by mounting the two instruments about 2 m apart on the top of a 15·5-m tower — a vertical rod supporting the Cardington probe. Owing to obstruction around the site, runs could

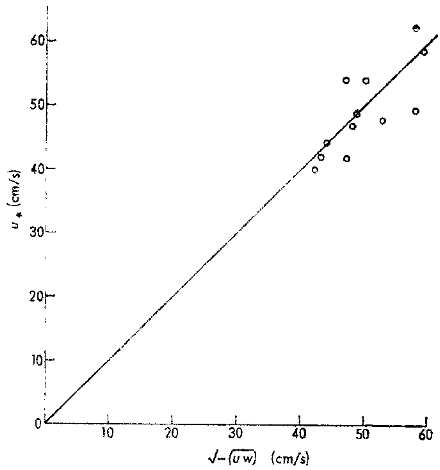


FIGURE 3—COMPARISON OF THE HOURLY VALUES OF $\sqrt{-(\overline{uw})}$ AND u_* OBTAINED FROM PROFILE MEASUREMENTS USING WEBB'S TECHNIQUE

$\overline{uw}$ is momentum flux and u_* the friction velocity.

only be done when the wind was coming from the west so it was only possible to do sixteen 10-minute and four 5-minute runs in the time available. The signals were processed on data-logging equipment with a frequency cut-off at 10 Hz and a sampling rate of 20 samples per second.[8]

Although the definition $\overline{W} = 0$ was used to determine the reference axes for the Cardington probe, the sonic anemometer was lined up using purely instrumental techniques. Thus the sonic-anemometer values refer to gravitation axes while those of the Cardington probe refer to the $\overline{W} = 0$ axes. This means that the two sets of values are not strictly compatible and that the spread in the difference between the estimates of u_* may be greater than was found at Cardington, especially as the uncertainty in the axes was a degree or two in this case (probably because of the poorer nature of the site in Boston). A further complication may have been introduced by the relatively slow response of the cup anemometer which would cause the Cardington probe to underestimate the momentum flux if there were a significant high-frequency contribution. (Incidentally this should not matter at the heights for which the captive balloon system is designed.) The rather small heat fluxes precluded any meaningful comparison of the heat fluxes or the temperature fluctuations.

In comparing the results of these tests (Figure 4) with those obtained from the mast runs (see Figure 2 and Table I) it is important to remember that only 18 values (the four 5-minute runs making 2 values) were available on this occasion; thus no significance can really be attached to the tails of the distribution. It would therefore seem reasonable to conclude that the results are roughly compatible, though the agreement between various values of σ_w, the standard deviation of vertical wind fluctuation, is slightly improved and that between the various values of σ_u, the standard deviation of horizontal wind fluctuation, and of u_* is slightly worse; these small changes are probably no more than a reflection of the shorter averaging period and the points raised in the previous two paragraphs.

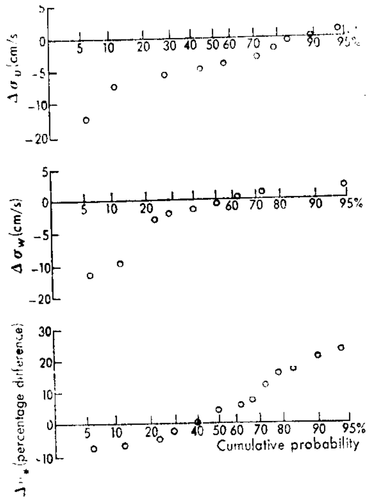


FIGURE 4—DISTRIBUTION OF THE DIFFERENCES BETWEEN THE SONIC ANEMOMETER AND THE CARDINGTON PROBE (10-MINUTE SAMPLES)

Comparisons were made at Boston, U.S.A., in October 1969.

It is relevant to note that the 10-minute wind speeds agreed to within a few centimetres per second, so these results were not biased by overspeeding (see Readings[11]). Furthermore, on the few occasions when a second sonic was available, the correlation between the two sonics was slightly less than that between the Cardington probe and each of them individually — the Cardington probe being positioned midway between them. This also points to the instruments having equivalent performances.

A preliminary study of the effects of balloon movement. The movement of a tethered balloon is transmitted to any instrumental packages attached to the cable. As these motions can be quite appreciable there is a strong possibility that they may introduce 'apparent' contributions to the measured turbulence variables, though mean values of variables such as wind speed and temperature should not be affected provided that the averaging period is long enough. For a given balloon/cable system, the motion of the balloon will depend mainly on the structure of the atmosphere and the position of the balloon in it. The movements of the actual instrument will also depend on its position on the cable relative to the balloon and may well be a scaled-down version of the balloon motion. However, the measurement errors will depend not only on these movements but also on any corresponding changes in temperature or wind in the vicinity of the instrument.

Although at present it is not possible to predict the magnitude of the errors, the equations relating them to the motion of the instrumental package can be written down :

$$\Delta\sigma_u = \frac{50}{\sigma_u^2}\left[\overline{\left(\frac{dx}{dt}\right)^2} - 2\,\overline{U_t\left(\frac{dx}{dt}\right)}\right] \qquad \ldots (1)$$

$$\Delta\sigma_w = \frac{50}{\sigma_w^2}\left[\overline{\left(\frac{dz}{dt}\right)^2} - 2\,\overline{W_z\left(\frac{dz}{dt}\right)}\right] \qquad \ldots (2)$$

$$\Delta\overline{uw} = \frac{100}{\overline{uw}}\left[\overline{\left(\frac{dx}{dt}\right)\left(\frac{dz}{dt}\right)} - \overline{U_z\left(\frac{dz}{dt}\right)} - \overline{W_z\left(\frac{dx}{dt}\right)}\right] \qquad \ldots (3)$$

$$\Delta\sigma_T = \frac{50}{\sigma_T^2}\left[\overline{z^2}(\Gamma^2 + 1) - 2\Gamma\overline{zT_z'}\right] \qquad \ldots (4)$$

$$\Delta\overline{w\theta} = \frac{100}{\overline{w\theta}}\left[\overline{T_z'\left(\frac{dz}{dt}\right) + \Gamma z\left(W_z - \frac{dz}{dt}\right)}\right] \qquad \ldots (5)$$

where Δ = the difference between the apparent value and the true value expressed as a percentage of the true value; x and z are the instantaneous co-ordinates of the instrument relative to its mean position, and subscript z denotes value of atmospheric quantity at height z; U is the horizontal wind, and u and w are fluctuations in the horizontal and vertical wind respectively; Γ is the mean lapse rate (a positive quantity); σ_T is the standard deviation of temperature fluctuations; $w\theta$ is the heat flux, θ being a temperature fluctuation; T_z' is the temperature fluctuation relative to the mean profile; t is time; and the horizontal bars refer to time-averaging. In deriving these equations it has been assumed that σ_T does not vary rapidly with height at 43 m, but this assumption is unlikely to be important as it involves only a small correction.

Approximate estimates of the effect of these motions on measurements of momentum flux have been made by Thompson (unpublished) who used two theodolites to monitor the movement of a fore-runner of the present Cardington probe as it recorded the instantaneous values of u and w. His analysis showed that the probe tended to underestimate the momentum flux. However, this examination only took into account the second term in equation (3).

In view of the relevance of this problem to balloon-borne measurements it was decided to try and measure the errors directly by comparing measurements made from a fixed support at the top of the 43-m tower at Cardington with those made simultaneously with another instrument mounted at the same height on the flying cable of a tethered balloon. A series of one-hour runs were done with the balloon at one of four standard heights (60, 150, 300 and 600 m) above the instruments. However, from the outset it was clear that these measurements must be regarded as very preliminary in nature, as they were only made at 43 m and facilities for monitoring the movements of the balloon-borne probe were not available at that time. Their aim was therefore limited to ascertaining whether the errors were large enough to warrant a full-scale investigation.

It had been hoped to use the tower-mounted probe to provide the 'true' values but unfortunately the $\overline{W} = 0$ assumption did not enable the axial reference to be fixed to better than a few degrees. Furthermore, this variability could not be reduced by doing a 'calibration' run at 8·5 m above the ground because the probe had to be dismantled to get it into position on top of the tower. As this uncertainty in the reference axes could well mask any effects due to balloon movement, it was decided to apply the $\overline{W} = 0$ assumption for the tower instrument when the balloon was at its maximum height (i.e.

600 m above the two probes). Then the axial reference of the balloon probe was determined by forcing the hourly-mean momentum fluxes to be equal during these runs. These two sets of axes were used for all the other runs carried out on that particular day — a 600-m run always being done.

The effect of balloon motion on the turbulence quantities was assessed only in respect of the variation of the motion of the instruments with the separation between the balloon and the instruments by comparing the difference curves (i.e. balloon minus tower values) for the other balloon heights with those obtained with the 600-m spacing. It does, however, seem likely that the 600-m balloon values were less affected by balloon movement and that therefore the foregoing comparison provides a first approximation to the absolute effect. Some evidence supporting this assumption was provided later by making some single theodolite observations of changes in the elevation of a probe attached to a balloon cable at the same height as during the runs. The elevation angle was recorded every 15 seconds and measurements were made with the balloon at all the standard heights used during the original experiments. Figure 5 is typical of the results obtained with the balloon in

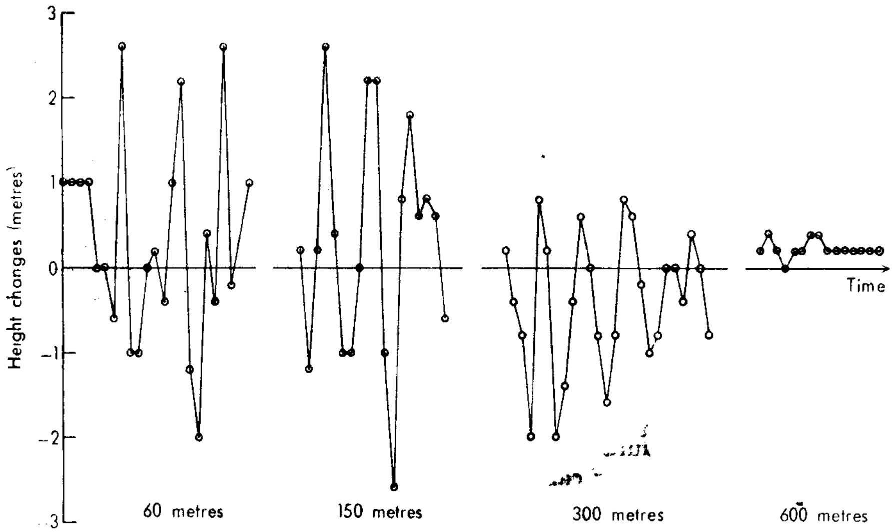


FIGURE 5—EXAMPLE OF THE VARIATION WITH TIME IN THE HEIGHT OF A PROBE ABOVE THE GROUND AS A FUNCTION OF ITS DISTANCE BENEATH THE BALLOON

Measurements were made every 15 seconds with a separation between balloon and probe of 60, 150, 300 and 600 metres.

the atmospheric turbulence layer and shows how the amplitude of the probe's vertical motion decreases as the vertical separation increases. However, it must be realized that although it seems reasonable to assume that the 600-m runs were less (if not negligibly) affected by balloon motion than were the others, it does not necessarily follow that the motion of the instrument decreased steadily as the vertical separation increased.

In all some 24 usable one-hour runs were done under various atmospheric conditions with z/L at 43 m varying between $-1{\cdot}0$ and $-0{\cdot}03$; though on three of the four days $z/L \approx -1{\cdot}0$. The probes were about 50 m apart and the tower was downwind of the balloon on all but one day when there was a crosswind.

As a first step in the analysis the successive 20-minute values of σ_u, σ_w, σ_T, $\overline{uw}$ and $\overline{w\theta}$ were compared on a day-to-day basis; two examples are shown in Figure 6. It was found that although the values did not agree as

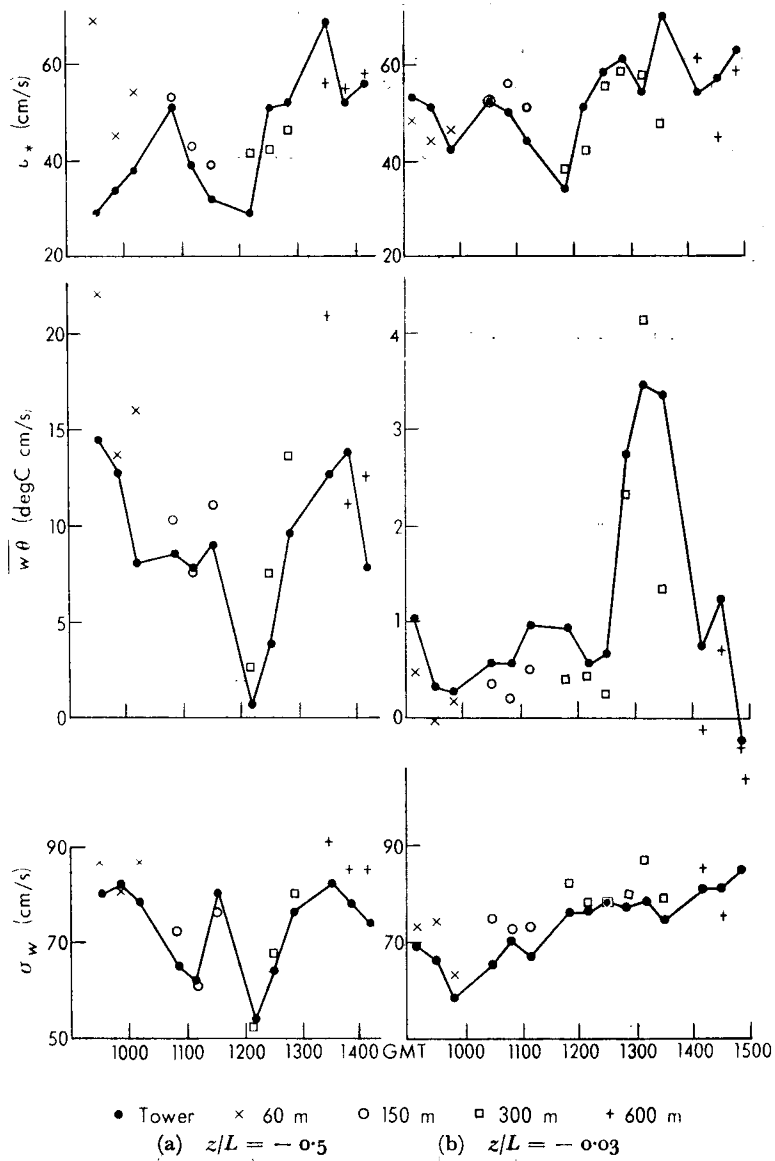


FIGURE 6—A COMPARISON OF TWO EXAMPLES OF VALUES MEASURED AT 43 METRES ON A TOWER AND AT THE SAME HEIGHT ON A BALLOON WITH FOUR SEPARATIONS BETWEEN BALLOON AND PROBE (20-MINUTE SAMPLES)

Separations between balloon and probe were 60, 150, 300 and 600 metres.

closely as during the mast runs described earlier, they nevertheless tended to follow each other quite well. Also, the scatter between the two sets of values seemed less on the non-convective day. However, as it was impossible to discern any correlation between the degree of agreement and the vertical distance between the probes and the balloon, it was decided to combine the results of all days and compare the percentage differences as a function of balloon height (these results are summarized in Figure 7 and Table II).

TABLE II—MEAN PERCENTAGE DIFFERENCES BETWEEN VARIOUS TURBULENCE QUANTITIES, AS MEASURED AT 43 M ON A FIXED SUPPORT AND ON THE BALLOON CABLE, AS A FUNCTION OF THE HEIGHT OF THE BALLOON ABOVE THE INSTRUMENTS

Quantity	Height of balloon above instruments				Mast runs
	60 m	150 m	300 m	600 m	
σ_u	9 ± 3	7 ± 3	6 ± 3	3 ± 2	−0·1 ± 0·3
σ_w	1 ± 3	−4 ± 4	4 ± 2	3 ± 4	−3·3 ± 0·5
$\overline{uw}$	51 ± 48	2 ± 22	−6 ± 11	3 ± 10	9 ± 2
σ_T	14 ± 5	−1 ± 3	3 ± 5	4 ± 7	1·9 ± 0·6
$\overline{w\theta}$	27 ± 31	−22 ± 12	−4 ± 13	33 ± 21	8 ± 2

Tabulated figures are mean percentage difference ± standard error.

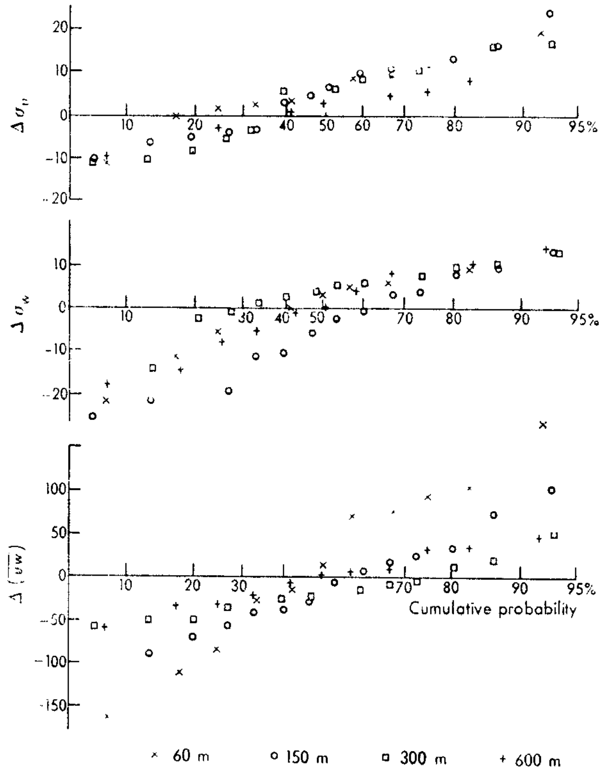


FIGURE 7—COMPARISON OF ALL VALUES MEASURED AT 43 METRES ON A TOWER AND AT THE SAME HEIGHT ON A BALLOON WITH FOUR SEPARATIONS BETWEEN BALLOON AND PROBE (20-MINUTE SAMPLES)

Separations between balloon and probe were 60, 150, 300 and 600 metres. Results are all expressed as percentage differences.

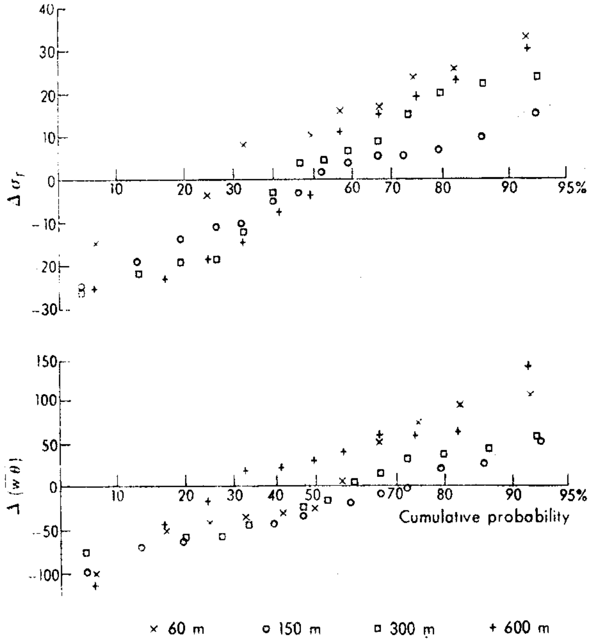


FIGURE 7—*continued*

In considering these results it is important to realize that even if there were no effects of balloon motion, the 600-m curves would not be straight lines of zero mean and zero slope as the two probes were about 50 m apart — for reference the corresponding figures for the mast runs are also listed in Table II. Furthermore, the distributions could be affected either way by the balloon motion (i.e. the apparent agreement may improve or worsen according to which terms dominate the appropriate equation).

Although $\Delta\sigma_u$ and $\Delta\sigma_w$ show a slight dependence on the vertical distance between balloon and instruments (Figure 7) the changes are only a few per cent and are therefore of not much concern, though they do imply that while the first term dominates equation (1) (i.e. the more positive values of Δ at lower separations) both terms contribute to equation (2). However, with $\Delta\overline{uw}$ quite large differences are observed and it appears that the balloon-borne measurements could be in error by 100 per cent or more in *either sense*. This implies that at least two of the terms in equation (3) can be significant and that if Thompson had been able to measure the other two terms, his results could have been drastically changed — as he pointed out at the time. However, the smaller range of $\Delta\overline{uw}$ for both 600 and 300-m curves raises the possibility of making the error insignificant by positioning the equipment sufficiently far below the balloon.

The curves of $\Delta\sigma_T$ are probably the most intriguing as the irregular way their shapes vary as the vertical distance between balloon and probe increases implies that both terms in equation (4) are significant — this means that local changes in temperature are associated with upward movements of the balloon, probably through the action of convective elements. However, the errors are not really large except for the 150-m spacing. The $\Delta\overline{w\theta}$ curves are also separated and the sense of this separation implies that the last term in equation (5) is probably very important. The errors are quite significant even with the 300-m spacing.

Concluding remarks. From the preceding discussions it may be concluded that on a fixed support the Cardington probe measures the various turbulence quantities *at least* to the accuracies summarized in Table I. Furthermore, the upper limits to the accuracy of the probe may well reflect atmospheric variability rather than instrumental inaccuracies. Thus the use of this relatively inexpensive instrument on fixed supports as well as on the tethering cable of a balloon becomes a very attractive proposition.

The preliminary studies of the effects of balloon motion seem to show that though σ_u, σ_w and σ_T are only marginally affected, the momentum and heat fluxes could be seriously in error if the instrument is mounted too close to the balloon. They point therefore to the necessity for carrying out an extensive series of measurements at greater heights above the ground with continuous monitoring of the probe and balloon movements. However, until these measurements have been made and analysed, it is advisable to fly the instruments as far below the balloon as possible and to monitor their motions.

Acknowledgements. The authors would like to acknowledge Dr D. A. Haugen for permission to refer to the Boston experiment and the help of all members of the Meteorological Research Unit at Cardington especially Mr R. Rayment and Mr R. H. Marles. They also benefited from many useful discussions with Dr F. Pasquill.

REFERENCES

1. GOSSARD, E. E., RICHTER, J. H. and ATLAS, D.; Internal waves in the atmosphere from high-resolution radar measurements. *J Geophys Res, Richmond, Va,* **75**, 1970, pp. 3523–3536.
2. READINGS, C. J.; Atmospheric probing using a tethered balloon. KJELAAS, A. G. (editor); Statistical methods and instrumentation in geophysics. Oslo, Teknologisk Forlag. 1971, pp. 237–242.
3. JONES, J. I. P. and BUTLER, H. E.; The measurement of gustiness in the first few thousand feet of the atmosphere. *Q J R Met Soc, London,* **84**, 1958, pp. 17–24.
4. JONES, J. I. P.; A portable sensitive anemometer with proportional d.c. output and a matching wind velocity-component resolver. *J Scient Instrum, London,* **42**, 1965, pp. 414–417.
5. JONES, J. I. P.; The measurement of turbulence near the ground. Porton, Chemical Defence Experimental Establishment. Porton Technical Paper No. 786, 1961.
6. READINGS, C. J. and RAYMENT, D. R.; The high-frequency fluctuations of the wind in the first kilometer of the atmosphere. *Radio Sci, Richmond, Va,* **4**, 1969, pp. 1127–1131.
7. RAYMENT, R. and READINGS, C. J.; The importance of instrumental tilt on measurements of atmospheric turbulence. *Q J R Met Soc, London,* **97**, 1971, pp. 124–130.
8. HAUGEN, D. A., KAIMAL, J. C. and BRADLEY, E. F.; An experimental study of Reynolds stress and heat flux in the atmospheric surface layer. *Q J R Met Soc, London,* **97**, 1971, pp. 168–180.
9. WEBB, E. K.; Profile relationships: the log-linear range, and extension to strong stability. *Q J R Met Soc, London,* **96**, 1970, pp. 67–90.
10. DYER, A. J. and HICKS, B. B.; Flux-gradient relationships in the constant flux layer. *Q J R Met Soc, London,* **96**, 1970, pp. 715–721.
11. READINGS, C. J.; Some comments on making measurements of wind and temperature in the atmosphere. KJELAAS, A. G. (editor); Statistical methods and instrumentation in geophysics. Oslo, Teknologisk Forlag, 1971, pp. 269–275.

551.5:06(b):37

THE METEOROLOGICAL OFFICE COLLEGE

By D. H. JOHNSON

Early days. Systematic centralized training began in the Meteorological Office in 1935. It took place in a special section of the Overseas Division at Croydon Airport. With the outbreak of war four years later, more elaborate arrangements became necessary and on 15 September 1939 the Meteorological Office Training School came into being at Berkeley Square House, London. Professor (later Sir David) Brunt was released temporarily from Imperial College, London, to take charge of the training programme. During the next decade the School had several moves until it found a more permanent home at Stanmore, Middlesex, on 22 August 1951. The development of the training programme up to that time was traced by P. J. Meade, who was then Head of the School, in the *Meteorological Magazine* in 1952.[1]

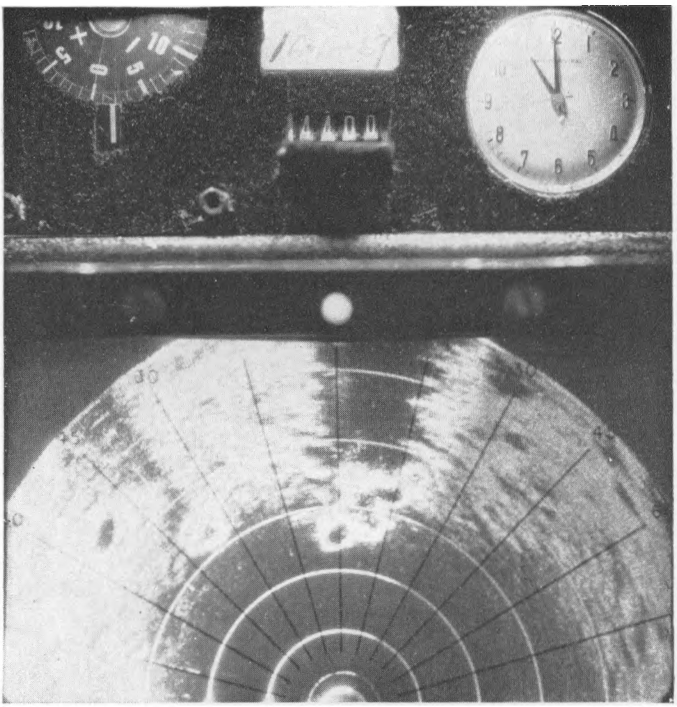
Training at Stanmore. At Stanmore professional training flourished, a stable pattern of instruction developed, and pride in the quality of the courses grew. The School acquired an international reputation. Students came from 75 countries and they could be trained for work in any region of the globe. A. H. Gordon has described[2] the expansion in the scope of the courses which took place over the years up to 1959. Since then the overall pattern of training has not greatly changed, but the courses themselves have kept pace with the quick development of the science. The principal courses, at the present time, are described in an Office leaflet issued annually (see page 301).

The Meteorological Office College. The establishment of training facilities at Stanmore in 1951 was a great step forward at the time. However, as general development took place in the area and accommodation standards changed, the restrictions on teaching imposed by the old wartime buildings and their environment were increasingly felt. In 1961 the various scattered units of the Meteorological Office Headquarters were brought together in a new building at Bracknell. It was intended[2] that the Training School would also be rehoused in the new Headquarters, but due to pressure of growth in other branches the move of the School to Bracknell did not take place. Weight was added to the case for re-location by a recommendation of the Parliamentary Estimates Committee in the third report of the Session 1966–67. It was felt that specialists working in the various branches of the science at the Headquarters at Bracknell should be able to participate more fully in the lecturing programmes. The search for a suitable site came to an end a year or two later when the Royal Air Force vacated the Flying Training Command Headquarters at Shinfield Park, near Reading. The Meteorological Office was offered a substantial part of the site. After a period of planning, work commenced in September 1970 on the conversion and extension of existing buildings to provide accommodation for a new Meteorological Office College. Training ended at Stanmore on Friday, 15 October 1971 and recommenced without break at Shinfield Park on the 18th. Photographs of some of the College facilities can be found at Plate II (others in the *Meteorological Magazine* for March 1972 and the Meteorological Office *Annual Report* for 1971).

Comparison of these pictures with those accompanying the articles by Meade[1] and Gordon[2] shows clearly the improvement in the quality of the teaching accommodation.

At Shinfield Park, skilful conversion has minimized the limitations imposed by the need for adaptation of the existing buildings. Two of these contain all the instructional facilities. In the Main Building, a former airmen's mess, there are seven spacious classrooms each equipped with light-tables, projectors and other aids for practical instruction in weather analysis and forecasting. Five of them are housed in a specially built extension to the original building and are grouped around an instruments lobby in which are continuously recorded atmospheric pressure, wet- and dry-bulb screen temperatures, surface wind speed and direction, cloud base, rainfall, total and direct incoming solar radiation, reflected solar radiation, the radiation balance, earth temperatures to a depth of one metre, and the temperature profile in the lowest metre of the atmosphere. Also within the Main Building is a tiered lecture theatre, the library, communications room, instructors' common room and administrative offices. School House, once an airmen's dormitory block, is used for training in the use and maintenance of meteorological instruments, weather observing, coding and plotting. There are also excellent facilities for the lectures in basic meteorological physics which form part of the syllabuses of the majority of the courses for Assistants (now Assistant Scientific Officers). In addition to three synoptic classrooms, offices and a students' common room, there is an outstation-routine room, a small tiered lecture theatre, an instruments classroom and a workshop. A cinema seating 94 has been built as an extension to School House. It is comprehensively equipped for lecturing as well as for showing the instructional films which form an important part of the curricula, and the acoustics are very good. The Services Kinema Corporation advised in its design.

In the early weeks of their courses students are taught to plot weather data and to analyse weather situations from the past. As the courses develop, however, it becomes necessary, in simulating operational working conditions, for current weather information to be available. The College is directly linked with the Telecommunications Centre at Bracknell by several teleprinter channels. The Bracknell centre is a hub of the global telecommunications circuit and can provide current data for all parts of the world. These data are raw material for courses in analysis and forecasting, not only for the Atlantic and European areas, but also for the Mediterranean countries, the Middle East, the Far East and many parts of the tropics. Thus the course for, say, the Seychelles staff is able to work with current material for the Indian Ocean and bordering countries, and to become familiar with the operational working of the proper local regional procedures. Two facsimile broadcasts are received from Bracknell by landline and the College takes radio-facsimile transmissions from overseas areas as required. Cloud and radiation pictures are received at the College from satellites via the ground station at Beaufort Park, near Bracknell, as they are broadcast. Satellite data have become an essential adjunct to the standard chart sequences selected and printed for the students' use. The main instruments enclosure is situated within an open area of grassland well clear of the College buildings, but there is also an array of teaching screens close to School House and the roof of the cinema serves as an observing platform. The many acres of parkland allow ample space



Photograph by courtesy of Royal Aircraft Establishment, Bedfor

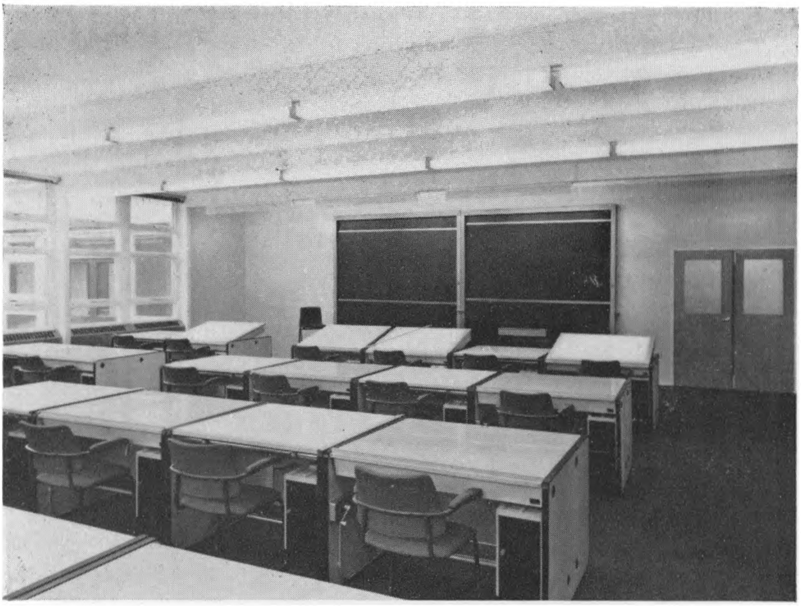
PLATE I—AIRBORNE 30-mm RADAR SHOWING 'SHADOW' CAST BY SHOWERS

The aircraft was at 20 680 ft (6·3 km) near 22° 25′N, 83° 37′E at 1630 IST (GMT + $5\frac{1}{2}$ hours). The radar antenna was depressed 2° below the horizontal. Ground returns appear at ranges greater than 30 n.miles (55 km) except where they are masked by the showers. (Range markers are at intervals of 10 n.miles.) See page 304.

(a) The Main Building

PLATE II THE METEOROLOGICAL OFFICE COLLEGE AT SHINFIELD PARK

See page 299.



(b) Classroom in the Main Building equipped with light-table and working tables in pairs. Slopes of table tops are adjustable.

(c) School House. The staircase leads to the observing platform on the roof of the cinema.

PLATE II—*continued*

To face page 301

Photograph by D. Tribble

PLATE III HAZE IN THE AUSTRIAN TIROL, LATE AFTERNOON ON 9 AUGUST 1954

See page 312.

for the field work which now forms an important part of the Scientific Officers Course, and for multiple theodolite pilot-balloon observations. Unrestricted base lines are available for such instruments as the cloud-base recorder, visibility lights and transmissometer.

At Shinfield Park the courses have become fully residential, the College being designed to accommodate 110 students, each of whom has a compact but bright and well-furnished study/bedroom which allows for quiet evening work. This represents a very considerable advance. Dependence at Stanmore on lodging accommodation meant that course members were hampered in their studies by unsatisfactory working and living conditions. Overseas students in particular had complaints of unheated rooms, inadequate diets and lack of sympathy in health problems. These difficulties are now of the past and the benefits of the new facilities have quickly been felt; course members are getting through more work with greater success and less stress. Domestic arrangements at the College are the responsibility of the Bursar, assisted by an Accounting Officer, Catering Officer and Matron. Social activities centre upon the Lodge, a small, early nineteenth century residence with extensions housing the dining room, games and television rooms and bar. The last amenity derives from the building's previous function as an officers' mess. Squash and tennis courts within the grounds have also been retained.

The future. The training programme must respond to changing circumstances and it is not difficult at this time to see directions from which pressure for change may come. Internationally, there is the world-wide problem of the effects of the pace of development of the science, and there is the trend to centralization of certain of the meteorologists' functions in response to the growth of the computer's role. Nationally, in the United Kingdom, recruitment during the past year has become, for one reason or another, more selective and academic standards are higher than in the past. There has also been the introduction into the Meteorological Office, in common with other departments of the Civil Service, of a new scientific class structure, combining the former Scientific Officer, Experimental Officer and Scientific Assistant classes. It is a little too soon to predict here what changes may result. Certain it is, however, that the new College facilities have come none too soon.

Shinfield Park is situated within a mile or two of the University of Reading, so the opportunity exists for co-operation with the Department of Geophysics in training projects of potential mutual benefit. In February 1973, students will arrive at Shinfield Park to embark upon the first phase of a new sandwich course leading to an honours bachelors degree in meteorology. The course will offer unique advantages in vocational training over the normal academic syllabus.

A leaflet giving the College calendar and the syllabuses for current courses is available on request from The Principal, Meteorological Office College, Shinfield Park, Reading, Berkshire, RG2 9AU.

REFERENCES

1. MEADE, P. J.; Training in the Meteorological Office. *Met Mag, London*, **81**, 1952, pp. 129–137.
2. GORDON, A. H.; Twenty years after. *Met Mag, London*, **88**, 1959, pp. 257–262.

551.501.81:551.507.352

A NOTE ON THE USE OF AIRBORNE 30-MILLIMETRE RADAR AT LONG RANGES

By S. G. CORNFORD

Summary. The radar beam of a cruising supersonic transport aircraft will sometimes be attenuated by showers at lower levels. Storms at the flight level may lie in the radar shadow of lower-level showers and may not be detected when they first come into radar range. The effect, due to the curvature of the earth, is alleviated somewhat by refraction.

Introduction. It is well established[1,2] that cumulonimbus clouds sometimes extend to heights of over 18 km, rising 3 or more kilometres into the stratosphere. Where they occur, such tall clouds may present a hazard to supersonic transport aircraft (SST). The SST pilot will need to begin avoiding action when the storms are still a long way ahead, perhaps 400 km or more, because of the large accelerations inherent in any but gentle manœuvres at supersonic speeds. Allowing time for decision making and so on, he will need to detect storms when they are even farther ahead. So that he may do this the aircraft will carry radar. For practical reasons this will operate on a wavelength of 30 mm, the wavelength used in most airborne radars. At the ranges involved in storm detection from SSTs, however, two factors become important which are usually ignored by users of airborne radar. They are the curvature of the earth and refraction of the radar beam. The factors are, of course, well known[3,4] but their importance in these circumstances may be of interest to aircrew and the meteorologists who advise them.

Geometry on a spherical airless earth. Consider Figure 1. Suppose an observer at O, at height z above a spherical and airless earth of radius R, wishes to see an object S at the same height above the earth's surface as himself. He must look not along the horizontal OHS but along the chord OMS. His line of sight passes through M at a depth d below him. The geometry of Figure 1 gives the depression d as $d \approx l^2/2(R + z)$ where $2l$ is the range of S from O along the arc OHS. The only approximation involved is that $\varphi \approx \sin \varphi$. Since l will not exceed a few hundred kilometres and

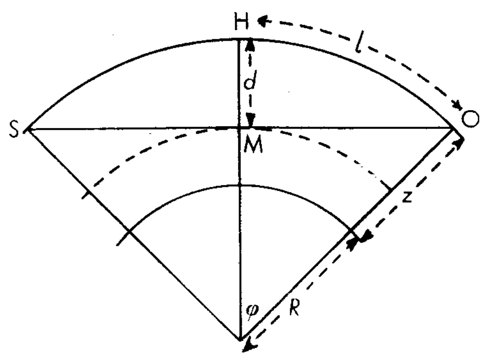


FIGURE 1—GEOMETRY ON A SPHERICAL AIRLESS EARTH

O Observer S Object being observed *R* Radius of earth

$(R + z) \approx 6000$ km, φ is small and is indeed approximately equal to sin φ. The relationship between d and $2l$ is shown by the full curve in Figure 2. As may be expected since $z \ll R$, d is insensitive to variations in z of a few tens of kilometres and is almost proportional to l^2.

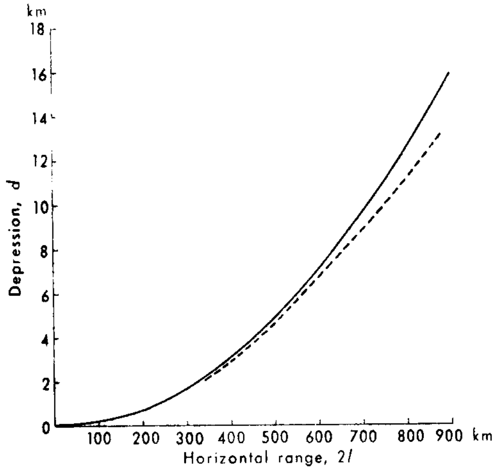


FIGURE 2—MAXIMUM DEPRESSION OF MICROWAVE BEAMS WITH RANGE

——— On a spherical airless earth with $R = 6377$ km. The depression, d, is insensitive to variations in the height, z, of the observer.

– – – For beams aimed from 100 mb at a target at the same level through air with the mean temperature and humidity profiles of a period when storm tops rose to over 18 km.

Refraction of microwaves in the atmosphere. The refractive index, n, of air for microwaves with wavelengths of tens of millimetres depends[3,4] upon the pressure, temperature and water-vapour pressure. The variation of n with height produces bending of microwave beams; see Figure 3.

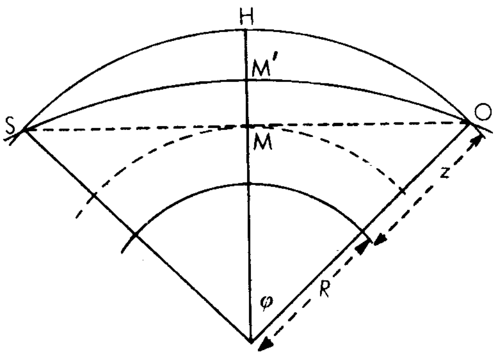


FIGURE 3—REFRACTION OF MICROWAVES IN THE ATMOSPHERE

Because the atmosphere forms a spherical shell, a beam which is horizontal at M′ passes into higher layers of air where n is smaller. At each higher level the beam is refracted 'away from the normal', although the curvature of the beam is smaller than that of the earth. Conversely a beam from O will travel along a path OM′S where M′ is above M. (On a smaller scale *n* may sometimes decrease quickly with height, e.g. at the base of an inversion, to give rise to anomalous propagation. Here, though, the rays pass through considerable depths of atmosphere.)

One of the parts of the world where storms are known to extend up to SST flight levels is north-east India (report by S. G. Cornford and C. S. Spavins, to be published). Because it was available from other work, a mean refractive-index profile based on soundings made from Calcutta during the pre-monsoon season of 1969 was used to trace rays such as OM′S. The soundings were made during a period when storm tops were observed at 18 km and above. A selection of rays is shown in Figure 4. They all start

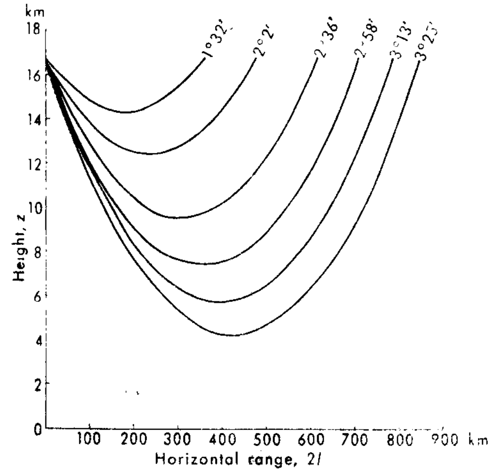


FIGURE 4—CALCULATED PATHS OF MICROWAVE BEAMS

The initial angle of depression is shown for each path.

and end at a height corresponding to 100 mb and, for ease of illustration, are shown relative to a flat earth. (The real sense of the curvature is that shown in Figure 3.) Although soundings from a storm-prone area were used, the paths of the rays are not very different from those in a standard atmosphere. Figure 4 has been used to derive the pecked curve on Figure 2. Comparison of the two curves of Figure 2 shows that refraction reduces the depression, *d*, of rays towards the earth by an amount which exceeds 1 km for ranges beyond 700 km.

Conclusions. Figure 4 shows that a Concorde pilot flying just below 17 km and using his radar to detect storms ahead of him must depress the radar below the horizontal. For a storm 600 km ahead, for example, the depression amounts to $2\frac{1}{2}°$ and the axis of the radar beam (and so most of the microwave energy) passes through air below 10 km. To detect storms 800 km ahead the axis of the beam would need to pass through air at between 5 and 6 km, where showers are often more frequent than at 17 km. Because they attenuate 30-mm radar beams, showers effectively cast radar 'shadows' and may mask more distant high-level storms; see Plate I. This effect appears to be a potential hazard and its implications (taking into account effects of beam-width, for example) should be worth exploring further. An assessment of its real importance must depend partly on an assessment of the relative probabilities of beams at different levels encountering one or more showers. If the radar were caused to nod continually over a range of a few degrees downwards from the horizontal, high-level storms could be spotted as soon as they came out of the radar shadows.

REFERENCES

1. ROACH, W. T.; On the nature of the summit areas of severe storms in Oklahoma. *Q J R Met Soc, London*, 93, 1967, pp. 318–336.
2. LONG, M. J.; A preliminary climatology of thunderstorm penetrations of the tropopause in the United States. *J Appl Met, Lancaster, Pa*, 5, 1966, pp. 467–473.
3. BATTAN, L. J.; Radar meteorology. Chicago, University of Chicago Press, 1959, pp. 14–19.
4. London, Meteorological Office; Meteorology of radio propagation. London, HMSO, 1953, pp. 1–11.

551.509.334:551.524.36:551.589

MONTHLY MEAN TEMPERATURE RELATED TO SYNOPTIC TYPES OVER BRITAIN SPECIFIED BY PSCM INDICES

By R. MURRAY

Summary. The seasonal and spatial variations of monthly mean temperature over Britain are discussed in relation to the main broad-scale synoptic types given by the *PSCM* indices of Murray and Lewis.

Introduction. The *PSCM* indices of Murray and Lewis,[1] based on the Lamb[2] catalogue of daily synoptic types, have been shown to be good indicators of broad-scale circulation near the British Isles. For instance, Murray and Benwell[3] presented some examples showing the close relationship between the indices in quintile form and the mean pressure anomalies over one, two and three months over the eastern Atlantic and western Europe. When the indices differ appreciably from average (quintile 3), pairs of P, S and C usually delineate fairly definite broad-scale types of synoptic situation near the British Isles; these synoptic types tend to be associated with characteristic temperature distributions. Murray and Benwell[3] also presented numerical correlations between the indices and monthly mean temperatures, and they briefly discussed the seasonal variations and the spatial variations over the United Kingdom. However, it is felt that to be of practical use these variations need to be described more explicitly.

The indices cover the period 1861 to 1969. The quintile boundaries (based on 100 years, 1865–1964) are given in Murray and Benwell,[3] together with information on monthly mean temperature.

Pairs of P, S and C indices. Blocked and progressive synoptic types are represented by P_{12} (quintiles 1 or 2 in P index) and P_{45} (quintiles 4 or 5 in P index) respectively. Synoptic types with a bias to north and south are given by S_{12} and S_{45} respectively. Anticyclonic and cyclonic synoptic types are represented by C_{12} and C_{45} respectively. When two indices, for example P_{12} and C_{45}, are taken together a blocked cyclonic type which is represented as $P_{12}C_{45}$ is obtained. Pairs of the P, S and C indices can be combined in a meaningful way to represent broad-scale synoptic types on the monthly time-scale. The frequencies of occurrence of various combinations of the indices in relation to the synchronous distribution of quintiles of monthly mean temperature in central England were readily obtained in percentage form. The actual frequencies of synoptic types varied between pairs of indices and also seasonally, but usually there were around 20 cases (14 to 28) per month for each pair.

The 12 subsections contained in Table I show how the monthly mean temperature varies according to the broad-scale synoptic type.

TABLE I—MONTHLY PERCENTAGE FREQUENCY DISTRIBUTION OF QUINTILES OF MONTHLY MEAN TEMPERATURE IN CENTRAL ENGLAND FOR COMMON SYNOPTIC TYPES,* 1861 TO 1969

Quintiles	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
(a) $P_{12}S_{12}$ (blocked northerly)												
1	**63**	**60**	**65**	**40**	**30**	22	33	24	**60**	**54**	**82**	**42**
2	22	35	30	26	25	22	33	24	17	13	13	23
3	10	5	5	20	25	22	14	24	17	13	5	31
4	5	0	0	7	10	22	10	16	6	20	0	4
5	0	0	0	7	10	12	10	12	0	0	0	0
(b) $P_{45}S_{12}$ (progressive northerly)												
1	6	0	0	17	**56**	41	**58**	33	17	14	16	5
2	22	32	19	**38**	32	0	8	**39**	39	**36**	26	25
3	22	10	27	33	6	41	17	22	39	32	**32**	20
4	22	16	27	6	6	6	17	6	0	6	16	25
5	**28**	**42**	27	6	0	12	0	0	5	14	10	25
(c) $P_{12}S_{45}$ (blocked southerly)												
1	18	28	15	5	0	15	6	0	0	5	7	25
2	**34**	14	25	25	17	23	6	7	11	14	7	15
3	24	22	25	**30**	11	15	29	36	22	19	20	20
4	24	**36**	25	20	17	**32**	18	0	**39**	10	**46**	15
5	0	0	10	20	**55**	15	**41**	**57**	28	**52**	20	25
(d) $P_{45}S_{45}$ (progressive southerly)												
1	0	0	0	0	0	14	10	12	0	0	0	0
2	0	0	0	7	6	18	25	19	6	0	10	13
3	17	12	7	0	25	27	15	25	25	18	5	13
4	25	19	36	36	31	9	25	19	**38**	36	35	20
5	**58**	**69**	**57**	**57**	**38**	**32**	25	25	31	**46**	**50**	**54**
(e) $P_{12}C_{12}$ (blocked anticyclonic)												
1	**50**	**50**	29	20	10	16	14	12	30	26	**54**	**48**
2	29	25	**41**	25	10	11	14	8	9	13	7	25
3	13	11	18	25	15	21	14	20	13	13	14	9
4	8	14	12	15	15	21	14	12	17	13	21	9
5	0	0	0	15	**50**	**31**	**44**	**48**	30	**35**	4	9
(f) $P_{45}C_{12}$ (progressive anticyclonic)												
1	0	0	0	0	6	7	7	8	0	8	9	0
2	7	0	8	22	**35**	21	7	0	**45**	**31**	27	29
3	36	22	8	17	18	21	20	31	22	23	9	21
4	14	22	**46**	17	18	14	27	**38**	11	15	9	**36**
5	**43**	**56**	38	**44**	23	**37**	**40**	23	22	23	**46**	14
(g) $P_{12}C_{45}$ (blocked cyclonic)												
1	29	**50**	**45**	25	23	23	25	21	29	25	**43**	**35**
2	21	42	11	19	**38**	23	**31**	**36**	29	8	21	29
3	**43**	0	22	19	23	12	25	29	13	17	7	6
4	7	8	11	12	8	**30**	13	14	29	**33**	21	12
5	0	0	11	25	8	12	6	0	0	17	7	18

Maximum percentages are bold if they are at least 3 per cent greater than the next highest percentage.

*Synoptic type is indicated by pairs of *P*, *S* and *C* indices.

TABLE I—*continued*

Quintiles	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
(h) $P_{45}C_{45}$ (progressive cyclonic)												
1	6	0	0	12	**35**	**43**	39	32	14	14	5	6
2	6	11	22	29	5	14	39	**42**	24	9	18	11
3	11	32	17	29	20	29	16	21	**48**	**29**	14	11
4	**44**	21	**33**	24	25	5	6	0	9	24	**36**	17
5	33	**37**	28	6	15	9	0	5	5	24	27	**55**
(i) $S_{12}C_{12}$ (northerly anticyclonic)												
1	**33**	**43**	25	21	16	11	25	25	**50**	33	**68**	29
2	22	29	**40**	**42**	32	6	25	15	31	**40**	18	**38**
3	11	14	15	16	32	**33**	20	**35**	6	7	9	14
4	17	5	15	5	10	28	15	15	13	13	0	19
5	17	9	5	16	10	22	15	10	0	7	5	0
(j) $S_{45}C_{12}$ (southerly anticyclonic)												
1	23	14	0	0	0	8	0	6	0	6	0	23
2	31	7	21	0	6	15	0	0	7	11	15	12
3	31	33	29	20	6	15	12	12	20	22	8	18
4	8	33	21	20	23	23	18	13	27	0	**46**	23
5	8	14	29	**60**	**65**	**38**	**70**	**69**	**46**	**61**	31	24
(k) $S_{12}C_{45}$ (northerly cyclonic)												
1	27	18	**67**	36	**72**	**62**	**50**	33	**40**	**40**	**36**	**46**
2	20	**27**	8	21	11	13	33	**50**	30	10	29	23
3	27	23	25	36	11	13	8	6	30	30	21	8
4	13	14	0	7	6	6	9	11	0	10	7	15
5	13	18	0	0	0	6	0	0	0	10	**7**	8
(l) $S_{45}C_{45}$ (southerly cyclonic)												
1	0	7	11	6	0	**29**	16	12	0	5	0	6
2	25	7	0	22	15	19	**37**	18	14	5	10	18
3	19	7	21	11	**35**	19	26	**46**	29	16	5	12
4	**31**	**50**	31	**44**	30	19	16	18	**50**	37	**45**	12
5	25	29	**37**	17	20	14	5	6	7	37	40	**52**

The first four types show combinations of *P* and *S*. Not unexpectedly, blocked northerly (a) and progressive southerly (d) types show markedly different temperature distributions, especially in the winter half-year. Progressive northerly (b) and blocked southerly (c) types have more complicated patterns. The next four types involve *P* and *C*. The blocked anticyclonic type (e) shows a pronounced seasonal variation, being cold in winter and warm in summer, whereas the progressive cyclonic type (h) shows broadly the reverse temperature pattern during the year. The progressive anticyclonic (f) and blocked cyclonic (g) types are also the reverse of each other in temperature pattern but they do not show such a strong seasonal change as do the blocked anticyclonic and progressive cyclonic types. The last four types in Table I involve the *S* and *C* indices. The southerly anticyclonic type (j) is generally warm except in winter; the opposite type, i.e. northerly cyclonic (k) is usually cold, especially in March, May and June. The northerly anticyclonic type (i) has a strong bias to cold from September to April; on the other hand, the southerly cyclonic type (l) tends to be warm from September to April.

Correlations between indices and temperature. Correlation coefficients between the individual indices and monthly mean temperature *(T)* at several places were given in Murray and Benwell.[3] The data for Braemar in north Scotland and Plymouth in south-west England are plotted in Figure 1 in order to illustrate seasonal and geographical differences and similarities.

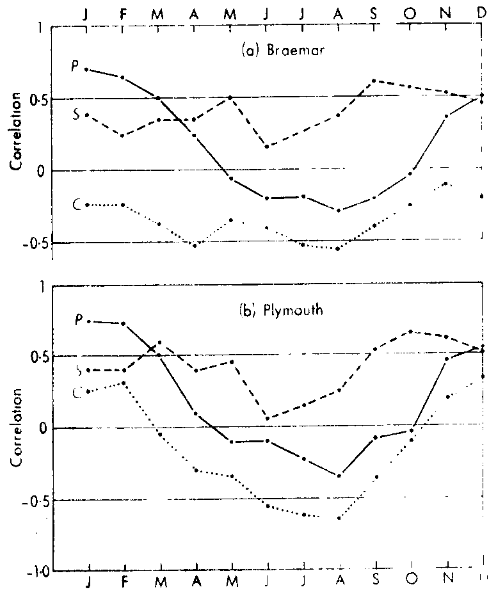


FIGURE 1—CORRELATION COEFFICIENTS BETWEEN INDICES AND MONTHLY MEAN TEMPERATURE FOR BRAEMAR AND PLYMOUTH (From Murray and Benwell[3])

At both places the correlations between P and T are positive in winter and negative in summer and this broad relationship applies in other parts of the United Kingdom. The correlations between S and T are positive throughout the year at both stations, although there is a seasonal variation with a minimum correlation in June and a maximum in autumn. At Braemar the correlations between C and T are always negative but at Plymouth they are negative only from March to October.

The seasonal variation of the correlations between C and T at Plymouth are quite typical of those in most other parts of England and Wales, as shown by the statistics for Kew (London), Oxford, Cambridge and Aberystwyth (Wales) and, in a weak form, for Stoneyhurst (Lancashire) and York. It is probable that the C and T correlations at Braemar are fairly typical of north and west Scotland (from Aberdeen and Dumfries data) and Northern Ireland (from Armagh data).

Multiple correlations have been computed between P, S and C indices and T for several stations. Examples involving central England and Edinburgh monthly mean temperatures were given in the paper by Murray and Benwell.[3] The regression equations for central England for January and August may be employed to illustrate the variation of monthly mean temperature according to the way in which the P, S and C indices in quintiles are combined.

The multiple regression equations for January (1) and August (2) are :

$$T(°C) = 2{\cdot}753 + 0{\cdot}058P + 0{\cdot}054S + 0{\cdot}006C, \qquad \ldots (1)$$

$$T(°C) = 15{\cdot}816 - 0{\cdot}009P + 0{\cdot}077S - 0{\cdot}035C. \qquad \ldots (2)$$

Each of the P, S and C indices may be divided into three classes, namely quintiles 1 and 2 (e.g. P_{12}), quintile 3 (e.g. P_3) and quintiles 4 and 5 (e.g. P_{45}). The values of each index at the quintiles 1 and 2 boundaries (given in Murray and Benwell[3]) may be taken as representative of P_{12}, S_{12} and C_{12} and at the quintiles 4 and 5 boundaries as representative of P_{45}, S_{45} and C_{45}. P_3 may be allocated the mean of the boundary of quintiles 2 and 3 and of quintiles 4 and 5, and similarly for S_3 and C_3. There are 27 combinations of the three subdivisions of indices *P*, *S* and *C*; these give 27 synoptic types, such as $P_{12}\ S_{12}\ C_{12}$, $P_{12}\ S_3\ C_{12}$, etc. The type $P_{12}\ S_{12}\ C_{12}$ is, of course, blocked northerly anticyclonic and can be equated to the anticyclonic north-easterly type in terms of monthly mean pressure anomalies. Similarly the other types can be described in simple and meaningful synoptic terms.

By using equation (1), typical or representative monthly mean temperatures may be allocated to each of the 27 synoptic types. A similar procedure can be carried out using equation (2) to give typical values for August. Table II shows the 27 synoptic types ranked according to the rank of the mean temperatures typically associated with them.

Table II shows several synoptic climatological features of interest. In January the coldest type is $P_{12}\ S_{12}\ C_{12}$ (blocked northerly anticyclonic) and the warmest is $P_{45}\ S_{45}\ C_{45}$ (progressive southerly cyclonic); in August the coldest is $P_{45}\ S_{12}\ C_{45}$ (progressive northerly cyclonic) and the warmest is $P_{12}\ S_{45}\ C_{12}$ (blocked southerly anticyclonic). In determining monthly mean temperature the primary index is clearly *P* in January, but *S* and *C* are more significant than *P* in August. It is also of interest that the $P_3\ S_3\ C_3$ or normal type is in the middle of the order in August but slightly on the warm side in January when the mean temperature distribution is negatively skew.

It must be remembered that the data in Table II were derived from quintile boundary values of the three indices. Quintiles 1 and 2 in, say, the *P* index covers a wide range of possible values each month. For example, taking the extreme values of *P*, *S* and *C* in January listed in Appendix II of Murray and Benwell[3] the regression equation (1) gives a likely minimum of − 1·7°C and a maximum of 7·9°C. The likely extreme temperatures in August derived from equation (2) are 12·0°C and 18·9°C. The two estimated maxima are slightly higher that the highest recorded monthly mean temperature; the estimated minimum is higher in January and lower in August than the minimum monthly mean temperature recorded during the period of the *PSCM* indices (i.e. since 1861).

In practical work, temperatures are mostly used in their quintile form. Figure 2 gives the relationship between the 27 main synoptic types and their characteristic temperature quintiles in diagrammatic form. The diagram shows quite clearly that in January the warm types are between north-west ($P_{45}\ S_{12}$) and south-west ($P_{45}\ S_{45}$), irrespective of cyclonicity. There are almost temperature discontinuities between north-west and north types and also between south-west and south types. Figure 2 emphasizes the importance of the *C* index in August. The warmest types are C_{12} from the south or south-east and the coldest type is C_{45} associated with roughly north-west flow.

It must be emphasized again that Figure 2 shows only typical temperature quintiles associated with values of *P*, *S* and *C* at the boundaries between quintiles 1 and 2 and between quintiles 4 and 5 and at roughly the mid-point of quintile 3. For example, if the type is $P_4\ S_1$ in January, with P_4 nearly equal to P_3 and S_1 well into the quintile 1 range, then the mean temperature will probably be quintile 2 rather than quintile 4 as shown in Figure 2. As another example, in a case of marked blocking in January, with *P* well into

TABLE II—SYNOPTIC TYPES* TYPICALLY ASSOCIATED WITH RANKED MONTHLY MEAN TEMPERATURES IN JANUARY AND AUGUST IN CENTRAL ENGLAND, DERIVED FROM REGRESSION EQUATIONS

Index	Temperature rank 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
	subscript of index																										
(a) January																											
P	12	12	12	12	12	12	3	3	12	3	12	12	3	3	3	3	3	3	45	45	45	45	45	45	45	45	45
S	12	12	12	3	3	3	12	12	45	12	45	45	45	45	45	3	3	3	12	12	3	3	3	3	45	45	45
C	12	3	45	12	3	45	12	3	12	45	3	45	12	3	45	12	3	45	12	3	45	12	3	45	12	3	45
(b) August																											
P	45	3	45	12	45	3	3	12	45	45	12	45	3	3	3	12	12	45	45	12	3	3	12	12	45	3	12
S	12	12	3	12	12	3	12	3	3	45	12	12	45	3	12	45	3	45	3	12	45	3	45	3	45	45	45
C	45	45	45	45	3	45	3	45	3	45	3	12	45	3	12	45	3	3	12	12	3	12	3	12	12	12	12

In January, Rank 1 = 2·16°C and 27 = 5·47°C. In August, Rank 1 = 14·45°C and 27 = 16·65°C.

* Synoptic types are indicated by indices.

the lowest quintile, the $P_1 S_3$ type is likely to be associated with temperature quintile 1 rather than with quintile 2. In other words the diagrammatic representation in Figure 2 must be interpreted sensibly. The likely temperature quintile can of course be assessed more accurately from the regression equations if the actual values of P, S and C are known or estimated.

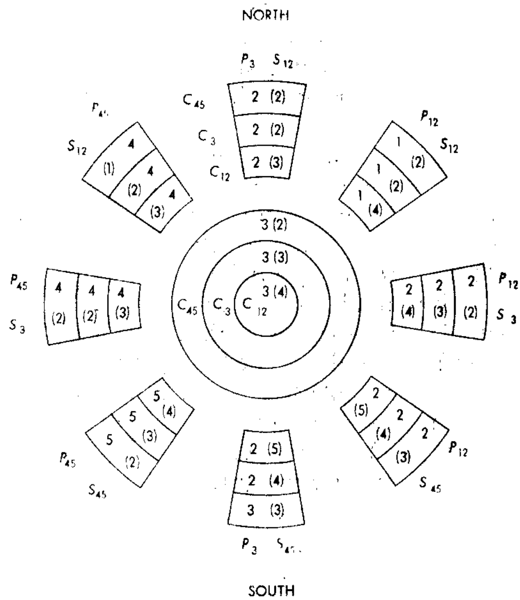


FIGURE 2—RELATIONSHIP BETWEEN THE 27 SYNOPTIC TYPES AND THEIR CHARACTERISTIC TEMPERATURE QUINTILES IN DIAGRAMMATIC FORM FOR JANUARY AND AUGUST

Typical quintiles of monthly mean temperature in central England in January and August (latter in brackets) associated with the 27 main synoptic types as given by combinations of P, S and C indices in their quintile form. Combinations of P and S give roughly the direction of the anomalous flow (P_3S_3 indicates normal flow); the cyclonicity (C) associated with each pair of P and S varies from C_{12} in the inner sector to C_{45} in the outer sector of each box.

A diagram similar to Figure 2 can be prepared for Edinburgh from the regression equation given in Murray and Benwell.[3] However, the discussion in this note of Figures 1 and 2 and Table I should be enough for qualitative assessments of the monthly mean temperature distribution over the United Kingdom associated with different broad-scale synoptic types.

REFERENCES

1. MURRAY, R. and LEWIS, R. P. W.; Some aspects of the synoptic climatology of the British Isles as measured by simple indices. *Met Mag, London*, **95**, 1966, pp. 193–203.
2. LAMB, H. H.; British Isles weather types and a register of the daily sequence of circulation patterns, 1861–1971. *Geophys Mem, London*, **16**, No. 116, 1972.
3. MURRAY, R. and BENWELL, P.; *PSCM* indices in synoptic climatology and long-range forecasting. *Met Mag, London*, **99**, 1970, pp. 232–245.

551.524.4:551.593.54

HAZE TOP IN THE AUSTRIAN TIROL

By E. N. LAWRENCE

The haze photograph, Plate III, was taken at about 16 GMT on 9 August 1954, from the top of Hahnenkamm (Austrian Tirol), altitude 1700 m (5500 ft), looking about north-north-west. The range of mountains in the background reaches about 2300 m (7500 ft) and the valley floor is at about 800 m (2500 ft). Small amounts of small cumulus cloud may be seen 'near' the mountains, at about the level of the haze top but projecting slightly above this level.

The synoptic pressure situation (at 18 GMT) shows the area to be in a feeble ridge between a small depression over Holland and a frontal trough from Sweden to the Adriatic. The area is situated at about the nodal point of the front joining these two systems. Some associated upper cloud is shown in the photograph. At 700 mb (at 15 GMT) winds were south-westererly about 35 knots to the north-west and light to the south-east.

The haze top is probably associated with the stable, inversion layer shown on the Munich (Riem) upper-air ascent for 15 GMT on 9 August (Figure 1). At Munich, some 100 km (60 miles) to the north-west of the site of the photograph, the height of the inversion layer is 870–846 mb and the top of the inversion is 1450 m (4750 ft) above MSL, that is, somewhat below the top of the mountain ridge shown in the photograph.

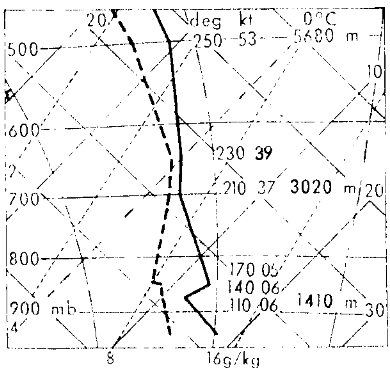


FIGURE 1—UPPER-AIR TEMPERATURES AND WINDS AT MUNICH AT 15 GMT ON 9 AUGUST 1954

——— Temperature - - - Dew-point

Heights refer to standard levels.

NOTES AND NEWS

Dr K. A. Browning — Special merit promotion to Senior Principal Scientific Officer

It is a pleasure to record that Dr K. A. Browning has been promoted to Senior Principal Scientific Officer under the scheme for promotion of scientists of special research ability. Dr Browning has been concerned with the application of radar to meteorological research throughout his career. His early research was at Imperial College, London, under the direction of Professor F. H. Ludlam in the early 60s. He continued his studies in the U.S.A. at the Air Force Cambridge Research Laboratories but returned to the United Kingdom in 1966, taking charge of the Meteorological Research Unit at Malvern, first as a Principal Research Fellow but from 1969 as a Principal Scientific Officer.

Dr Browning's researches have covered many aspects of atmospheric physics and cloud structure. His studies of the structure of severe storms, of the detailed structure of fronts, of clear-air turbulence and of the structure of hailstones have been particularly noteworthy. In all of them he has exploited the potentialities of radar to the full. As leader of the small team of meteorologists and radar specialists engaged on meteorological problems, he has been able to digest the voluminous data from the radars in a remarkably short time, and to present a graphic and understandable picture of the atmospheric system observed, whether it be a cumulonimbus, clear-air turbulence or a mountain wave.

The Meteorological Office is fortunate that his promotion permits Dr Browning to continue to lead the Malvern group and to exploit the powerful radars available there for meteorological research.

J.S.S.

REVIEWS

Inadvertent climate modifications. Report of the Study of Man's Impact on Climate. 220 mm × 155 mm, pp. xxi + 308, *illus.* The M.I.T. Press, 126 Buckingham Palace Road, London, SW 1, 1971. Price: £5·85, paperback £1·40.

This book presents the results of an international symposium held in Stockholm in 1971. Thirty of the world's leading atmospheric scientists from 14 countries met to discuss and study the impact of man on climate. The study was intended as a follow up of an earlier Study of Critical Environmental Problems (SCEP) held in the U.S.A. in 1970.

The 30 scientists include many famous names, Budyko, Flohn, London, Machta, Manabe, Van Mieghem, G. D. Robinson and Twomey, for instance, and there is no doubt that they have produced a thoroughly worthwhile and most timely report.

The report is directed at the scientific community in general, partly in the hope that young scientists will be stimulated to study some of the unsolved problems to which the report draws attention. Even more important, it is hoped that the conclusions and recommendations will influence the international scientific community so that progress towards their implementation may be made. In this latter respect it was clearly intended that the report should be studied carefully by delegates to the recent United Nations Conference on the Human Environment. It is recognized that only by airing the problems involved at such a unique forum is the necessary research effort likely to be allocated by governments.

The layout of the book leads to a good deal of repetition. One would not complain at the collection in Part I of the major conclusions and recommendations of the whole study, but Parts II, III and IV also contain a good deal of repetition. Part II describes climatic changes which have taken place in the geological past from 550 million years ago right up to the 20th century and this is followed by some discussion of the various ways in which it is possible that man may be influencing climate. Part III describes in more detail the factors which govern climate — radiative processes, ocean/atmosphere transport processes, hydrological processes, etc. — and then goes on to describe the general theory of climate and the progress which has been made towards producing a satisfactory mathematical model to represent the way in which climate is determined. Part IV discusses in some detail the possible ways in which man is, or may be, changing the climate as a result of the changes he is making. This part is divided into three sections :

(a) *At the surface.* Urban effects; changing the earth's albedo by the increase of agriculture, deforestation, etc.; changing the surface water area, and hence evaporation, by means of artificial lakes, drainage of swamps, etc.; changes in the hydrological cycle due to control of run-off; the mining of ground water, etc.
(b) *In the troposphere.* Addition of particulate matter, aerosols, gaseous products such as carbon dioxide and sulphur dioxide, and water vapour which may effect cloud formation, etc.
(c) *In the stratosphere,* where, owing to their longer residence time, any contaminants may have more chance of seriously influencing photochemistry, especially that involving ozone.

Throughout the book the authors stress the importance and probable instability of the polar ice; a 1 per cent change of incoming solar radiation, keeping mean cloudiness constant, is likely to change the mean global temperature by 1·5 degC and that of the Arctic by about 5 degC. A 1 per cent change in global albedo is also likely to change the mean global temperature by 2·3 degC — more in high latitudes — so that it is clear that polar ice is extremely sensitive to changes in the global radiation budget. If the polar ice once melted completely it is considered very doubtful whether it would re-form, because the change in the albedo would lead to greater absorption of heat by oceans in high latitudes.

The importance of carbon dioxide is also stressed; it seems likely that the increase to 375 parts per million expected in the atmosphere by 2000 AD would lead to about a 0·5-degC global temperature rise which would be enhanced by absorption of heat due to the increased water vapour in the atmosphere. However, if mean cloudiness increased by 1 per cent this rise of global temperature would probably be more than counterbalanced by a fall due to the changed albedo. From these sorts of arguments it is clear that the study has served a very useful purpose in drawing attention to the need for much more research and in spelling out the most profitable areas for carrying out this research.

This volume is very readable with generally good diagrams and it is thoroughly up to date with many references to work done in 1970 and 1971, and even to work not yet published. Apart from H. H. Lamb, however, British meteorologists get scant reference. Errors in the text are few although the reference to Lamb's long series of January and July charts on p. 41 should be for the period since 1750 and not since 1790 as stated. More seriously the scale of Figure 3.5, showing the changes in the frequency of westerly weather types since 1860 over Britain, is completely wrong, indicating a year-to-year variability from 70/170 instead of about 70/120.

Nevertheless, the study is thoroughly recommended as a balanced view, based on the current state of knowledge, of the possibilities of inadvertent climatic change. It makes it clear that man may possibly have reached the stage when he could be influencing the climate on a global scale, but the accent throughout is cautious and stresses the necessity for further knowledge before a proper judgement can be made.

R. A. S. RATCLIFFE

New Zealand: the physical environment, by D. J. Hooton (editor). 245 mm × 155 mm, pp. 70, *illus.*, Auckland University Press, and Oxford University Press, Ely House, 37 Dover Street, London W 1, 1970. Price: £1 (paperback).

Anyone entering the Geological Museum in South Kensington, London, at the appropriate moment will be faced by a rotating globe showing almost a hemisphere of water — the Pacific Ocean — liberally sprinkled with islands, the largest of which are the North and South Islands of New Zealand. Their nearest continental neighbours are Australia, about 1100 miles (1770 km) to the west, and South America, some 5000–6000 miles to the east.

This extreme isolation is the result of earth movements which gradually separated New Zealand from its parent continent, Australia and Antarctica combined. In the first century of European colonization, New Zealand, with its biological affinities with Australia, South America and Antarctica, was a paradise for the natural scientists, but less so for the physical scientists.

Recent developments in meteorology and geophysics have now shown that New Zealand offers unique opportunities for research in these fields as well, its very isolation from continental masses being a valuable asset in certain important fields, such as the circulation of air and water currents and the electron content of the ionosphere.

The booklet under review consists of a series of six lectures delivered at Auckland in the (southern) winter of 1969 by specialists in geology, physics, geophysics, meteorology and oceanography.

As Professor Hooton says in his preface, these six lectures 'range from outer space to the hot interior of the earth' and on the way they mention some of the special fields of research in which New Zealand is engaged. The Director of the New Zealand Meteorological Office, Dr J. F. Gabites, describes how New Zealand fits into the global scheme and shows a striking picture of the track of a balloon — launched from Christchurch, New Zealand, during the GHOST project (Global Horizontal Sounding Technique) — which had travelled more than seven times round the hemisphere in 102 days at a height of 12 km.

The ionosphere is being investigated by means of signals radiated from satellites, and another figure shows the electron content, on 11 days in winter and summer 1965, along a path between a geostationary satellite (at a height of 30 000 km over the equator north of New Zealand) and Auckland.

New Zealand has also been prominent in the study of 'whistlers' — disturbances of radio reception due to distant lightning flashes. The dispersion of the whistler signal between one hemisphere and the other was first demonstrated experimentally in 1955 between Wellington, New Zealand, and Unalaska in the Aleutian Islands.

Of about 800 volcanoes now active on the face of the earth, 62 per cent are situated in the narrow 'Girdle of fire' round the Pacific Ocean. Volcanic eruptions and earthquakes can give rise to the destructive ocean waves known as 'tsunamis', which travel enormous distances at recorded speeds of up to 600 miles/h, according to the depth of the ocean. The wavelength is typically tens of miles long and waves of more than 100 ft in height have built up on some shores.

Because of its isolated position, New Zealand is ideally situated to record, by hydrophone, underwater volcanoes, earthquakes likely to produce tsunamis and man-made signals in the SOFAR channel, along which underwater sound can travel many thousands of miles before being lost in the general background noise. Instances are given of projects exploiting this capability (Neptune, Chase V).

T. C. MARWICK

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NOTICES

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SCIENTIFIC PAPERS

No. 31 The three-dimensional analysis of meteorological data

By R. Dixon, B.Sc. and E. A. Spackman, M.Sc.

The advent of modern observational devices such as satellites and long-life free drifting balloons has greatly complicated the process of data analysis by computer. This paper presents a possible method for effecting this data analysis by fitting a high-power polynomial to all the observations from within a large volume of the atmosphere.

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No. 32 The Bushby-Timpson 10-level model on a fine mesh

By G. R. R. Benwell, M.A., A. J. Gadd, Ph.D., J. F. Keers, B.Sc., Margaret S. Timpson, B.Sc., and P. W. White, Ph.D.

A full description is given of the 10-level numerical weather prediction model which has been developed by the Meteorological Office during the past few years for use in investigating the dynamics of fronts and in predicting rainfall. The formulation includes representation of the effects of surface friction, topography surface exchanges of sensible and latent heat, sub-grid-scale convection, and lateral diffusion. An example of a recently computed forecast is included.

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Vol. 101, No. 1204, November 1972

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SOME ASPECTS OF CIRCULATION CHANGES IN THE NORTHERN HEMISPHERE IN JANUARY IN THE 20th CENTURY

By N. E. DAVIS

Summary. *PSCM* type indices are calculated for January for various longitudes at 50–60°N for each year from 1899 to 1968. The indices show a considerable biennial oscillation but the overall correlation between longitudes 60° apart is small. Long-period changes in the mean values of the indices are related to the intensity of the centres of action in the atmospheric circulation.

Introduction. Murray and Lewis[1] derived four monthly indices *(P, S, C* and *M)* from the catalogue of daily weather types over the British Isles given by Lamb. Precise definitions are given in the paper, but briefly the *P* index is a measure of the difference in frequency of days of progressive and days of blocked synoptic types — *P* is positive when the bias is towards progressive types. The *S* index measures the difference in frequency of southerly and of northerly days — positive *S,* southerly bias. *M* measures the frequency of days with meridional (i.e. northerly or southerly) synoptic types. The *C* index gives the difference between the frequency of cyclonic and of anti-cyclonic days — *C* is positive when cyclonic days predominate. Recently Lamb[2] has revised his catalogue and Murray and Benwell[3] have brought the *PSCM* indices up to date. Murray and Benwell showed how the indices were related to rainfall and temperature at places in the United Kingdom and how the indices had varied since 1865.

It was considered likely that if such indices were calculated for other longitudes their interrelation and long-term variability would show how global circulation changes affected various parts of the northern hemisphere and hence throw some light on the causes of such changes.

Derivation of data. The surface synoptic maps of the daily historical weather series from 1899 to 1962 were examined and for each day in January for each of the five 10-degree squares latitude 50–60°N and longitudes 50–60°E, 110–120°E, 170–180°E, 120–130°W and 60–70°W, a letter was assigned from the Lamb classification to describe the surface circulation over that particular square. Lamb in his classification of the U.K. (50–60°N, 0–10°W) circulation considered the situation over the whole 24 hours (midnight to midnight) but the historical weather series gave only one chart per day. This had to be taken as representing the circulation for that day. This slight difference in the method of assigning letters would lead to slightly fewer cases of the non-directional types *Y* (anticyclonic) and *Z* (cyclonic) being recorded at the other longitudes than would have been recorded if the classification procedure of Lamb had been followed strictly. The overall effect on the *PSCM* indices would be mostly in the *M* index which would tend to have higher values. For the period since 1962 for which historical maps have not yet been issued, synoptic maps published by the major meteorological centres in the northern hemisphere have been used.

The *PSCM* indices for each January for each of the 10-degree squares were then calculated according to the method given by Murray and Lewis.[1] Table I gives the overall 70-year mean of the *PSCM* indices for each longitude.

TABLE I—MEAN VALUES OF THE *P*, *S*, *C* AND *M* INDICES FOR JANUARY OVER THE 70 YEARS 1899 TO 1968

Index	0–10°W	50–60°E	110–120°E	170–180°E	120–130°W	60–70°W	Hemisphere
P	+14	+ 8	+ 3	−33	−13	+12	−1·5
S	+ 2	+ 8	−11	− 3	+20	−18	−0·3
C	− 4	− 3	−18	+18	+ 3	+ 1	−0·5
M	+14	+21	+21	+24	+24	+26	+22

General circulation and mean values of the indices. The broad features of the circulation in January can be interpreted in terms of the values of the indices in this table by reference to the mean surface-pressure map for January over the 70 years 1899 to 1968 which is given in Figure 1.

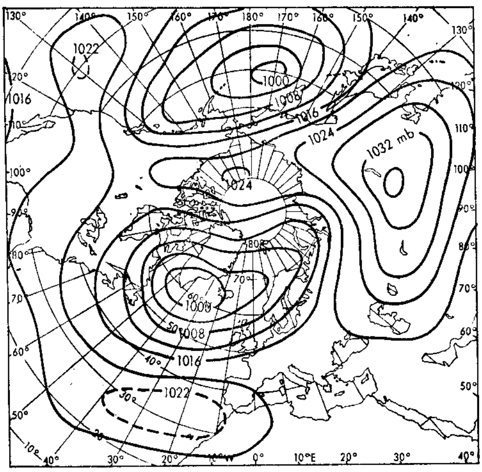


FIGURE 1—JANUARY MEAN SURFACE PRESSURE, 1899–1968

The Siberian anticyclone centred near 50°N, 100°E produces strongly negative values of the *C* index in the square 50–60°N, 110–120°E with weak progression but strong northerly bias leading into the Aleutian low which dominates the entire Pacific. The centre is near 50°N, 170°E, giving an intense cyclonic block in the square 50–60°N, 170–180°E. There is a marked southerly bias over the eastern Pacific and western North America with a mainly south-easterly flow over the square 50–60°N, 120–130°W to the north of the trough which extends eastward from the Aleutian low between latitudes 50° and 55°N. Over Labrador (50–60°N, 60–70°W) a strong northerly outflow between the Icelandic low and the north-west Canadian surface high gives a minimum *S* value and a maximum *M*. The Icelandic low shows a marked trough extending into the Barents Sea giving maximum progressivity and minimum meridionality over the U.K. This progressivity continues into Russia but shows an increasing southerly component (at 50–60°N, 50–60°E) on the western flank of the Siberian anticyclone.

Table II gives the maximum and minimum values of each index at each longitude and its year of occurrence.

TABLE II—MAXIMUM AND MINIMUM VALUES OF THE INDICES AT EACH LONGITUDE

Index		0–10°W	50–60°E	110–120°E	170–180°E	120–130°W	60–70°W	Hemisphere
P	Max.	+62	+54	+49	−2*	+26	+47	+25
		1921	1934	1962	1937, 1967	1904	1934	1949
	Min.	−52	−46	−42	−62	−62	−49	−32
		1941, 1963	1945	1940	1902	1907	1955	1940
S	Max.	+26	+38	+ 8	+27	+41	+ 6	+ 6
		1924	1915, 1938	1911	1950	1958	1963	1966
	Min.	−23	− 8	−32	−32	0	−39	− 9
		1945	1950, 1964	1933	1931	1922	1912	1945
C	Max.	+27	+36	+ 7	+41	+26	+18	+ 7
		1948	1950	1946, 1961	1905	1925	1931	1913
	Min.	−30	−39	−37	− 3	−19	−19	−12
		1953	1945	1944	1956	1950	1956	1954
M	Max.	+40	+38	+36	+39	+41	+41	+29
		1967	1915, 1938	1942	1950	1958	1961	1967
	Min.	0	+ 5	+ 9	+12	+ 7	+13	+16
		1921	1945	1913	1916, 1943	1917, 1937	1962	1902

* +11, 1969

All longitudes have shown years with both positive and negative values of the *PSC* indices except 120–130°W where the minimum *S* value has been zero. This variability in the values of the indices shows that in some years the normal flow over a particular square is reversed and the major centres of action are absent or far removed from their normal positions. As an example, Figures 2 and 3 give the mean surface-pressure maps for January 1940 and January 1949, the years with minimum and maximum values of *P* on a hemispheric basis, i.e. the years with minimum and maximum mean values of the *P* index averaged over the six longitudes. At 70°N between 10°E and 90°E, the pressure was more than 25 mb lower in 1949 than in 1940 but more than 25 mb higher near 45°N, 150°W. In 1949, the Icelandic low was displaced some 2000 km north-east, the Aleutian low 500 km north-west, and the Siberian high 500 km south, of the normal positions. The Icelandic low was 10 mb deeper and the Aleutian low 5 mb deeper than usual. In 1940, on the other hand, the Icelandic low was 1500 km south-west, the Aleutian low 1000 km south-east and the Siberian high 800 km north, of the normal positions. The Siberian high was 6 mb more intense, the Icelandic low 5 mb less deep and the Aleutiau low 10 mb deeper than usual. Between 50°N and 60°N in 1940, an anomalous easterly gradient occurred all round the hemisphere but in 1949 an anomalous westerly gradient occurred between the same latitudes.

Considering Tables I and II together, the minimum mean values of the *P* index and maximum mean value of the *C* index is at 170–180°E. It is also the longitude with the minimum variability of the *P* index (a range of 60 (73 if the 1969 value is included) from − 2 to − 62 compared with a range of 114 at 0–10°W from + 62 to − 52) but maximum variability of the *S* index. These facts would point to the Aleutian low being the most constant

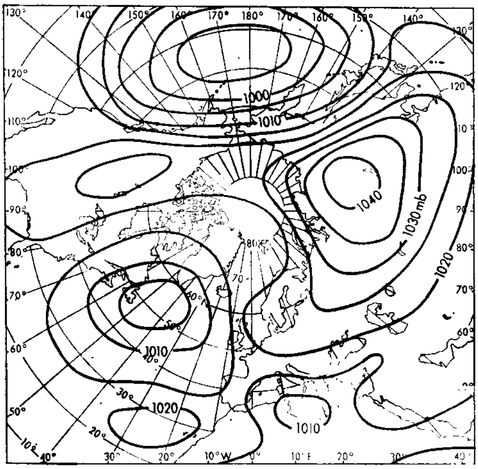


FIGURE 2—MEAN SURFACE PRESSURE, JANUARY 1940

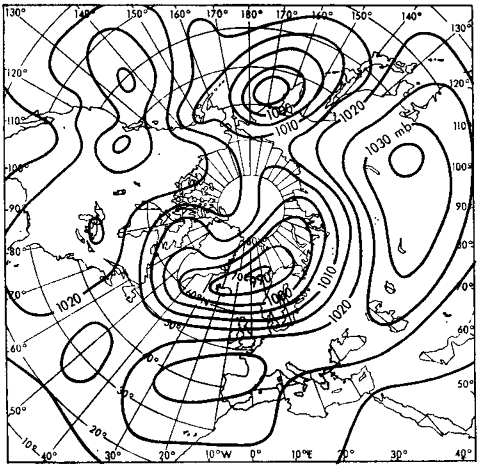


FIGURE 3—MEAN SURFACE PRESSURE, JANUARY 1949

and dominant feature of the January circulation with its major variation being in an east–west direction about its normal position near 50°N, 170°E. On the other hand, the European sectors 0–10°W and 50–60°E show the greatest variation in both the *P* and *C* indices, which indicates that the Icelandic low, especially its extension into the Barents Sea, is the least-constant feature of the January circulation. Figure 4 maps the standard deviation for the 70 Januarys about the 70-year mean. It shows maximum standard deviation near the centre of the Icelandic low with an area of high values extending eastwards well into the Arctic basin. In the Pacific the maximum standard deviation is not over the centre of the Aleutian low but some 20–30° to the east.

Correlation between the indices at the various longitudes. Table III gives the correlation coefficients between the indices at the various longitudes. Most of the correlation coefficients are insignificant and the table contains

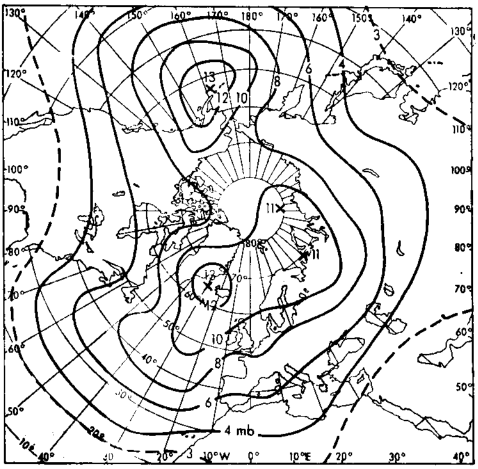


FIGURE 4—STANDARD DEVIATION OF MONTHLY MEAN SURFACE PRESSURE FOR JANUARY, 1899–1968

TABLE III—CORRELATION COEFFICIENTS BETWEEN INDICES AT VARIOUS LONGITUDES

Position	Lag	Position	Correlation coefficient
P index			
0–10°W	0	110–120°E	+0·36
0–10°W	0	60–70°W	+0·49
50–60°E	0	110–120°E	+0·35
110–120°E	0	170–180°E	+0·29
0–10°W	1	110–120°E	−0·23
50–60°E	1	50–60°E	−0·28
50–60°E	1	110–120°E	−0·29
170–180°E	2	170–180°E	+0·33
120–130°W	2	170–180°E	−0·32
120–130°W	2	120–130°W	+0·26
60–70°W	2	50–60°E	+0·31
0–10°W	2	50–60°E	+0·40
S index			
0–10°W	0	50–60°E	−0·32
0–10°W	0	120–130°W	−0·31
50–60°E	0	120–130°W	+0·25
110–120°E	0	60–70°W	−0·28
170–180°E	0	120–130°W	−0·23
60–70°W	1	60–70°W	+0·24
110–120°E	1	60–70°W	−0·29
170–180°E	1	50–60°E	+0·24
50–60°E	2	110–120°E	−0·24
110–120°E	2	170–180°E	+0·24
120–130°W	2	110–120°E	−0·29
C index			
0–10°W	0	50–60°E	−0·28
170–180°E	0	60–70°W	+0·25
110–120°E	1	50–60°E	+0·25
120–130°W	1	120–130°W	+0·32
60–70°W	1	50–60°E	+0·27
60–70°W	1	120–130°W	+0·31
120–130°W	2	120–130°W	+0·25
60–70°W	2	110–120°E	+0·25
60–70°W	2	120–130°W	+0·25
M index			
110–120°E	0	60–70°W	−0·26
60–70°W	1	170–180°E	+0·26

only those with the correlation coefficient $\geqslant 0{\cdot}23$. With 70 pairs of values a correlation of about 0·23 is significant at the 5 per cent level and 0·30 at the 1 per cent level. Each part of Table III effectively considers about 90 correlation coefficients so that about 4 to 5 coefficients would by chance exceed 0·23 and about 1 would exceed 0·30. The actual numbers in Table III are two to three times greater — for the *P*, *S* and *C* indices — so that some of these coefficients must be significant. But there are only 2 correlation coefficients $\geqslant 0{\cdot}23$ for the *M* index, and these are therefore less likely to be significant.

Table III shows that for the *P* index there are correlations between the longitudes associated with the Icelandic low and its extension into the Barents Sea. This is a very variable part of the January circulation, and such correlations must mean that an exceptionally blocked or progressive situation over the U.K. (0–10°W), often covers Europe and extends its influence across the Atlantic or into Siberia. There is a negative correlation in the *P* index with one-year lag at 50–60°E, which implies a biennial oscillation in the Barents Sea low. There are also positive correlations with a two-year lag at 170–180°E and at 120–130°W, but a negative correlation with a two-year lag between 170–180°E and 120–130°W. This implies a biennial oscillation in the Pacific but the oscillations in the eastern and western Pacific are out of phase.

The correlation coefficients for the *S* and *C* indices are more difficult to interpret. The mean of the *S* index at 60–70°W over the period 1899–1933 is −21 and the mean over 1934–68 is −15, which indicates an overall trend, namely a decrease in the northerly flow. Such an overall trend would account for the positive correlation coefficient in the *S* index with one-year lag. Again at 120–130°W, the mean of the *C* index over the period 1899–1933 is + 7 and the mean over 1934–68 is −2 which indicates an overall trend, namely a decrease in cyclonicity. Such an overall trend would account for the positive correlation coefficients in the *C* index with one- and two-year lags.

Long-period changes in the values of the indices. Table IV gives the mean values of the *PSCM* indices for each 10-year period from 1899–1908 to 1959–68.

These tables show considerable fluctuations in the indices between one 10-year period and another, indicating preferred periods for certain types of circulation. They also show that on a hemispheric scale the first 30 years were generally progressive ($P \geqslant 0$) whilst the last 30 were blocked ($P < 0$), but that individual longitudes were at times not in phase. For example, the last 10 years, 1959–68, were the least progressive at 0–10°W and 60–70°W but at 170–180°E they were more progressive than the average for the 70 years. Very broadly, the climatic changes in the indices can, to some extent, be explained by changes in the position of the main polar vortex between the Alaskan and European/Asian sectors of the Arctic causing variations in the strength and latitude of the main jet stream, accompanied by changes in the planetary wavelength in these sectors. The *S* index indicates what some of the wavelength changes may have been. The progressive period (1899–1938) at 0–10°W and 60–70°W was accompanied by a southerly component at 0–10°W and a northerly at 60–70°W, which indicates a trough in the Atlantic; but in the blocked period 1939–68, there was a northerly component at 0–10°W and the

TABLE IV—MEAN VALUES OF THE INDICES FOR SPECIFIED PERIODS FOR VARIOUS LONGITUDES AND THE HEMISPHERE AS A WHOLE

Period	0–10°W	50–60°E	110–120°E	170–180°E	120–130°W	60–70°W	Hemisphere
P index							
1899–1908	+21	+18	+11	−37	−15	+18	+3
1909–18	+14	+22	− 3	−30	−16	+14	0
1919–28	+35	+ 3	+19	−37	+ 2	+19	+7
1929–38	+13	+ 2	− 2	−33	−13	+22	−2
1939–48	+ 3	− 3	− 9	−43	− 7	+ 8	−9
1949–58	+15	+11	+ 4	−28	−27	+ 6	−3
1959–68	− 1	0	+ 3	−29	−14	− 3	−7
1899–1968	+14	+ 8	+ 3	−33	−13	+12	−1
S index							
1899–1908	+4	+ 8	− 6	− 7	+14	−20	−1
1909–18	+2	+10	− 5	− 1	+20	−25	0
1919–28	+5	+ 3	−12	− 3	+17	−21	−2
1929–38	+4	+ 9	−14	− 4	+17	−15	−1
1939–48	+3	+ 9	−17	−11	+23	−17	−2
1949–58	−3	+ 9	−13	+ 5	+23	−11	+2
1959–68	−1	+11	−12	+ 3	+24	−15	+2
1899–1968	+2	+ 8	−11	− 3	+20	−18	0
C index							
1899–1908	−8	+ 3	−17	+21	+8	+5	+2
1909–18	−8	+ 7	−18	+19	+8	+6	+2
1919–28	+5	− 7	−21	+23	+8	+1	+1
1929–38	−7	−13	−23	+18	0	+4	−4
1939–48	+1	− 7	−18	+17	−1	−2	−2
1949–58	−7	− 3	−18	+12	−7	−6	−5
1959–68	−5	+ 1	−12	+17	+2	+1	+1
1899–1968	−4	− 3	−18	+18	+3	+1	−1
M index							
1899–1908	13	21	19	21	20	25	20
1909–18	16	21	16	26	23	30	22
1919–28	10	21	23	26	23	29	22
1929–38	15	21	21	25	23	25	22
1939–48	15	21	24	21	27	24	22
1949–58	15	18	21	27	26	25	22
1959–68	16	22	21	23	26	27	23
1899–1968	14	21	21	24	24	26	22

northerly at 60–70°W was at a minimum, which indicates an eastward movement of both the ridge over North America and the trough in the Atlantic.

Figures 5(a) and (b) give the 10-year running means of the *P* index. Figure 5(a) shows that longitudes 0–10°W, 110–120°E and 120–130°W all had maximum progressivity in the '20s and a minimum around 1940. But, whereas 110–120°E then returned to a near-average value for the 10 years 1959–68, the other two longitudes had lower minima, for 120–130°W in the period 1950–59 and for 0–10°W in the period 1959–68. The other three longitudes, Figure 5(b), show a minimum in the '20s, a maximum in the '30s and a minimum in the '40s. However, 170–180°E has recovered to near average and 60–70°W has fallen to a lower minimum in recent years. The overall conclusions from Figures 5(a) and (b) are that during the early part of the century, alternate longitudes (60° apart) tended to vary out of phase, that all longitudes reached a minimum around 1940 but, whereas the longitudes associated with the Pacific have shown near-average progressivity in recent years, the Atlantic longitudes have shown a further minimum (in recent years), especially at 0–10°W and 60–70°W, where the amount of progressivity (westerliness) has been less than at any time during the century. Figure 6 shows the 10-year (1959–68) mean departure of the surface pressure from the average for the whole period 1899–1968. During these 10 years, pressure averaged 9 mb above average over eastern Greenland and 3 mb below average north-west of the Azores, giving an anomalous easterly gradient across the Atlantic. In central England, with an anomalous east-north-east airflow, only the last two Januarys in the 10-year period showed mean temperatures

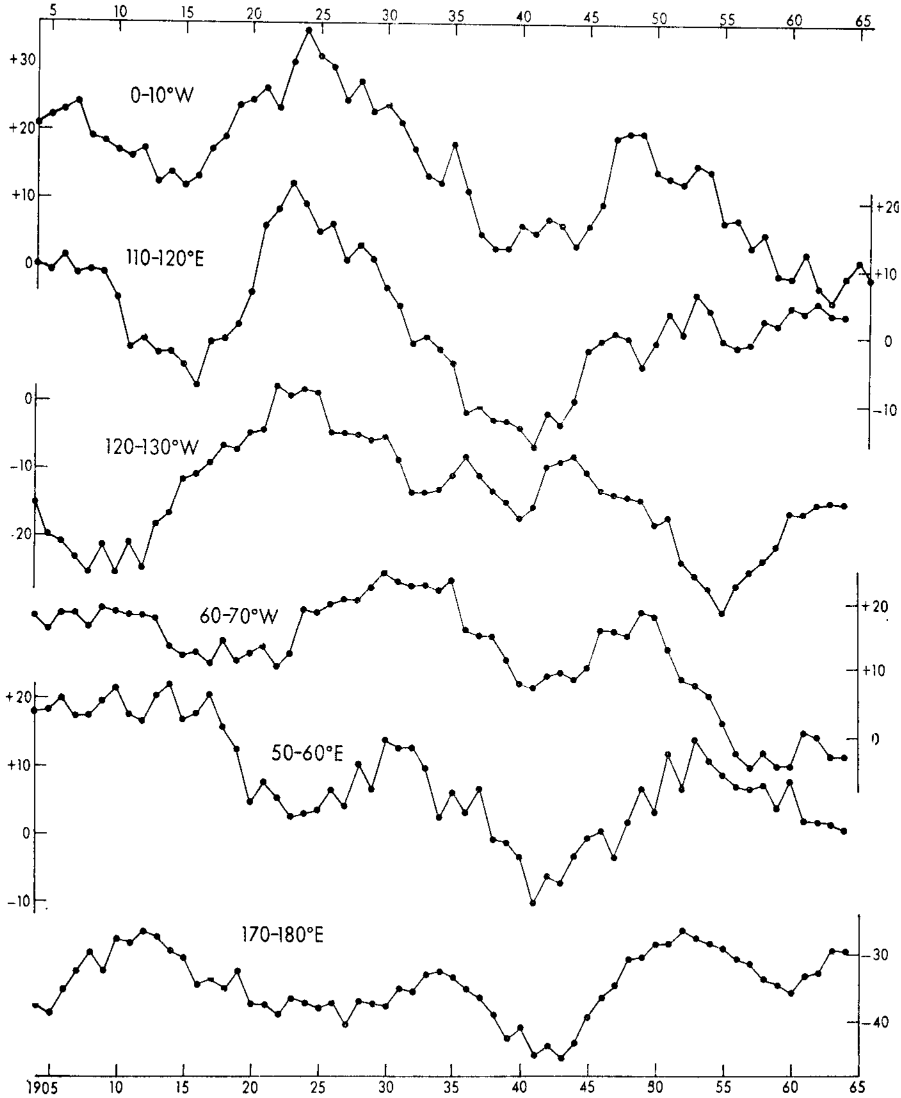


FIGURE 5—10-YEAR RUNNING MEANS OF *P* INDEX AT 50–60°N FOR VARIOUS LONGITUDES, JANUARY 1899–1968

Means are centred on the middle of the 10-year period.
(a) 0–10°W, 110–120°E, 120–130°W (b) 60–70°W, 50–60°E, 170–180°E

above average whilst in Newfoundland, with an anomalous easterly gradient from the Atlantic, only January 1964 showed below-average temperature. At the same time, pressure was below average over Kamchatka and above average near the centre of the Siberian anticyclone, giving increased progressivity at 110–120°E and 170–180°E. By contrast, Figure 7 shows the 10-year mean departure of the surface pressure from the average for the whole period for the 10 years 1919–28 when progressivity was at a maximum at 0–10°W.

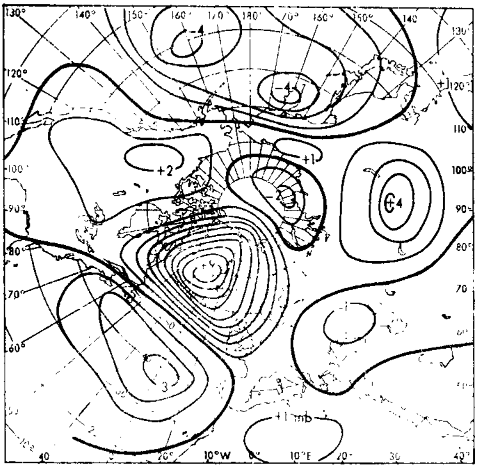


FIGURE 6—MEAN PRESSURE FOR JANUARY 1959–68 MINUS MEAN PRESSURE FOR JANUARY 1899–1968

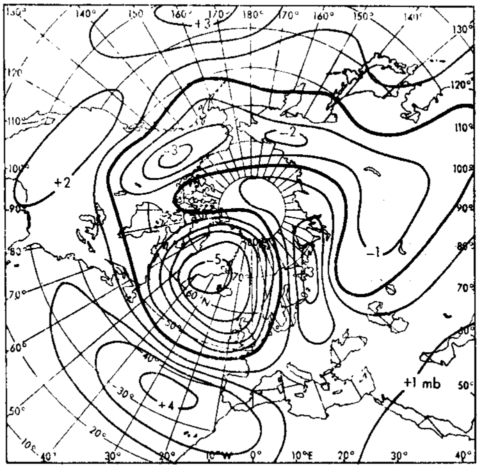


FIGURE 7—MEAN PRESSURE FOR JANUARY 1919–28 MINUS MEAN PRESSURE FOR JANUARY 1899–1968

During these 10 years pressure was 5 mb lower than average over the Denmark Strait and 4 mb above average near the Azores, giving an anomalous westerly gradient across the Atlantic into the U.K. In central England, only 1919 showed mean temperatures below average.

Figure 8 gives the 10-year running means of the *S* index. A minimum is shown for 60–70°W in the period 1911–20, for 120–130°W in 1921–30, for 50–60°E in 1923–32, for 110–120°E in 1936–45, for 170–180°E in 1938–47 and for 0–10°W in 1951–60. In this last period all other longitudes except 110–120°E show a maximum of the *S* index. Figure 9 shows the 10-year (1952–61) mean departure of the surface pressure from the average for the whole period 1899–1968. Pressure was 5 mb above the long-period average over Greenland and 3 mb below near the Gulf of Bothnia and near 40°N, 60°W.

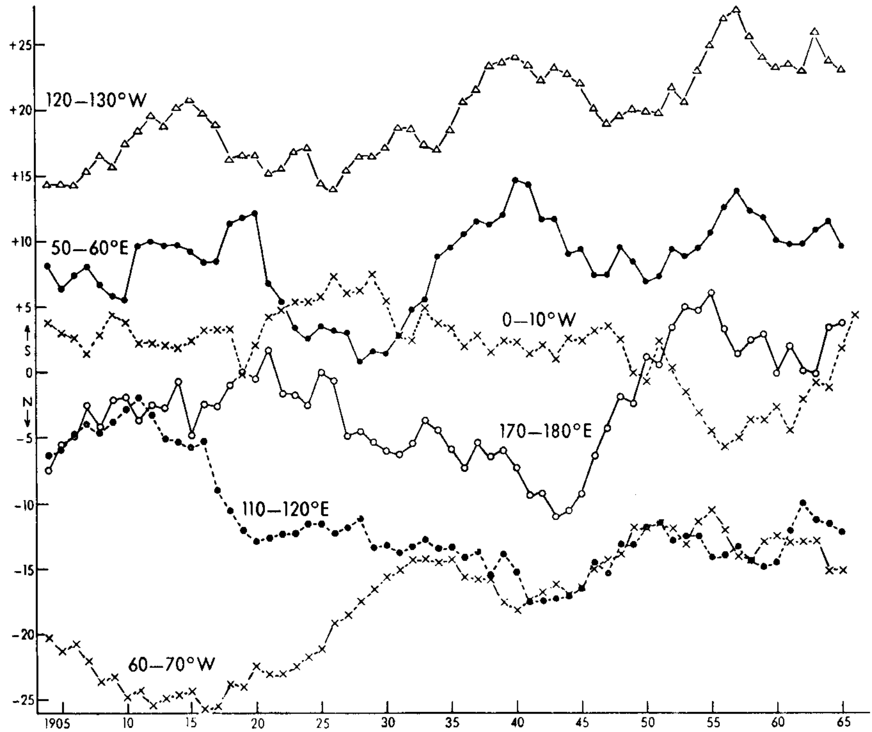


FIGURE 8—10-YEAR RUNNING MEANS OF *S* INDEX AT 50–60°N FOR VARIOUS LONGITUDES, JANUARY 1899–1968

Means are centred on the middle of the 10-year period.

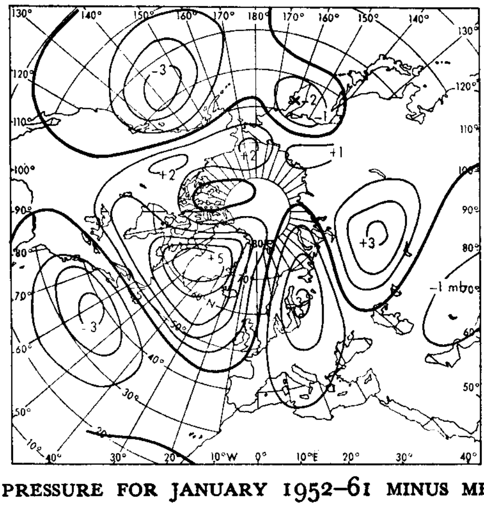
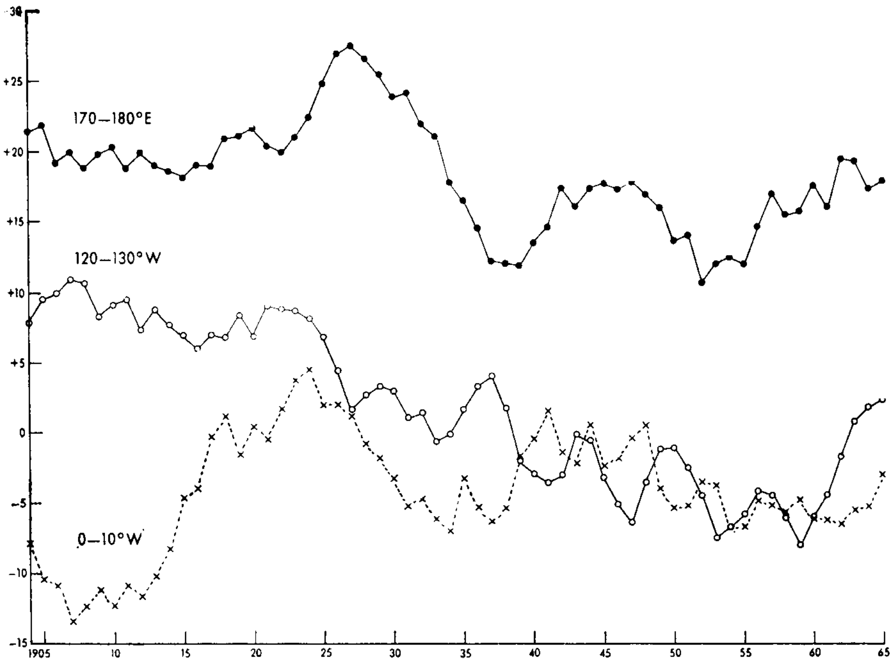


FIGURE 9—MEAN PRESSURE FOR JANUARY 1952–61 MINUS MEAN PRESSURE FOR JANUARY 1899–1968

There was only one January (1957) with temperature above average in central England in this 10-year period, and only one cold January (also 1957) in Newfoundland, whilst the Black Sea area had above-average temperatures, except in 1954 and 1957. Figure 8 also shows the increase in the *S* index at 60–70°W, which probably accounts for the positive correlation with one-year lag in Table III.

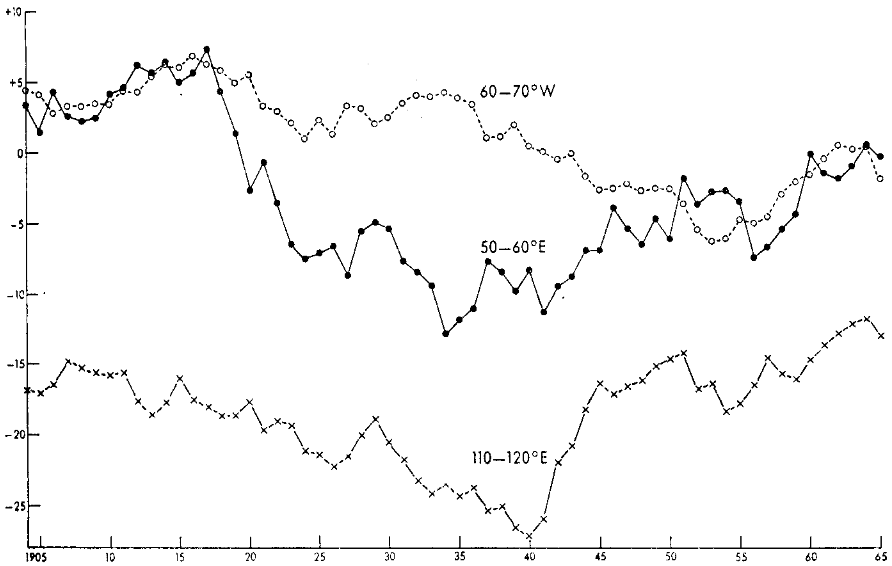
Figures 10(a) and (b) show the 10-year running means of the *C* index. Most longitudes show a long-period fluctuation in cyclonicity, e.g. 120–130°W (Figure 10 (a)) shows a maximum near the beginning of the period and a minimum around 1959 with a recovery since. At 120–130°W, both the maximum and minimum cyclonicity are associated with a minimum of the *P* index (see Figure 5(a)), though the *C* index is also high at the maximum of the *P* index around 1921. The 10-year mean surface pressure anomaly maps show these changes quite well; the period 1902–11, for example, shows a positive centre of +8 mb at 70°N, 140°W and a negative centre of −2 mb at the southern edge of the 50–60°N, 120–130°W square, giving a cyclonic block over this square; but for the period 1917–26 a negative centre of −4 mb is centred at the northern edge of the same square giving a progressive cyclonic type, consistent with the *P* index maximum around 1921. For the period 1948–57 a positive anomaly centre of + 4 mb is centred at the northern edge of the 120–130°W square giving an anticyclonic block consistent with the generally low values of the *C* index about this time.



(a)

FIGURE 10—10-YEAR RUNNING MEANS OF *C* INDEX AT 50–60°N FOR VARIOUS LONGITUDES, JANUARY 1899–1968

Means are centred on the middle of the 10-year period.



(b)
FIGURE 10—*continued*

In Figure 10(b), the longitude 110–120°E also shows a long-period fluctuation in cyclonicity with a maximum near the beginning and end of the 70-year period and a minimum around 1940. This fluctuation is mainly in the opposite sense to that at 120–130°W.

An examination of charts depicting the pressure anomaly over 10-year periods from 1873 shows that :

(a) The North Pacific in January was dominated by above-average pressure from about 1873 to 1920 and by below-average pressure from about 1925 to 1968, though a rise of pressure has apparently begun over the Aleutian Islands in recent years but not (yet) over Kamchatka.

(b) Above-average pressure prevailed in the Iceland area in January from about 1873 to 1895 and again from 1940 to 1968 whilst below-average pressure prevailed from about 1900 to 1935.

(c) Below-average pressure prevailed in January over Russia (north of 50°N and between 30°E and 120°E) from about 1873 to 1890, 1900 to 1925 and 1950 to 1960 but above-average pressure prevailed from 1890 to 1900, 1925 to 1948, and 1960 to 1968.

(d) Below-average pressure prevailed over northern Canada in January from about 1875 to 1885, 1895 to 1905 and 1920 to 1945 but above-average pressure prevailed from 1885 to 1895, 1905 to 1918 and 1945 to 1968.

The oceanic areas appear to have a long 90–100-year cycle in surface pressure whilst the continental areas have shorter cycles of 30–50 years.

From the above it can be seen that the circulation changes over the northern hemisphere in January in the last 100 years have been highly complex. The major centres of action (the Aleutian and Icelandic lows) have undergone a long-period change with the probability that one whole cycle is nearing completion. The oscillations in the two oceans are not in phase, the Pacific lagging behind the Atlantic. As a result, the continental areas show shorter-period oscillations in surface pressure as the planetary wavelength responds to the oceanic oscillations.

REFERENCES

1. MURRAY, R. and LEWIS, R. P. W.; Some aspects of the synoptic climatology of the British Isles as measured by simple indices. *Met Mag, London*, **95**, 1966, pp. 193–203.
2. LAMB, H. H.; British Isles weather types and a register of the daily sequence of circulation patterns, 1861–1971. *Geophys Mem, London*, **16**, No. 116, 1972.
3. MURRAY, R. and BENWELL, P. R.; *PSCM* indices in synoptic climatology and long-range forecasting. *Met Mag, London*, **99**, 1970, pp. 232–245.

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A BRIEF SUMMARY OF THE METEOROLOGICAL RESEARCH FLIGHT DIGITAL MAGNETIC-TAPE DATA-RECORDING AND DATA-PROCESSING SYSTEM

By D. N. AXFORD

Summary. A new digital magnetic-tape data-recording system has been developed for use in the Meteorological Research Flight aircraft. The initial installation will be made into the MRF Canberra in 1972, and a similar system will be fitted into the Hercules C–130 aircraft due for delivery to MRF in 1973.

Introduction. A data-recording system has been developed by the British Aircraft Corporation for use in the Meteorological Research Flight (MRF) aircraft. The initial installation into the Canberra will be made in 1972, and a similar system will be fitted into the Hercules C–130 aircraft due for delivery to MRF in 1973. The following is a brief description of the system for the use of potential users of the C–130 or Canberra. Further details can be supplied by MRF if required.

General description of the MRF system. A block diagram of the recording and processing system is shown in Figure 1. The equipment (see Plates I–IV) consists of four separate parts :

(a) The airborne equipment.
(b) The system test-box.
(c) The ground replay unit.
(d) The transcription and data-processing system.

The airborne-equipment signal conditioning unit accepts the transducer inputs which may consist of various levels of d.c. voltage, synchros, variable resistances or digital information, and converts them into either a d.c. voltage of 2-volt peak-to-peak full scale, or a suitable binary digital output. The analogue signals are fed to a multiplexer which connects them serially through a sample-and-hold amplifier to an analogue-to-digital converter (ADC) within the data acquisition unit. Digital inputs are interleaved with the analogue inputs via a separate digital multiplexer, and the final all-digital data are fed to the tape recorder serially at 640 samples per second.

The system test-box allows simulated digital and analogue signals to be fed into the airborne equipment, giving an overall functional test to the system. Calibrations of the transducers themselves are normally made the subject of a separate laboratory experiment.

The ground replay unit consists basically of a tape transport for replay, a decommutator and control box and an ultraviolet (UV) recorder. This enables analogue recordings to be made from the eight most (or least) significant bits from any six data channels and the time channel. A display of recorded time is also provided and an indication of parity errors. Also an edit track can be added to the tape by means of a switch. Both the test box and the replay unit are transportable by air and can be used in any part of the world.

The transcription and data-processing system is installed in the MRF building at the Royal Aircraft Establishment, Farnborough. An interface unit detects whether the edit track has been added (or whether a manual switch has been set) and if so transfers the data into blocking stores in the memory core of a small general-purpose computer (PDP8/I). The PDP8/I controls the blocking of the data and the recorder control functions, and uses its data-break facility to transfer the data, in a suitable format, on to a computer-compatible tape in the form of two 6-bit words plus a parity bit for each 12-bit data word. The computer is also used to change data words with parity errors into an easily recognized 'all-ones' data word. IBM compatible tape marks, inter-record gaps and inter-file gaps are also generated by the PDP8/I. The computer-compatible tape may be read back into the PDP8/I at a later stage for further processing on-site, or alternatively it may be presented to a large computer for more lengthy analysis with, perhaps, the use of sophisticated output peripherals.

The airborne recording equipment (Plate I). The airborne recording system (see Figure 1) consists of five main blocks, namely :

(a) A signal conditioning unit.
(b) A data acquisition unit.
(c) A tape recorder.
(d) A remote-control panel.
(e) Power supplies.

Data are recorded in digital format on 16-track magnetic tape. Fifteen of the tracks are utilized during the airborne recording, the remaining track being used for editing purposes during replay and transcription. Three of the tracks are used for clock, parity and multiplexer frame-synchronization signals, while the remaining 12 tracks constitute the 12-bit data word. The track allocation on the tape is shown in Table I.

TABLE I—TRACK ALLOCATION ON AIRBORNE RECORDING TAPE

Track numbers	Signals
1 to 6	Data (track 1 is LSB)
7	Clock
8	Parity
9 to 14	Data (track 14 is MSB)
15	Frame synchronization
16	Not used in air (reserved for edit facility)

LSB = least significant bit MSB = most significant bit

The units (a) and (b) above are shown in block-diagram format in Figures 2 and 3. While the initial installation is designed particularly to accommodate the Canberra inputs described in Table II, the circuits used for signal conditioning can be generalized to deal with a variety of other inputs, and space has been left for future expansion.

The initial programme (defined by the parameter allocations shown in Table III) can be changed by rewiring two matrix patch boards within the data acquisition unit.

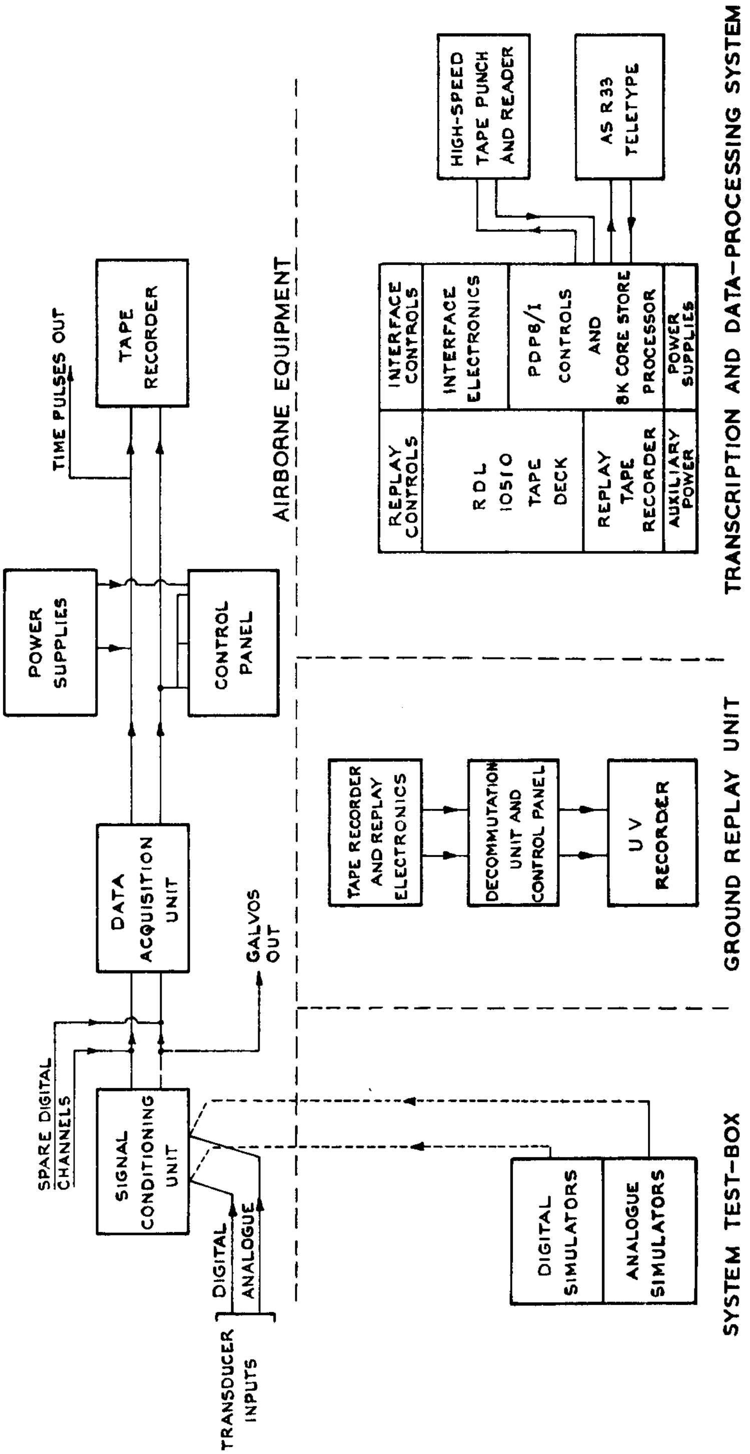

FIGURE 1—MRF DATA-RECORDING AND PROCESSING SYSTEM

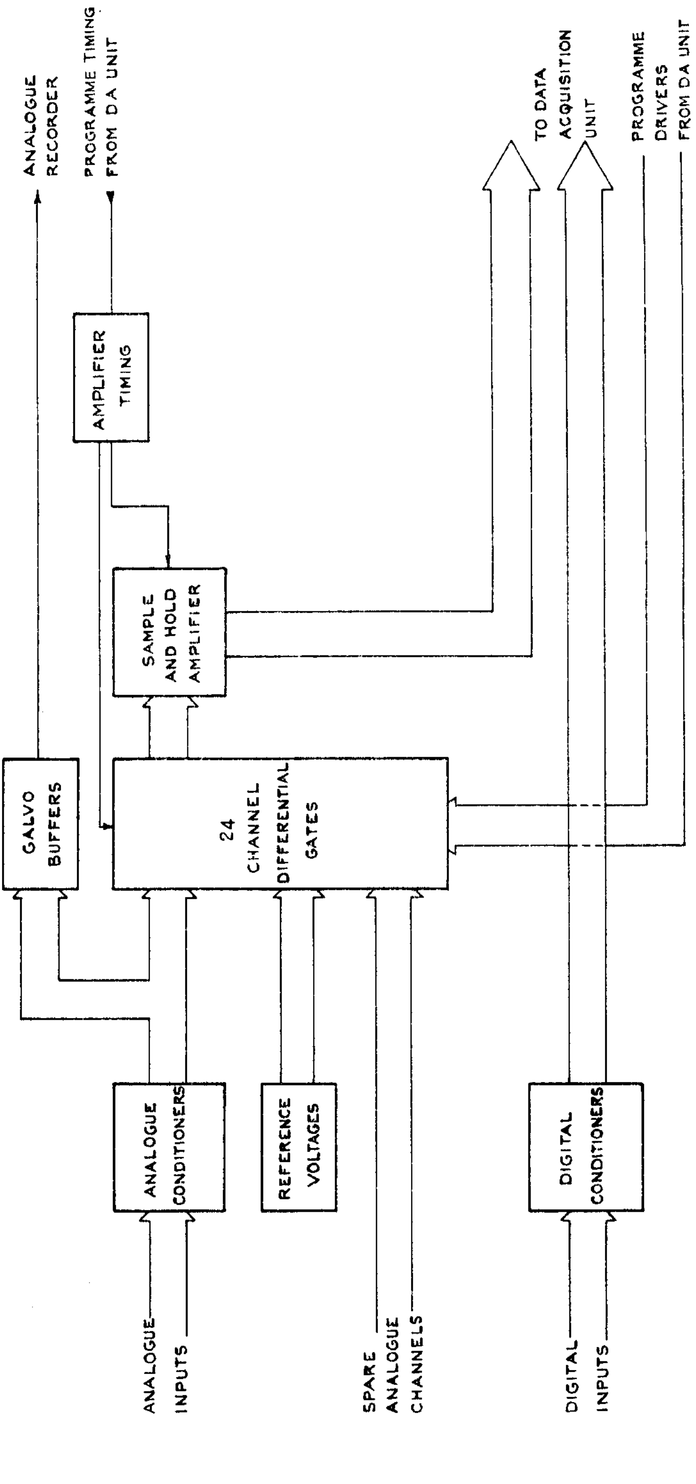

FIGURE 2—SIGNAL CONDITIONING UNIT

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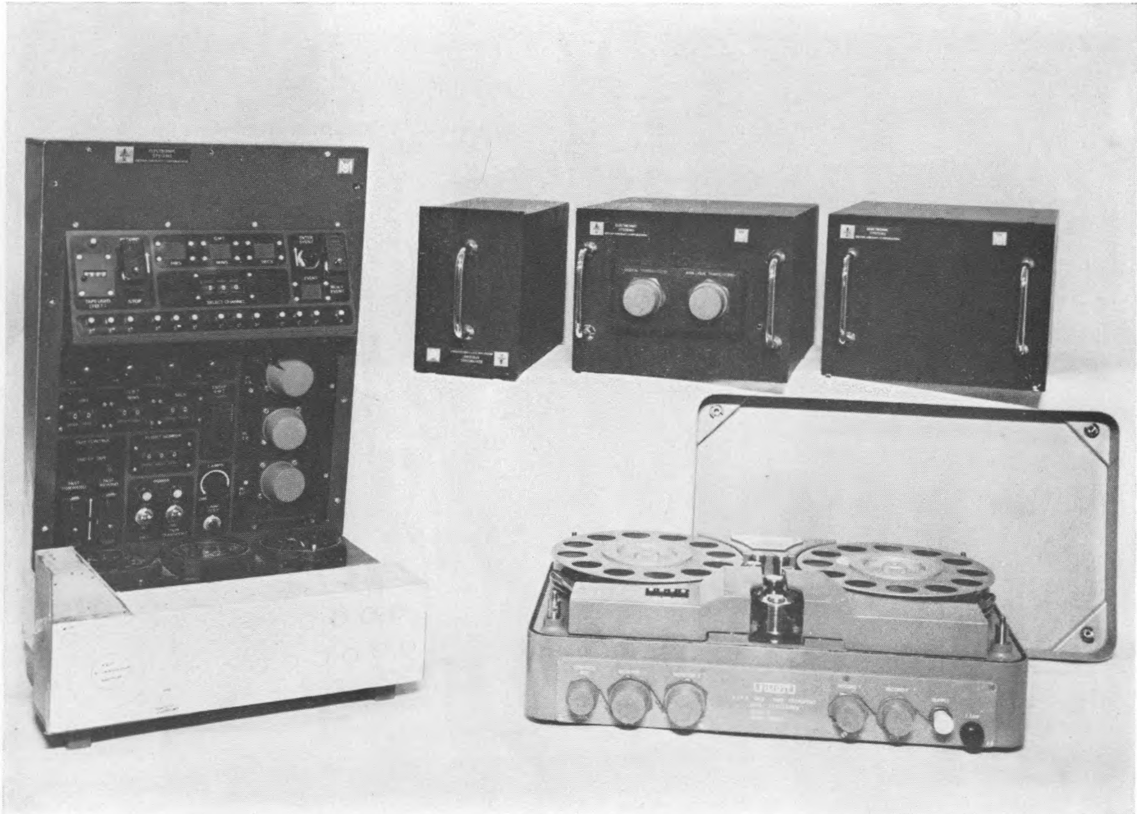

PLATE I—METEOROLOGICAL RESEARCH FLIGHT AIRBORNE RECORDING EQUIPMENT

See page 329.

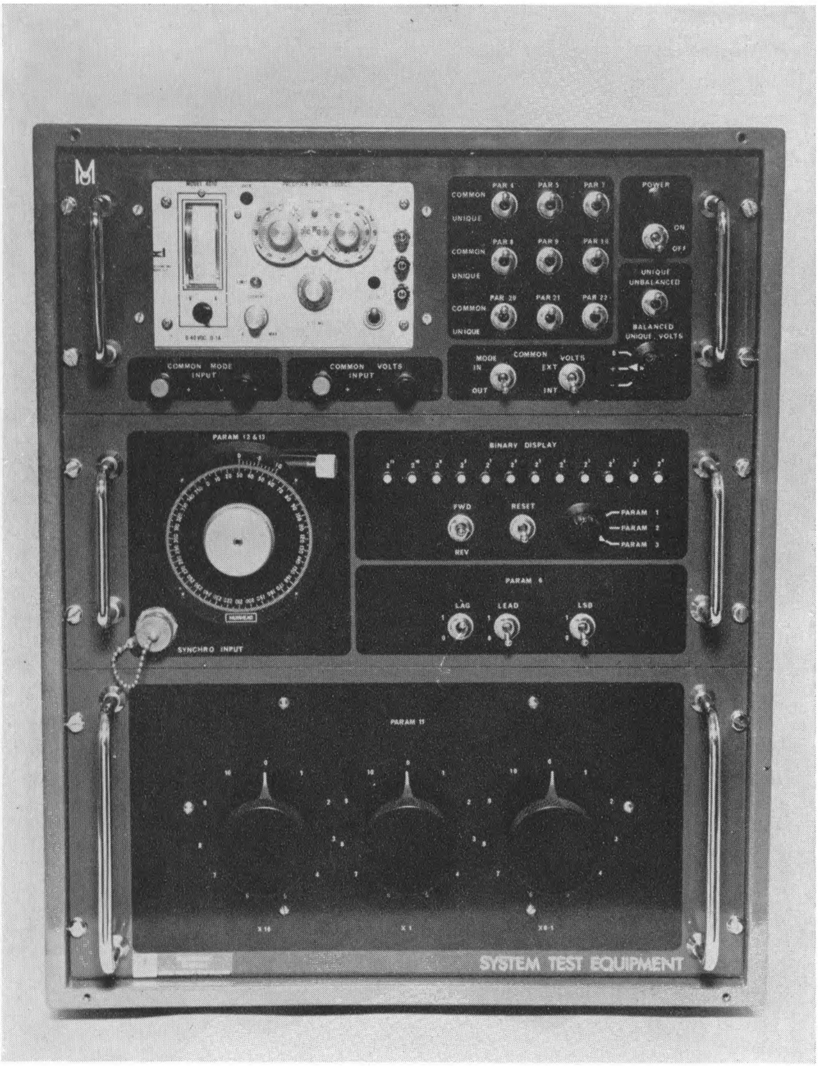

PLATE II—THE SYSTEM TEST-BOX

See page 329.

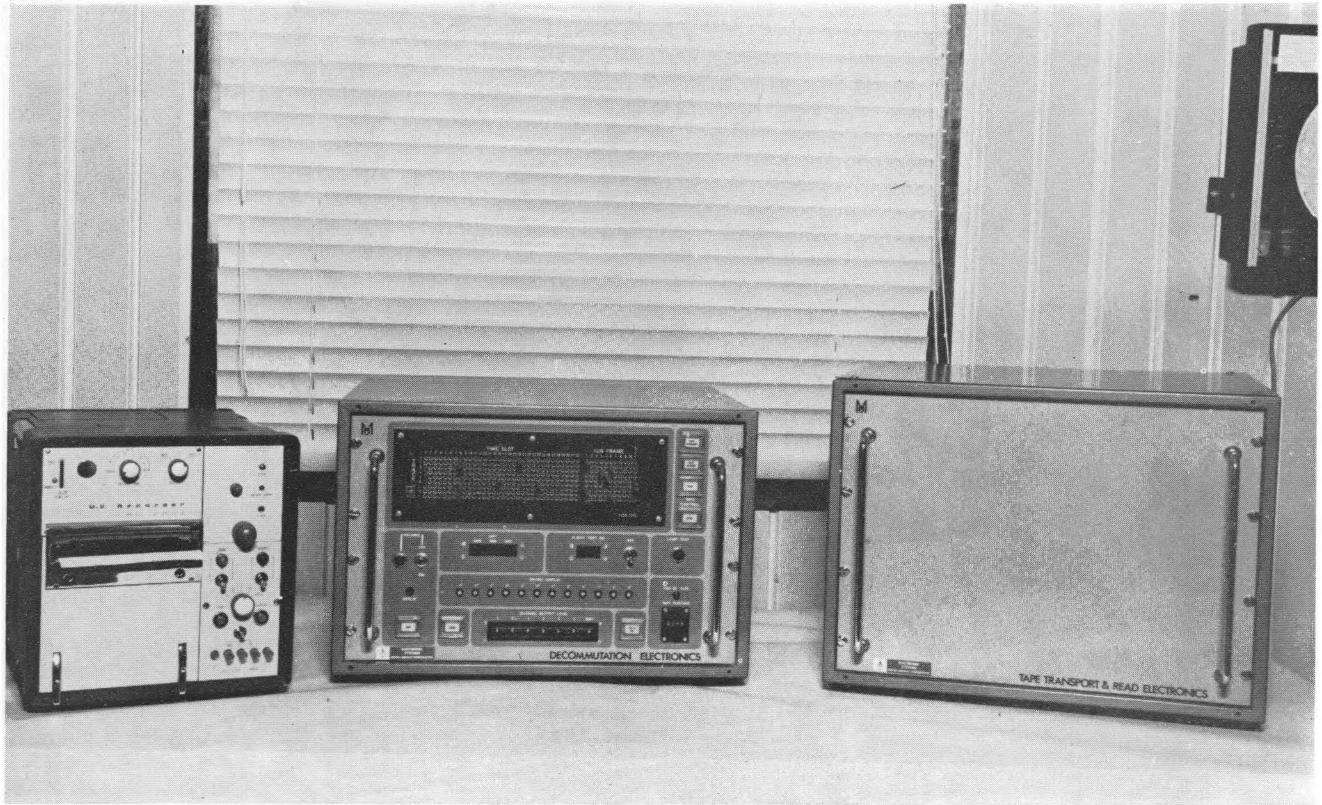

PLATE III—GROUND REPLAY UNIT

See page 329.

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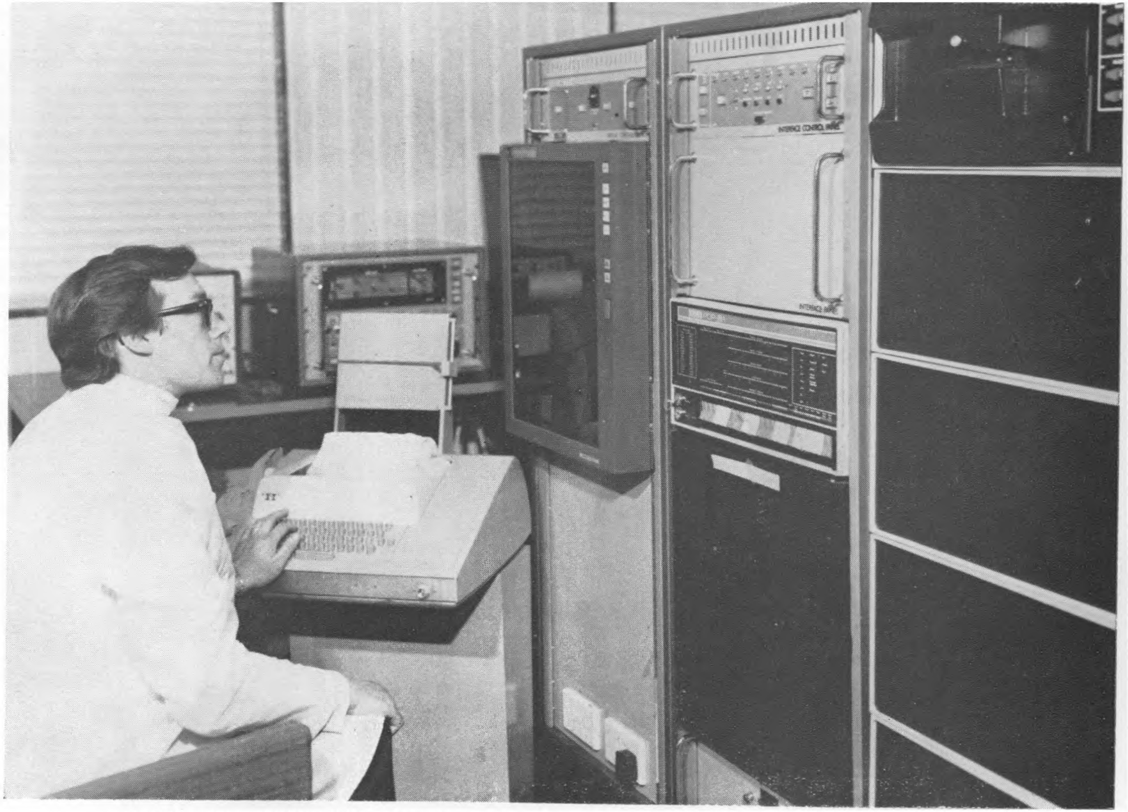

PLATE IV—METEOROLOGICAL RESEARCH FLIGHT TRANSCRIPTION EQUIPMENT

See page 329.

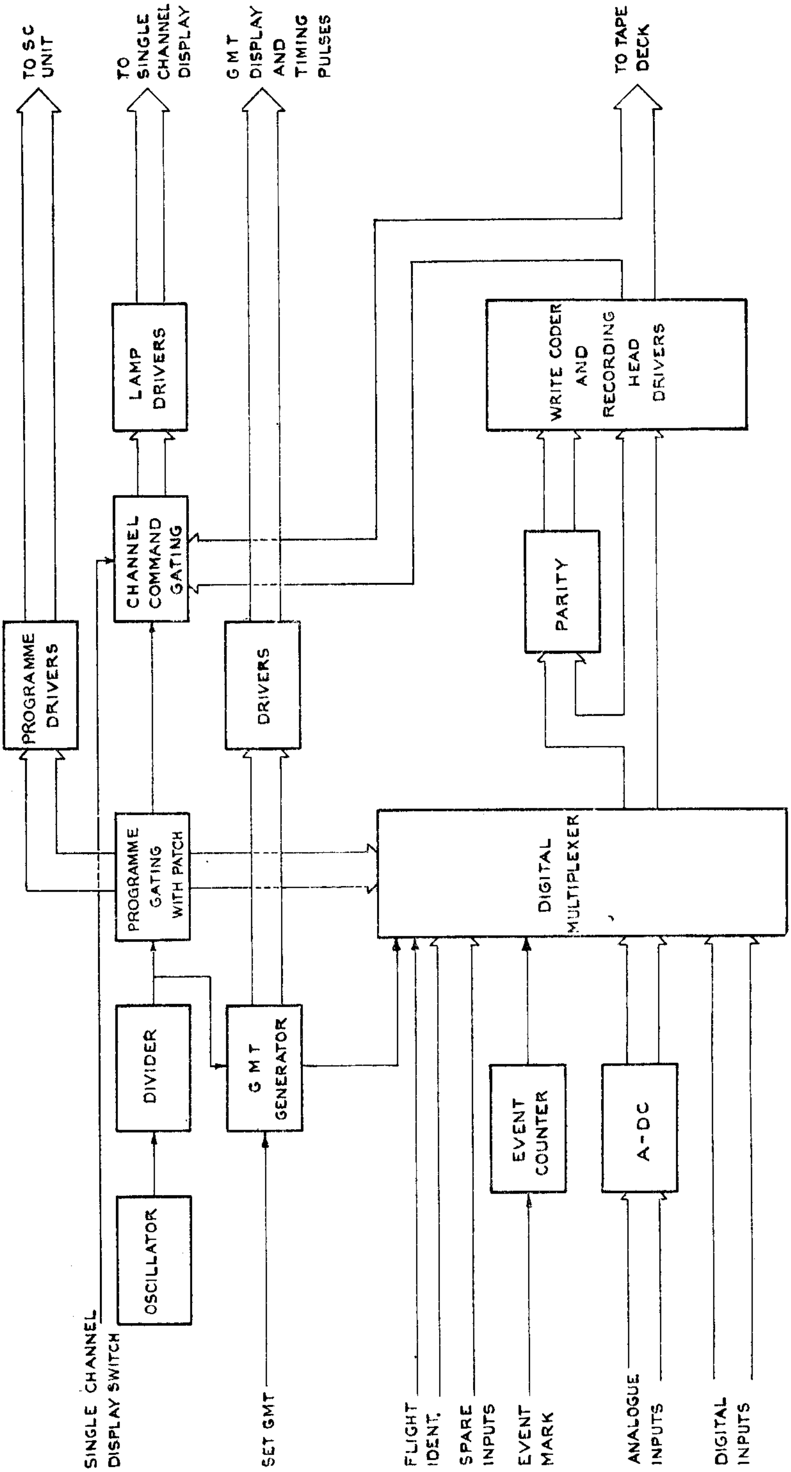

FIGURE 3—DATA ACQUISITION UNIT

TABLE II—DETAILS OF TRANSDUCER INPUTS USED IN THE METEOROLOGICAL RESEARCH FLIGHT CANBERRA

	Parameter	Unit	Range	Instrument	Minimum sampling rate per second	Absolute accuracy	Resolution	Type A=analogue D=digital
						per cent of full excursion		
1.	Vertical velocity	ft/s	±100	INS	20	±0·25	0·25	D
2.	Ground speed E–W	ft/s	±800	INS	20	±0·025	0·025	D
3.	Ground speed N–S	ft/s	±800	INS	20	±0·025	0·025	D
4.	Pitch angle	degree	± 10	INS	20	±0·25	0·1	A
5.	Roll angle	degree	± 20	INS	20	±0·5	0·25	A
6.	Azimuth angle	degree	0–360 (a) 11 LSB	INS	20	±0·01 (of 360°)	0·01	D
			(b) 11 MSB	INS	4	±0·1 (of 360°)	0·1	D
7.	Angle of attack	degree	± 10	Wind vane	80	±0·25	0·1	A
8.	Angle of sideslip	degree	± 10	Wind vane	80	±0·25	0·1	A
9.	Static pressure	mb	100–1050	Capacitive	20	±0·15	0·05	A
10.	Pitot static pressure	mb	0–300	Capacitive	40	±0·25	0·1	A
11.	Temperature	°C	+40 to −80	Platinum resistance	40	±0·2	0·01 (0·1 with range splitting)	A
12.	Doppler ground speed	kt	100–700	Synchro-digital converter	2	±0·1	0·1	D
13.	Doppler drift angle	degree	± 20	Synchro-digital converter	2	±0·25	0·25	D
14.	Standard time	second	24 hours	Crystal oscillator	2	10^{-7}	(a) x 1 s, x 10 s, x 1 min	D
							(b) x 10 min, x 1 h, x 10 h	D
15.	Event mark	number	0–99	Contact	4			D
16.	Temperature switch position	number	0– 9	Contact	4			D
17.	Reference voltage	volts	+0·45	BAC reference	2	±0·05	0·05	A
18.		volts	0	BAC reference	2	±0·05	0·05	A
19.		volts	−0·45	BAC reference	2	±0·05	0·05	A
20.	Vertical velocity	ft/s	±600	INS	2	±0·25	0·1	A
21.	Ground speed E–W	ft/s	±4500	INS	2	±0·25	0·1	A
22.	Ground speed N–S	ft/s	±4500	INS	2	±0·25	0·1	A
23.	Flight identifier		000–999	Switched	2			D

INS = inertial navigation system LSB = least significant bit MSB = most significant bit

TABLE III—INITIAL PARAMETER ALLOCATIONS

(a) Allocations in the multiplexer sub-frame

	A				D				A				D			
Sub-frame positions	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Parameter allocations	LF	7	8	11	6a	–	–	LF	4	7	8	10	–	–	–	1

	A				D				A				D			
Sub-frame positions	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Parameter allocations	9	7	8	11	6a	–	–	2	5	7	8	10	–	–	–	3

(b) Low-frequency allocations

Sub-frame number	1	2	3	4	5	6	7	8	9	10
Analogue parameter	—	—	20	21	22	17	18	19	—	—
Digital parameter	14a	15	16	12	13	14b	15	16	6b	23

A = analogue D = digital LF = low frequency

Summary of the airborne recording equipment specification.

Inputs	Initially 13 analogue, 12 digital. Can be expanded to 24 analogue, 24 digital.
Analogue signal levels	Standardized to 2-volt peak-to-peak in the signal conditioning unit. Initial unit accepts the parameters shown in Table II.
Digital inputs	12 bits.
Input filtering	Low pass, cut off above 4 Hz, greater than 34 dB down at 20 Hz with stable frequency and attenuation characteristics. Applied to parameters 4, 5, 7 and 8 in Table II.
Sampling rate	640 samples per second consisting of two 320-sample main frames. Each main frame consists of 10 sub-frames consisting of 32 samples. Sampling rates can be chosen between 2 samples per second and 80 samples per second by suitably wiring a matrix board.
Time standard	Time is set by thumbwheel switches and started by means of an 'enter' button. It is recorded in binary-coded decimal format in hours, minutes and seconds.
Time standard accuracy	Better than 1 part per million.
System accuracy	$\pm$0·1 to $\pm$0·25 per cent absolute accuracy for selected parameters.
Bit errors	Less than 1 in 10^5 bits.
Tape-deck specification	See Table IV.
Power supplies	200-volt 400-Hz 3-phase aircraft supplies.
Environment	-10°C to $+35$°C; sea level to 50 000 feet, specified vibration, shock, acceleration and crash conditions defined in *British Standard* BS 2G 100, Part 2.

TABLE IV—SUMMARY OF THE AIRBORNE TAPE DECK SPECIFICATION

1.	Tape tracks	16 on one-inch tape.
2.	Tape heads	33-track type Gresham AE10 of which only the centre 16 tracks are fitted. Nominal gap width 100 micro-inches.
3.	Capacity	2300 feet of 0·001 inch base 'thin oxide' tape on 8 inch precision spools.
4.	Tape speeds	$\frac{15}{32}$, $\frac{15}{16}$, $1\frac{7}{8}$, $3\frac{3}{4}$, $7\frac{1}{2}$, 15, 30 inches per second. $\frac{15}{16}$ in/s used during airborne recording giving a maximum record time of 8 hours 7 minutes. Fast forward and rewind.
5.	Recording technique	NRZI (non return to zero mark).
6.	Character density	$682\frac{2}{3}$ samples per inch.
7.	Tape controls	Remote. Footage indicator also remote.
8.	Physical dimensions	$19 \times 11 \times 5\frac{1}{4}$ inches, 45 lb weight ($\approx$ 20 kg).
9.	Power supplies	28-V d.c. aircraft supplies, 5-amp max.
10.	Operational environment	Temperature: -10°C to $+35$°C. Altitude: sea level to 50 000 feet ($\approx$ 16 km). Vibration, shock and crash conditions: as laid down in relevant parts of *British Standard* BS 2G 100 Part 2.

The system test-box (Plate II). A simple method of calibrating and ground testing the recording system is of great importance. In general the calibration of the transducers themselves is a separate matter, but the calibration of the rest of the system is achieved by using a test-box which will simulate the presence of the transducers. The digital display of one channel of data is then immediately available for examination on the control panel, and also the signals can be recorded on the magnetic tape, and replayed and processed in the normal way.

The test-box provides the following facilities :

(a) Precision ($\pm$0·05 per cent) d.c. supplies from which simulated analogue signals of known voltage are derived.

(b) A precision ($\pm$0·05 per cent) 3-decade resistance box to simulate the temperature resistance bridge.

(c) A synchro fitted with a vernier setting dial accurate to 10 minutes of arc energized from a 400-Hz static inverter.

(d) A simulated 14-bit digital input controlled by switches to test the azimuth decoding circuits.

(e) A motor-driven contact arrangement similar to that employed in the inertial navigation system (INS) (see Table II). The motor can be driven backwards or forwards, and a display of the total contact counts is provided. This tests the logic circuits of the pulse counters used for parameters 1, 2 and 3.

The test-box will occasionally be taken with the aircraft away from MRF both in the United Kingdom and abroad but it will not be operated in the air.

The ground replay unit (Plate III). This unit is intended to provide a 'quick-look' replay and editing facility for the airborne recording equipment. It will be taken abroad with the aircraft for ground use at the field base, and thus is built to meet a world-wide environment. The unit allows the airborne magnetic tape to be replayed, and provides the following facilities :

(a) Analogue traces of any six parameters selected from the data on the magnetic tape may be recorded on a UV recorder by suitably programming a patch board. A further trace is recorded giving an indication of the standard time. The airborne tape can be replayed at eight times the recording speed. Also an event mark is made if a parity error occurs on the data, and a 'parity fail' lamp is lit for 1 second on the display.

(b) A digital lamp display of the 12-bit data word selected from any channel.

(c) A three-decimal visual display of the flight identifier.

(d) A visual decimal display of the recorded standard time in hours, minutes and seconds.

(e) During replay, selected portions of the flight tape may be marked in the 'edit' track by means of a button or switch. This 'edit' mark may be used by the transcription system.

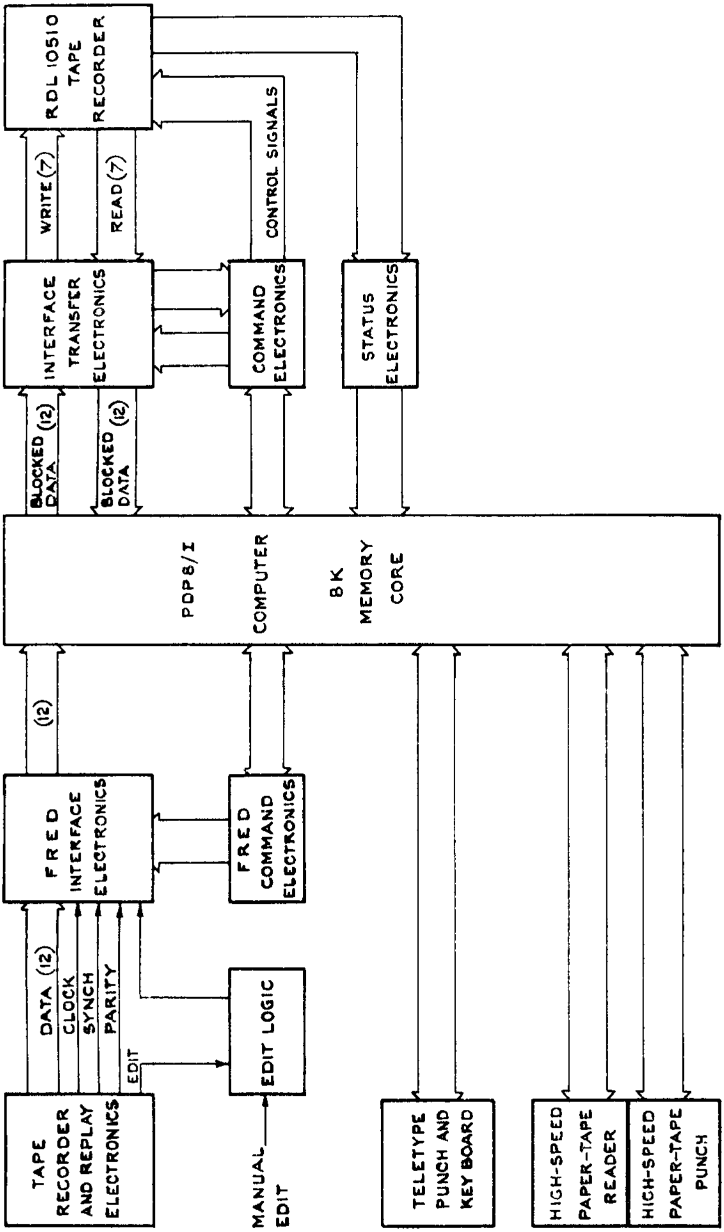

FIGURE 4—TRANSCRIPTION AND DATA-PROCESSING SYSTEM

The transcription and data-processing system.

(a) *The transcription equipment* (Plate IV). The transcription equipment provides a means for the automatic conversion of selected portions of the flight tape into 7-track computer-compatible tape. The system, shown in Figure 4, uses the tape recorder and replay electronics from the ground replay unit to provide the initial data. The edit signal is either added by means of a switch on the unit, or has already been added during the replay phase. In either case the flight replay edited data (FRED) interface electronics detect the presence of the edit signal and thereupon transfer the 12-bit data words into blocking banks within the memory core of a small inexpensive general-purpose computer (a Digital Equipment Corporation PDP8/I). This computer is used to control the data-blocking and recorder control functions, and to provide further facilities. In particular, the presence of a parity error is detected in the incoming data word, and the word is replaced with an 'all-ones' character in the memory in place of the erroneous data. The data are read out on to a standard commercial computer-type magnetic-tape handler via the computer's 3-cycle data-break facility. This enables the transfer from the memory core to be very rapid since it by-passes the computer accumulator stores and acts in response to a request initiated by the interface electronics. The 12-bit data are broken into two 6-bit words in the interface, and a parity bit is generated for each. The output tape is written at a packing density of 556 rows per inch. The computer is programmed to provide the necessary inter-record gaps, and inter-file gaps. A standard IBM-type tape mark can also be added by means of a push button.

The system also includes the facility to retrieve data from the computer tape, reassemble the 6-bit characters into 12-bit words and store them in the PDP8/I memory core as a block of data. Again the 3-cycle data-break transfer-mode is used. This allows data to be read back into the computer for initial processing in the laboratory. In addition the computer has been extended by the inclusion of a standard high-speed paper-tape reader and punch to allow for rapid reprogramming when desired.

(b) *Data processing.* The collection of digital data on a computer-compatible tape is only of use provided the necessary software (programming) has been developed so that the tape can be played back through a computer to obtain printed or graphical outputs of the relevant meteorological measurements. With a recording rate of 640 samples per second, 2 304 000 measurements of raw data will be made each hour so it is essential that the software be capable of dealing with this mass of data quickly and efficiently.

Tapes produced by the transcription system can be fully processed on a large computer (the RAE ICL 1907 or the Meteorological Office IBM 360/195), and they may also be partially processed by the PDP8/I. Programmes to deal with the current requirements are being developed at MRF, and further extensions and improvements to the system are under active consideration.

Acknowledgements. This system has been developed over several years and many people have been involved. In particular Mr D. R. Grant (MRF 1962–66) who initiated the first specification and Mr C. J. M. Aanensen, Head of MRF 1966–71, should be mentioned. Expert advice and encouragement have been freely given by the Instrumentation and Ranges Department of RAE Farnborough.

551.501.45:551.577.21:311.214:681.31/.34

THE ROUTINE PROCESSING OF CURRENT RAINFALL DATA BY COMPUTER

By P. G. ALLEN

Summary. The method used by the Meteorological Office for the routine work of checking and summarizing current rainfall data in 1971 is outlined. The processes have been developed from those described by Bleasdale and Farrar in 1965 and now include Scottish and Northern Irish data. Futher developments are due to take place shortly using the new IBM 360/195 computer.

Nature of rainfall data available. Originally there were only two types of reports, either daily or monthly, with a few weekly records being included with those from monthly gauges. Now there are increasing numbers of so-called 'daily' reports which do not include weekend readings. This has been caused by the decline in the numbers of truly private observers and the spread of 5-day working among local authority, water board, and river authority staffs. The situation is causing difficulties in some areas where it affects 25 per cent of the daily reports received. An attempt to use the computer quality control to estimate correct daily figures has been made. All data for England and Wales from 1961 and from Scotland and Northern Ireland from 1971 have been so amended; however, these estimates have not been annotated in any way so there is the danger they may be used in the future as genuine daily values.

From 1 January 1971, Scottish and Northern Irish data have also been included in the full cycle of data processing. Earlier use of a computer for checking and summarizing data was described in 1965.*

Types of error in order of prevalence.

(a) Misreadings, misplaced decimals, mistakes in copying and mistakes in arithmetic.

(b) Accumulations over more than one day, sometimes indicated, but quite often entered as normal daily readings.

(c) Displacement of correct readings to incorrect days, persistently, fairly often but irregularly, or only occasionally and erratically; frequently caused by observations made at non-standard times.

(d) Inadvertent omissions, observations made but not written down.

(e) Occasional errors due to temporary disturbance of exposure or mischievous interference.

(f) Systematic errors due to faulty exposure or defective equipment. A new defect, more prevalent in the last two years, is the breaking off of the rim on certain glass-fibre laminate gauges. The rim on these gauges is attached by ferrous rivets to the main body so that in normal use rusting takes place and the rim becomes detached. The removal of this rim increases the diameter such as to increase the catch by approximately 42 per cent. If more than one gauge in an area is damaged in this way it can make the task of detection by computer processes very difficult. A special watch on this type of tulip-shaped glass-fibre gauge is therefore necessary.

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* BLEASDALE, A. and FARRAR, A. B.; The processing of rainfall data by computer. *Met Mag, London*, **94**, 1965, pp. 98–109.

In an attempt to reduce errors (a), (b) and (c) a leaflet, giving a standard method of entry of readings on the postcard forms, has been issued to all stations where difficulties were noticed.

Maps. As an aid to quality control the areal analysis programme has been adapted so that station values can be plotted by computer. This routine is available to plot data on any one of five scales for a maximum of 8 consecutive days, or for monthly or annual totals. The scale recommended is 1 : 250 000 so that the computer output can be used with the existing computer area-index maps on a light-table to identify the stations. A maximum of 8 'area-days' for each run is recommended, i.e. one area for 8 days, two areas for 4 days, etc. The programme will also produce isohyets from the data, in contour print form, using all available stations in the area on the scale 1 : 625 000. An area of exceptionally close isohyets or apparently unrealistic patterns suggests data errors in the vicinity.

Computer programmes for quality control. The steps of the procedures covering the routine monthly input of data on to magnetic tape and the quality control of the data are limited by the capacity of the computer used. The present machine KDF9 handles up to 400 stations at a time as opposed to the 256 of the earlier one. The areas at present in use are based mainly on natural river basins, groups of basins within river authority areas, or tributary areas in the larger basins. Figure 1 gives a map of the computer areas and it has recently been found necessary to subdivide areas 34 and 35 as they were too large for practical use. A flow diagram and timetable for the steps of the quality control are given in the appendix; the process from initial punching of paper tapes to final transfer of magnetic tape to archives takes about 1 year 9 months from the beginning of the year of the data concerned.

For any one month and a given area, the steps may be described as follows.

Firstly a backing-tape (register of station particulars) of all stations currently forwarding data is made. This backing-tape is produced for each month by up-dating the previous version; each station contains particulars of the station number, height above sea level, average annual rainfall, grid reference, and county number.

Programme 1 (Inserting rainfall readings to magnetic tape containing backing-tape details).

(a) Reports already sorted into numerical order and computer areas are sent to be punched on to paper tape in a form that includes indicators used in subsequent processing.

(b) This programme then transfers the data to magnetic tape if the station is registered on the backing-tape and is for the correct month. If not, a print-out of the station number not accepted is given.

(c) For data accepted certain checks are made :
   (1) Arithmetical — print-out of total of daily values if not in agreement with that given.
   (2) Too many or too few daily values — actual number on paper tape listed.
   (3) No total — station listed and correct value given.

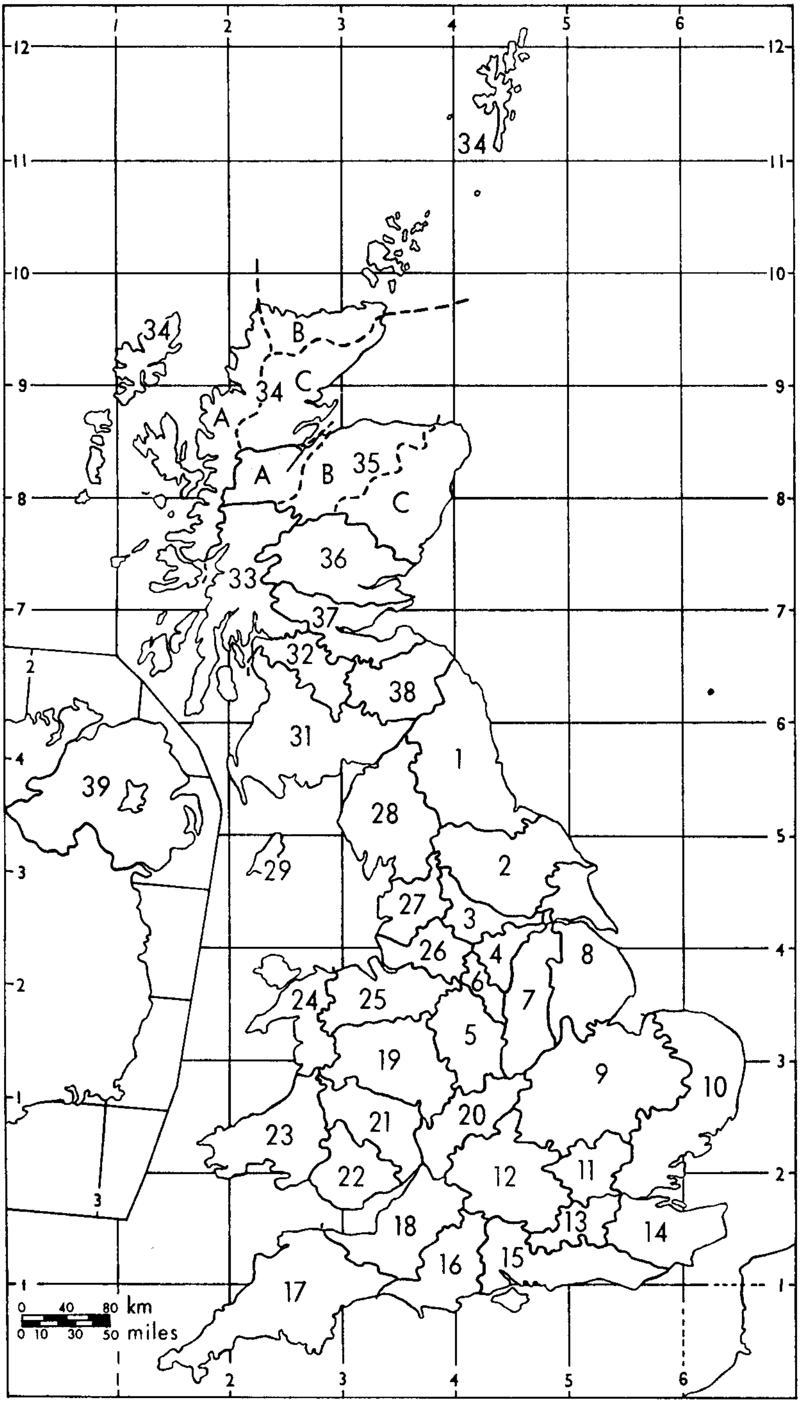

FIGURE 1—MAP OF THE COMPUTER AREAS

Values for stations reporting 12-hour amounts are added by the programme and the resultant 24-hour amounts checked as above. For data queried by checks (1), (2) and (3) a separate tabulation of all readings is given.

(d) A print-out of all data accepted, whether queried or not, is then given, plus a missing-station list.

This input programme is repeated as necessary, including amendments to queried stations until the data are considered complete and devoid of processing errors. See Appendix (a)–(c).

Programme 2 (Main quality control). With this programme a quality control is made of the reported rainfall amounts. As inch readings are now in the minority it is carried out in millimetres, with inch reports being converted by the programme.

The various steps are :

(a) *Indicated accumulations.* Indicators have been put on tape for accumulated values which are now subjected to checking. Comparisons are made with up to six stations within a square area of 12·8 km semi-diagonal. Stations used and estimates suggested are tabulated and printed separately, the estimates also being stored and annotated so as to be used in subsequent checks and printed at the end of this programme.

(b) *Daily values assessed.* The main development in this section of the programme has been to relate the assessments to per cent of average annual rainfall. In this way allowance has been made for the variation between sites and for elevation and geographical position.

Calculations are made of the area mean daily falls which are then converted to daily mean percentage, A, of area annual average; the standard deviation, σ_d, of the station values used in finding the mean is noted. The values of the mean percentage plus $2\sigma_d$ (i.e. $A + 2\sigma_d$) and the mean percentage minus $2\sigma_d$ (i.e. $A - 2\sigma_d$) are registered for each day of the month. All station daily values are then converted to percentages, S, of station annual average. These station daily percentage figures are then checked to identify those which appear too high or low, on the following basis :

$$\text{Too high} \quad \frac{S - (A + 2\sigma_d)}{S} > 0{\cdot}25,$$

where 0·25 is a control factor which has been found acceptable over 10 years of data from England and Wales.

$$\text{Too low} \quad S < (A - 2\sigma_d).$$

All values found outside these limits are then annotated for later tabulation and a separate list is given of suspect actual values, daily station percentages and the control factors.

(c) *Monthly values assessed.* Each monthly total is tested by comparison with up to six stations within a square area of 12·8 km semi-diagonal, but the values used are the totals expressed as percentages of station annual averages.

A control factor $(T - B)/\sigma_m$ is used where

T = total under consideration expressed as percentage of station annual average.

B = mean of the monthly values for the six stations used in the comparison, expressed as a percentage of the annual average of the stations.

σ_m = standard deviation of the station values used for B.

Stations are suspected if this factor is outside the limits $+1{\cdot}5$ to $-1{\cdot}5$.

The control factor is unreliable when σ_m is small (that is, when all other totals are much the same) so an overriding check is now built in. No stations are indicated as suspect unless $T/B \leqslant 0{\cdot}85$ or $\geqslant 1{\cdot}15$.

(d) *Check on daily values of zero.* All zeros are now tested for any day on which the mean for the area (in original units) is more than 2·5 mm and the standard deviation of those values is less than the mean. Otherwise the check is, as yet, unchanged from the 1964 version (see footnote, p. 340), except that suspect values are annotated with M for missing value or U for indicated accumulation, in the main tabulation.

(e) *Tabulation of all values for manual checking.* A full print-out of all daily and monthly values is made. The 1971 version is now in millimetres with an indicator against reports originally made in inches. Modifications giving extra information are :

(1) Monthly totals as per cent of station annual average.

(2) All suspect values and accumulated values in (a), (b) and (d) are annotated thus: H for high; L for low; M for missing; A for indicated accumulation with E for last day of accumulation; U for unindicated accumulation.

(f) *Heavy falls.* A separate print-out of all daily falls of 50·0 mm or more is used for special investigations.

After the tabulated print-outs have been produced they are scrutinized and subjected to futher checks by eye. Correspondence then takes place with observers or authorities whose reports have not been accepted. Final amendments are made, and then transferred to magnetic tape, with any late data, via paper tapes and programme 1. Appendix (d).

Programme 3. This programme is then run; it is a monthly routine of recycling (subjecting the data to another cycle of quality control) the monthly totals of all stations, the total for a station (as per cent of annual station average) being compared with the mean for the six nearest stations — a similar process to programme 2(c). The departures are not printed if they fall within a certain narrow range, so that those which are printed indicate monthly values approaching or exceeding the criterion of acceptability. For a station with a missing value the programme estimates a probable value using the six nearest stations' percentage figures. This programme, using only station monthly totals, can compare stations across computer area boundary lines and is therefore an important step in co-ordinating one area with another. Appendix (e).

Amendments found necessary on expert scrutiny are also written to magnetic tape via paper tape and programme 1. Appendix (f).

Programme 4. The final step in quality control, is to recycle the whole year's monthly totals, check them and give seasonal values (in absolute as well as percentage units). The programme is run from an annual magnetic tape consisting of all the 12 monthly tapes combined with an annual backing-tape section. Appendix (g), (h).

Any amendments necessary after checking and reading-back against original data have then to be inserted by a special annual tape-amendment programme. Appendix (i). The decision as to whether or not data are fit for publication is made at this stage. Appendix (j).

APPENDIX

Flow diagram and timetable for steps in quality control

Progression of data	Timetable	Total time taken
(a) Paper tapes punched: magnetic-tape input using programme 1 as required.		
(b) Rainfall extracted from CLIMAT reports using paper tapes and programme 1.	1 month Between 5 and 10 runs of programme 1	
(c) Programme 2 giving main quality control print-out.		$M+1$ month
(d) Amendments and late information input via paper tapes and programme 1.	2 months Approximately 3 more runs of programme 1	$M+3$ months
(e) Recycling of monthly totals using programme 3.	1 month	$M+4$ months
(f) Amendments and very late data input via paper tapes and programme 1.	12 separate monthly cycles 2 runs of programme 1 per month	$Y+4$ months
(g) Monthly tapes combined to form annual magnetic tapes.	A few days	$Y+5$ months
(h) Annual recycling via programme 4.	2 or 3 months	$Y+8$ months
(i) Amendments and insertions of back data to annual tape via special programme.	1 month	$Y+9$ months
(j) Clean archives annual magnetic tape.		

M = month of data concerned Y = year of data concerned

REVIEWS

Computer processing of meteorological data, by S. L. Belousov, L. S. Gandin and S. A. Mashkovich. 245 mm × 173 mm, pp. vi + 210, *illus.* (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), Keter Press Ltd, 15 Provost Road, London NW3 4ST, 1971. Price: £6·30.

This is a well-written book which does not appear to have suffered in translation from Russian to English. As far as I am aware it is the only textbook which deals specifically with the problems of automatic processing of meteorological data and the book lives up to the high reputation of the authors.

The subject is not one which has been given a great deal of publicity but it is a very important one. Operational numerical weather prediction is quite impracticable unless the data are processed automatically with a high degree of quality control and it is also becoming increasingly advantageous to have climatological data stored in machine assimilable form. The complexity of the computer programmes required to achieve an adequate data bank is considerable and I welcome this textbook which highlights some of the principles which are involved, frequently describing with the assistance of flow diagrams the best way in which the programme should be written.

The novel part of the book is contained in the first chapter which deals with the extraction and decoding of usable meteorological data from the telecommunication system. Methods of quality control of data are gone into at some length, and it is this first chapter that makes the book worth while. The following three chapters deal with various aspects of objective analysis, theoretical and practical considerations both being considered. The authors have done their best to deal with the techniques that are being practised in different countries, but have naturally been rather more expansive concerning the techniques currently in use in the Soviet Union. The final chapter deals with practical problems which arise in an operational environment concerned with numerical weather prediction.

My one criticism of the book is that it over-emphasizes those aspects of data processing related to numerical weather prediction and omits other requirements such as the preparation of data banks in machine assimilable form for climatological and research purposes, where there is time to effect a higher degree of quality control. Nevertheless, I strongly recommend this book to anyone concerned with automatic data-processing or objective analysis of meteorological data.

F. H. BUSHBY

Atmospheric circulation and the related wind fields over the North Pacific, by A. I. Sorkina. 245 mm × 175 mm, pp. iv + 218, (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), Keter Press Ltd, 15 Provost Road, London NW3 4ST, 1971. Price: £5.

The original book by A. I. Sorkina was published in Moscow in 1963 and the English translation by M. Levi was published last year. The author classified nearly all the daily synoptic maps for the North Pacific for the years 1899–1939 and 1954–59 (over 16 000 synoptic maps in all) into eight main types and eight sub-types of large-scale synoptic process. Detailed information is presented on the frequency of occurrence of each synoptic type for each month of the period investigated. Most of the book is then concerned with presenting and discussing statistical synoptic information such as the seasonal and secular variations in the frequency of occurrence of the synoptic types, the mean duration of individual types at different times of the year and the chance of any particular synoptic type being followed by the other types.

The synoptic-type classification approach is a well-established method which has inherent drawbacks. Subjective selection is involved in deciding what the fundamental types are, as well as in trying to put the daily synoptic maps into the correct class. Despite these faults, the method has produced in this instance meaningful statistical data on broad-scale synoptic processes over the North Pacific, and this information is not readily available elsewhere in English.

This small book is easy to understand but tedious to read. The main value rests in the tables and diagrams which form about half the book. One irritation to the reviewer was the inadequate bibliography which omitted information on several authors who were actually referred to in the book.

R. MURRAY

General circulation of the atmosphere, edited by B. L. Dzerdzeevskii and Kh. P. Pogosyan. 240 × 165 mm, pp. x + 402, *illus.* (translated from the Russian by the Israel Program for Scientific Translations, Jerusalem). Keter Publications Ltd, 15 Provost Road, London NW3 4ST, 1971. Price: £5.

This book consists of 24 contributions on a wide range of subjects presented at a conference in the U.S.S.R. at the end of 1964. However, the book was not published (in Russian) till 1968 and this translation appeared in 1971. Thus some of the contributions are inevitably somewhat dated, e.g. those on numerical models (Mashkovich), uses of satellites (Malkevich), stratospheric and mesospheric circulation (Dubentsov), laboratory models (Bonchkovskaya) and planetary atmospheres (Golitsyn and Moroz).

Of the remainder the four longest reports (30 to 34 pages each) are among the most interesting. Kolesnikova and Monin present a rather detailed review of spectra with discussions of the minimum centred around 30 minutes, of climatic fluctuations and of the absence of a peak near 11·5 years associated with the sunspot cycle. Pogosyan, Pavlovskaya and Shabel'nikova give results of a study using Kats' circulation indices (referenced but not defined) of zonality and meridionality at 500 mb and 100 mb for three regions; they reach conclusions unfavourable to the use in long-range forecasting of classifications of circulation types or relationships between adjoining regions such as are described by Girs in this collection; also 'the role of the stratosphere as well as of sunspot changes is not predominant in the development of synoptic processes in the troposphere'. Kitaigorodskii and Volkov review the problem of determining surface momentum and heat fluxes between ocean and atmosphere and attribute the wide range of estimates of surface drag coefficients and the uncertain relation of z_0 to u_* to the dependence of the atmospheric turbulence on the complex structure of the swell due to other than local winds. Petrosyants discusses the forcing of the flow by mountains, especially the central Asian massif. This paper is open to criticism in its use of maps of divergence without discussion of accuracy, but at least the evidence is presented to the reader — in contrast to several of the other contributions where, perhaps through a desire for brevity, insufficient evidence or only a reference is provided.

Other useful contributions include that by Feigel'son who stresses the difficulties of allowing properly for the optical properties of clouds in radiation calculations (part of a wider field reviewed by Rakipova and Shneerov), Khrgian's discussion of attempts to model the ozone distribution and Girs' review of his and others' work on circulation types and epochs. The last includes a forecast for 1965–78 which seems too vague for failure! Girs' epochs (1900–28, 1929–39, 1940–48, 1949–60) differ from those derived by Dzerdzeevskii (up to 1916, 1916–52 approximately) who used his daily classifications by 'elementary circulation mechanisms' from 1900, presumably because different criteria were used. Girs considers the sunspot cycle important and Dzerdzeevskii reviews the literature on this topic.

Other subjects covered include use of orthogonal functions with pressure fields (Yudin) (his conclusions should be read in the light of Kutzbach's results*), kinetic-energy partitioning (into mean/eddy and zonal/meridional components) (Gruza), three aspects of atmospheric energies (Borisenkov), southern-hemisphere circulation (Astapenko and Gaigerov), the use of jet streams as circulation indicators (Dzhordzhio) and pressure–wind relations near the equator (Dobryshman). An ocean–atmosphere interaction model is proposed by Laikhtman, Kagan and Timonov, but the solutions to a simple version are not well presented. Marchuk and Temnoeva's solution of quasi-steady equations seems out of place (a discussion of finite-difference methods might have been more appropriate). Obukhov and Fortus's 3 pages on correlation functions are spoiled by a poorly explained diagram and Drozdov's 14 pages on rainfall–temperature relations are indigestible, only partly because of a complete lack of diagrams and a missing table.

The large number of references (over 600, two-thirds of them Russian) may be of value. There are far too many errors, some of them new in the translation, e.g. omission of a figure caption on p. 294. Reading the book is also made more difficult by occasional incorrect or stilted translation, e.g. 'eddy' instead of 'vorticity', 'influence of shores' instead of 'coastal effects'.

To summarize, the value of this collection is reduced by the uneven coverage of its subject, the poor presentation by some of the writers and its delayed publication. It is not a book to be read from cover to cover, but the specialist may find in it interesting viewpoints or some useful references.

P. R. ROWNTREE

PUBLICATIONS RECEIVED

The following have been received from the Meteorological Institute of the University of Thessaloniki :

Observations météorologiques de Thessaloniki, 1966 and 1967. 1972.

The cooling power in Thessaloniki — Greece. By G. C. Livadas and Chr. J. Balafoutis.

* KUTZBACH, J. E.; Large-scale features of monthly mean northern hemisphere anomaly maps of sea-level pressure. *Mon Weath Rev, Lancaster, Pa,* **98**, 1970, pp. 708–716.

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MONSOONS AND THE GLOBAL CIRCULATION

By J. M. WALKER

Department of Maritime Studies, University of Wales Institute of Science and Technology, Cardiff

Summary. This paper considers the role of monsoons within the global circulation of the atmosphere. Previous work on this subject is reviewed briefly and the role of the monsoon is discussed in terms of the essentially convective nature of the troposphere.

Introduction. It is inevitable that extensive reorganizations of the tropical cell of the general circulation of the atmosphere will have widespread repercussions elsewhere, for the principle of continuity is fundamental in meteorology. It would be surprising if these repercussions were confined to the tropical zone, because extratropical circulations are known to extend well into tropical latitudes.[1,2,3] Accordingly, it is to be expected that repercussions of monsoons will be evident in middle latitudes.

Early attempts to establish relationships between monsoons and atmospheric behaviour elsewhere, reviewed critically by Normand,[4] employed statistical analyses, with only scant regard for physical justification. Some intricate statistical associations between Indian monsoon phenomena and diverse atmospheric factors far away were derived (e.g. Ramdas *et alii*[5]) but the paucity of upper-air information precluded a satisfactory physical understanding of the associations. Consequently, the associations were unreliable as tools for the forecasting of Indian monsoon behaviour, for which primarily they were intended.

Normand mentioned that Sir Gilbert Walker, about 50 years ago, attempted, albeit inconclusively, to explain in *physical* terms a statistical relationship he discovered between South American pressure in April and May and Indian monsoon rainfall between June and September. Walker's work led to the discovery of the phenomenon which he called 'the southern oscillation'. Normand described this phenomenon briefly as 'a tendency for air to be removed from the whole Pacific area from Tokyo to South America at the same time as air accumulates in and around the Indian Ocean and vice versa'. The phenomenon is evident not only in values of surface pressure but also in temperature and rainfall records of India, Indonesia and Australia. Walker showed by correlation techniques that the Indian monsoon rains are related to later, rather than earlier, atmospheric events over the globe.

Troup[6] discussed at length and updated Walker's work and suggested a mechanism for the oscillation in terms of a direct toroidal circulation between the warmer eastern and the cooler western hemispheres. Wright[7] mentioned that certain aspects of the southern oscillation may be influenced by a biennial cycle in tropospheric circulations and suggested that this cycle is tidal in origin.

Aerological relationships. One of the earliest comprehensive aerological investigations of the onset of the Indian monsoon was carried out by Yin.[8] He reviewed briefly earlier aerological studies and then showed from his own analyses that the onset in 1946 was associated with a disappearance of the upper-tropospheric westerly flow over northern India and with a rearrangement of the pattern of long waves over the northern hemisphere. Frost[9] established that the height of the tropopause over the Middle East alters abruptly from near 220 mb to near 80 mb at the end of May and vice versa in October, and Sutcliffe and Bannon[10] showed additionally that a simultaneous reversal of direction of the upper-tropospheric flow over the Middle East correlates well with the date of onset of the monsoon rains on the Indian Malabar coast. Likewise, Ananthakrishnan and Rangarajan[11] found that the tropopause characteristics over the northern part of the Indian subcontinent alter markedly from extratropical to tropical, and vice versa, with the onset and retreat respectively of the Indian south-west monsoon.

Yeh *et alii*[12] claimed that the abrupt change of the upper-tropospheric circulation is not a special condition, found only in Asia, but a world-wide phenomenon. They proposed that there are only two natural atmospheric seasons, winter and summer, of which winter is the longer. Spring and autumn, they said, are merely short transition periods between the natural seasons. They mentioned also that a good correlation exists between the beginning of the 'Mai-yü' period over eastern Asia and the establishment of the Indian monsoon. Moreover, they suggested that the 'Indian summer' in North America and the 'old wives' summer' in Europe may be related to the October upper-tropospheric transition period. Dao and Chu[13] showed that there is a correspondence between movements of the surface anticyclone over the north-western Pacific Ocean and variations of the upper-tropospheric anticyclone over Tibet (see also Neyama,[14] and Gordon[15]). Chang[16] has reviewed the many studies made of relationships, known or suspected, between circulations over eastern Asia and the Indian monsoons.

De la Mothe and Wright[17] pointed out that, despite the sufficiency of upper-air data in the extratropics, not much attention had been paid to relationships which were known to exist between the onset of the Indian south-west monsoon and changes in the circumpolar westerlies of middle and high latitudes. Accordingly, they examined 500-mb trough–ridge patterns over Europe and Asia in search of a relationship with the onset of the Indian summer monsoon. They concluded that the 500-mb flow in the circumpolar westerlies over Eurasia plays a significant role in the mechanism of the onset of this monsoon and they advised that 'close attention' should be given to the Asian ridge, and changes of wavelength of the long-wave pattern across it, at the time of monsoon onset (see also Gordon[18]).

The work of Anjaneyulu and Sikka[19] supported Sir Gilbert Walker's conclusion that circulation changes in higher latitudes are determined largely *by* monsoons. Pisharoty[20] too was of the opinion that the Indian monsoon is a source of energy which exerts a significant influence on the general circulation of the atmosphere. Indeed, it is surely unrealistic to attempt to show that circulation changes in middle latitudes are *responsible* for the Indian summer monsoon since the sun is the principal energy source for the global circulation. However, it is expected that extratropical circulations provide feedback within the atmospheric system to the tropics, thereby exerting a regulating influence.

Monsoons and extratropical circulations. The schematic vertical section of flow in deep tropospheric convection shown in Figure 1 is due to Green *et alii*.[1] According to these authors :

> 'The pattern of vertical motion is markedly asymmetrical, the upward velocities being large and concentrated into a small part of the system where the condensation of water vapour occurs. In and near this region the flow is rapid and may be nearly adiabatic, and a large part of the condensed water is precipitated. Outside it, descending motion is cloud free and, for return to the surface layer in the same latitude, is limited to the slow rate determined by radiative heat loss.'

They estimated that air may take three weeks or more to return from the upper to the lower troposphere. Further, they suggested that subsiding air is moistened in regions of small-scale convection, illustrated in Figure 1, and thereby provided with potential energy. This moistened air then enters middle-latitude trough–ridge circulations (termed by Green *et alii*[1] 'large-scale slope-convection systems') and ascends on the eastern flanks of troughs, and the potential energy is converted into the kinetic energy of jet streams. Published examinations of these proposals are scarce, but Walker[21,22] showed that their ideas could be applied to winter jet streams near 300 mb and to the associated cloud and precipitation events over the coasts of Iran and West Pakistan, at the foothills of the Himalayas and over the plains of central Asia.

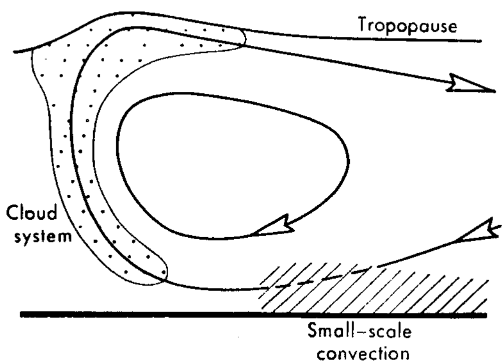

FIGURE 1—SCHEMATIC VERTICAL SECTION OF FLOW IN DEEP TROPOSPHERIC CONVECTION (after Green *et alii*[1])

Ramage[23] concluded that air which subsides widely over south-west Asia in summer ascends originally over a relatively small area in Indian monsoon rain systems. The present author's analyses, based upon both climatic and daily surface and aerological observations and employing, in particular, winds and wet-bulb potential temperatures, support Ramage's conclusion and indicate that air which ascends in monsoon rain systems over Ethiopia and over western North Africa subsides subsequently over the central Sahara Desert and the eastern North Atlantic Ocean respectively. The lack of data over large tracts is, of course, a hindrance in such studies. Suggested trajectories are shown in Figures 2 and 3.

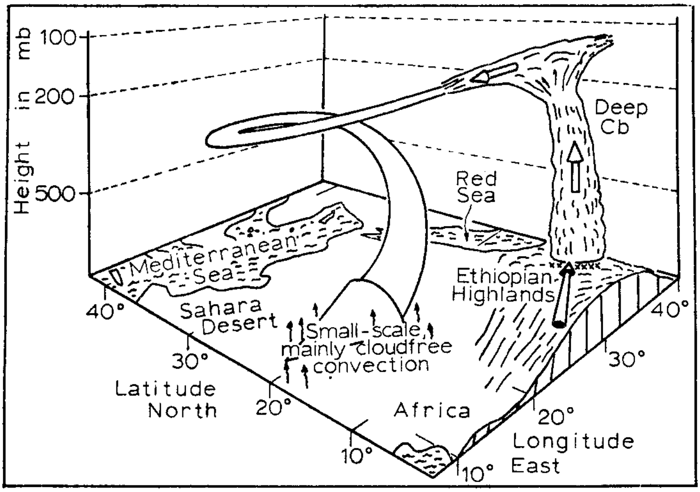

FIGURE 2—MODEL OF FLOW IN THE MONSOON CIRCULATION OF EASTERN NORTH AFRICA

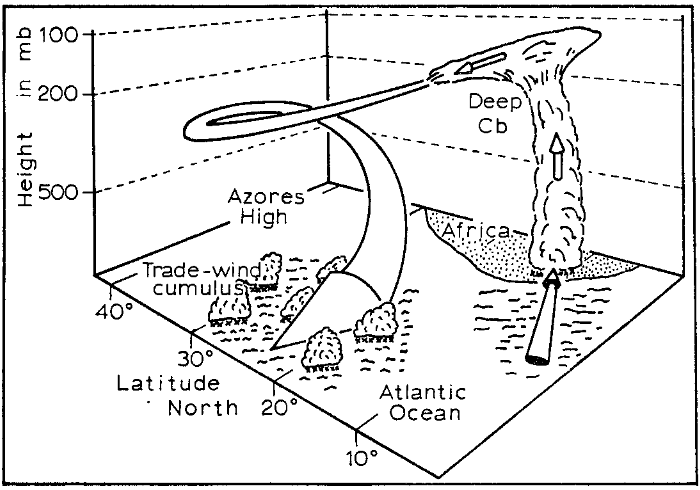

FIGURE 3—MODEL OF FLOW IN THE MONSOON CIRCULATION OF WESTERN NORTH AFRICA

Hence, a plausible explanation is provided for the well-known summer intensification and extension eastward of the subtropical anticyclone over the North Atlantic Ocean (the so-called 'Azores high'). In summer this anticyclone contains, in addition to air subsiding from the intertropical convergence zone over the Atlantic Ocean in a conventional Hadley-type circulation, air subsiding from the monsoon rain systems over western North Africa. This suggests that the intensity of the Azores high is controlled to some extent by the monsoonal activity; there is some observational evidence, on both synoptic and seasonal time-scales, that this is indeed so, but the idea needs a thorough investigation.

Carlson and Ludlam[24] and Green *et alii*[1] mentioned that subsiding air may be prepared in regions of small-scale convection over the Sahara Desert for ascent on the eastern flanks of summer troughs over Europe. Spectacular evidence for the participation of Saharan air in such troughs was provided by the dust fall of 1 July 1968 over southern Britain (Stevenson[25]); scientific analyses of this dust indicated that its origin was near the southern edge of the Sahara Desert, near the Ahaggar Mountains. Stevenson remarked that broad southerly airstreams from North Africa ordinarily occur several times a year and it is perhaps surprising that noticeable falls of dust are not more frequent.

Cyclogenesis is favoured beneath divergent regions in the upper troposphere. The assumption that the upper-tropospheric easterly flow in the tropics in summer decelerates *gradually* downwind from India is not supported by observations. It is true that the average strength of this flow is greatest over India but it happens often that upper-tropospheric winds are stronger over eastern North Africa than over India. Moreover, both climatically and on individual days, separate wind-speed maxima can be identified downwind of India, one above the Ethiopian Highlands and another above western North Africa (Figures 4 and 5). Accordingly, although there is, as Flohn[26] has shown, a general tendency for subsidence to occur in the middle and upper troposphere between the western Sahara and Pakistan, the precise distribution of convergences and divergences from day to day is complex.

The suggestion implicit in the present author's analyses is that subsiding air from Ethiopian monsoon rain systems arrives in the lower troposphere over the central Sahara Desert. Preparation for ascent takes place there in

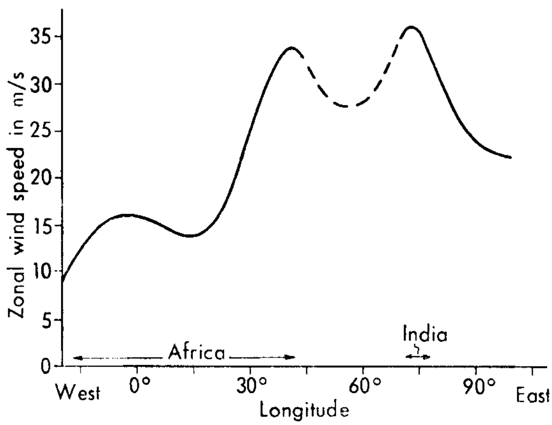

FIGURE 4—MONTHLY MEAN ZONAL WIND SPEEDS AT 150 mb IN JULY BETWEEN WESTERN NORTH AFRICA AND SOUTH-EAST ASIA

The cross-section is approximately along latitude 12°N.

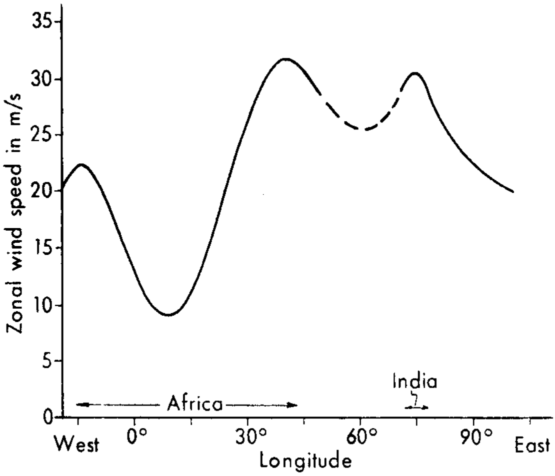

FIGURE 5—ZONAL WIND SPEEDS AT 150 mb AT 00 GMT ON 28 JULY 1966 BETWEEN WESTERN NORTH AFRICA AND SOUTH-EAST ASIA

The cross-section is approximately along latitude 12°N.

small-scale, generally cloud free, convection, in association with divergence aloft, the divergence being associated with fluctuations in the strength of the upper easterly flow over North Africa. Support for such a mechanism is provided by satellite photographs, which often reveal frontal cloud-bands extending from the Sahara well into western Europe (see Flohn[3]), and the origin, near the Ahaggar Mountains, of the aforementioned dust is also consistent with this mechanism.

Conclusion. Figure 6 summarizes the main features of the suggested collaboration of small-scale, monsoon-scale and large-scale slope convection over North Africa. Such collaboration between the various scales of convection

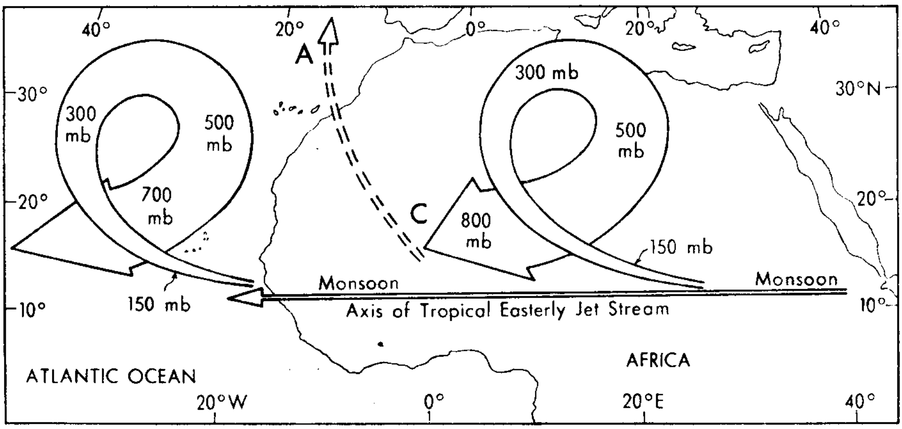

FIGURE 6—SUMMARY OF MAIN FEATURES OF SUGGESTED COLLABORATION OF THE VARIOUS SCALES OF CONVECTION OVER NORTH AFRICA

In the small-scale convection (C) over the central Sahara Desert the subsided outflow from the Ethiopian monsoon is prepared for ascent (A) in European trough–ridge systems. The outflow from the monsoon over western North Africa subsides over the Atlantic Ocean.

is an essential feature of the global tropospheric circulation (Ludlam[27]) and must form the basis of any investigation into the role of monsoonal reorganizations of the troposphere within that circulation.

REFERENCES

1. GREEN, J. S. A., LUDLAM, F. H. and MCILVEEN, J. F. R.; Isentropic relative-flow analysis and the parcel theory. *Q J R Met Soc, London*, **92**, 1966, pp. 210–219.
2. RIEHL, H.; On the role of the tropics in the general circulation of the atmosphere. *Weather, London*, **24**, 1969, pp. 288–304.
3. FLOHN, H.; Tropical circulation pattern. *Bonn Met Abh, Bonn*, Heft 15, 1971.
4. NORMAND, SIR CHARLES; Monsoon seasonal forecasting. *Q J R Met Soc, London*, **79**, 1953, pp. 463–473.
5. RAMDAS, L. A., JAGANNATHAN, P. and GOPAL, RAO, S.; Prediction of the date of establishment of southwest monsoon along the west coast of India. *Indian J Met Geophys, New Delhi*, **5**, 1954, pp. 305–314.
6. TROUP, A. J.; The 'southern oscillation'. *Q J R Met Soc, London*, **91**, 1965, pp. 490–506.
7. WRIGHT, P. B.; A widespread biennial oscillation in the troposphere. *Weather, London*, **23**, 1968, pp. 50–54.
8. YIN, M. T.; A synoptic-aerologic study of the onset of the summer monsoon over India and Burma. *J Met, Lancaster, Pa*, **6**, 1949, pp. 393–400.
9. FROST, R.; The upper-air circulation in low latitudes and its relation to certain climatological discontinuities. London, Meteorological Office, 1952. (Unpublished, copy available in the Meteorological Office Library, Bracknell.)
10. SUTCLIFFE, R. C. and BANNON, J. K.; Seasonal changes in upper-air conditions in the Mediterranean — Middle East area. *Scient Proc Int Ass Met, London*, 1954, pp. 322–334.
11. ANANTHAKRISHNAN, R. and RANGARAJAN, S.; Some features of the thermal structure of the atmosphere over India and neighbourhood. Wellington, New Zealand Meteorological Service. Proceedings of the Symposium on Tropical Meteorology, Rotorua, 1964. 1964, pp. 62–71.
12. YEH TU-CHENG, DAO SHIH-YEN and LI MEI-TSIUN; The abrupt change of circulation over the northern hemisphere during June and October. *Acta Met Sin, Peking*, **29**, 1958, pp. 249–263.
13. DAO SHIH-YEN and CHU FU-KANG; The 100-mb flow pattern in southern Asia in summer and its relation to the advance and retreat of the west-Pacific subtropical anticyclone over the Far East. *Acta Met Sin, Peking*, **34**, 1964, pp. 396–407.
14. NEYAMA, Y.; The morphology of the subtropical anticyclone. *J Met Soc Japan, Tokyo*, **46**, 1968, pp. 431–441.
15. GORDON, A. H.; Seasonal changes in the mean pressure distribution over the world and some inferences about the general circulation. *Bull Am Met Soc, Lancaster, Pa*, **34**, 1953, pp. 357–367.
16. CHANG JEN-HU; The Chinese monsoon. *Geogrl Rev, New York*, **61**, 1971, pp. 370–395.
17. DE LA MOTHE, P. D. and WRIGHT, P. B.; The onset of the Indian south-west monsoon and extratropical 500-mb trough and ridge patterns over Europe and Asia. *Met Mag, London*, **98**, 1969, pp. 145–155.
18. GORDON, A. H.; Air mass transfer and the northern hemisphere summer of 1959. *Weather, London*, **16**, 1961, pp. 3–13.
19. ANJANEYULU, T. S. S. and SIKKA, D. R.; Equatorward extension of troughs in the upper westerlies and the relation of upper tropospheric flow to onset of monsoon rains over India *from* Preliminary results and future plans of the International Indian Ocean Expedition (Proc Sem, Bombay, 1963). 1963, pp. 68–81.
20. PISHAROTY, P. R.; Monsoon pulses. Wellington, New Zealand Meteorological Service. Proceedings of the Symposium on Tropical Meteorology, Rotorua, 1964. 1964, pp. 373–379.
21. WALKER, J. M.; Some ideas on winter atmospheric processes over south-west Asia. *Met Mag, London*, **96**, 1967, pp. 161–167.
22. WALKER, J. M.; A case study of winter cyclogenesis over central Asia. *Tellus, Stockholm*, **22**, 1970, pp. 399–402.
23. RAMAGE, C. S.; The summer atmospheric circulation over the Arabian Sea. *J Atm Sci, Lancaster, Pa*, **23**, 1966, pp. 144–150
24. CARLSON, T. N. and LUDLAM, F. H.; Large-scale conditions for the occurrence of severe local storms. *London, Imp Coll Sci Tech, Dep Met, A Summ Rep* No. 1 (Grant AF EOAR 64–60), 1965, pp. 1–74.
25. STEVENSON, C. M.; The dust fall and severe storms of 1 July 1968. *Weather, London*, **24**, 1969, pp. 126–132.
26. FLOHN, H.; Investigations on the tropical easterly jet. *Bonn Met Abh, Bonn*, Heft 4, 1964.
27. LUDLAM, F. H.; Cumulus and cumulonimbus convection. *Tellus, Stockholm*, **18**, 1966, pp. 687–698.

551.577.21(261.26/.27):551.579.1

HYDROLOGY OF THE NORTH SEA: RUN-OFF AND PRECIPITATION

By J. GRINDLEY

Summary. Values of total accession of fresh water to the North Sea have been presented for the months January 1941 to December 1960. The data are shown separately for run-off from the rivers draining to the North Sea, for precipitation over the Sea and as a combined total. A graphical technique, relating specific discharge to average areal rainfall, was used to estimate run-off for areas for which no flow data were available. Precipitation was estimated by taking the mean of values from a number of stations ringing the Sea.

Introduction. The purpose of this synopsis is to provide information concerning total accession of fresh water to the North Sea in the form of run-off from the land areas of Europe draining to the Sea and precipitation over the Sea.

The data are provided for each month in the period January 1941 to December 1960. It is hoped that this period is sufficiently long to permit an adequate representation of the range and seasonal variation in the accession of fresh water.

The data are provided in three parts: total run-off; total precipitation; and total accession of fresh water, run-off and precipitation combined.

Total run-off to the North Sea. Table I shows total monthly run-off in cubic metres $\times 10^9$ contributed by all rivers draining to the North Sea in the period 1941–60. The data were obtained in the following way.

Eastern Britain. River flow data were obtained from the *Surface Water Year Books* prepared at that time by the Ministry of Housing and Local Government and the Scottish Office. The total area of eastern Britain for which river flow measurements were available was 24 834 km^2 in 1941 and 54 804 km^2 in 1960; the total area of eastern Britain draining to the North Sea is 115 472 km^2. That is, even in 1960, river flow measurements were available for less than half the area of Britain draining to the North Sea.

It was necessary, therefore, to estimate run-off for the portion of the country for which flow data were not available. The estimates were made by plotting, for each year, specific discharge (discharge per unit area) against average annual rainfall for all areas where river flow data were available. In most years, a close relationship was apparent and a smooth curve could be drawn. River flow from the non-gauged areas was computed for each hydrometric area (major river-division) by entering the graph for a particular year with estimated general rainfall over the non-gauged area and reading off a specific discharge. Total discharge from the non-gauged area was then obtained by multiplying specific discharge by area; to this was added the measured discharge to obtain a value of river flow for the whole hydrometric area.

The apportionment of annual amounts to individual months within the year was less satisfactory. River flow in the largest catchment in each hydrometric area and any other catchment of area greater than 130 km^2 was expressed as a percentage of the annual river flow for each year and the percentage values for each month were meaned to give a general percentage estimate for the whole of eastern Britain. The mean percentage value for each month was

TABLE I—TOTAL MONTHLY RUN-OFF TO THE NORTH SEA IN THE PERIOD 1941–60

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
						cubic metres × 10^9							
1941	27	30	34	27	25	34	24	22	17	19	23	28	310
42	19	14	28	24	23	30	26	21	23	27	21	22	278
43	25	26	20	23	27	36	31	20	19	23	14	15	279
44	25	22	17	21	25	33	32	25	18	22	30	38	308
45	18	42	29	24	29	35	27	18	16	18	13	18	287
46	20	39	29	23	24	31	33	21	24	13	19	19	295
47	17	9	35	30	30	27	18	8	15	20	15	15	239
48	45	34	21	23	24	27	29	20	27	27	20	21	318
49	23	19	19	21	30	35	27	20	16	24	14	18	266
50	17	27	22	17	29	36	28	21	24	28	20	25	294
51	29	21	24	24	26	27	27	25	22	13	22	30	290
52	32	21	26	31	30	23	29	21	19	17	28	35	312
53	22	25	24	17	27	34	27	21	18	22	22	20	279
54	16	13	16	16	26	30	26	24	27	35	27	37	293
55	36	27	21	21	23	31	38	20	18	21	15	22	293
56	28	16	25	18	27	36	35	27	21	33	20	29	315
57	28	33	29	20	22	31	32	23	26	28	22	24	318
58	27	32	29	20	30	35	38	26	18	28	21	23	327
59	32	16	20	20	26	24	20	17	10	11	17	15	228
60	20	19	18	14	24	25	18	20	20	27	29	34	268
Mean 1941–60	25	24	24	22	26	31	28	21	20	23	21	25	290

then applied to the annual value for eastern Britain (obtained by summation of measured flow and flow calculated graphically) to give an estimate of discharge in each month for the whole of eastern Britain.

Western Denmark. Flow data for the whole of that part of Denmark draining to the North Sea (10 850 km^2) were provided by Det Danske Hedeselskabs Kulturtekniske Afdeling, Hydrometriske Undersøgelser.

Netherlands. Flow data for the Rhine at Lobith (160 000 km^2) and the Meuse (Maas) at Lith (29 500 km^2) were provided by the Dutch Rijkswaterstaat, Directie Waterhuishouding en Waterbeweging.

Germany. Flow data for the Ems to its mouth (12 480 km^2), Weser to its mouth (45 253 km^2) and Elbe to its mouth (144 055 km^2) were provided by the Bundesanstalt für Gewässerkunde.

Norway. Flow data for the area of Norway between Lindesnes and 62°N, draining to the North Sea were provided by Norges Vassdrags- og Elektrisitetsvesen, Vassdragsdirektoratet, Hydrologisk Avdeling.

Residual waters draining to the North Sea. Although measurements or estimates of flow were made available for the greater part of Europe draining to the North Sea, a number of residual areas remained for which neither estimates nor measurements were available. The largest of these areas was the Scheldt (21 000 km^2). Professor Tison, then General Secretary of the International Association of Scientific Hydrology, was able to provide a limited amount of flow data for the Scheldt and its tributary the Rupel at their confluence. It was clear that, because of abstractions, diversions and feeding of canals, the measured flow in these rivers in no way represented the natural contribution of their catchment areas to run-off to the North Sea. It was necessary, therefore, to estimate flow for the Scheldt and for the remaining residual areas, namely the Rhine below Lobith (5500 km^2), the Meuse below Lith (3370 km^2), the coastal streams of Flanders (3231 km^2) and the Ijsel (3600 km^2).

The estimation was carried out by using a method similar to that adopted for estimating river flow in the non-gauged areas of eastern Britain. That is, average annual rainfall was estimated over the areas for which flow data (measured or estimated) were available and also over the residual areas. The mean specific discharge (cubic metres per second per square kilometre) for the years 1941–60 was obtained for each of the areas for which flow data were available and these specific discharges were graphed against average annual precipitation. Estimates of mean specific discharge were obtained for the residual areas by entering the graph with estimates of average annual precipitation over these areas. The average annual precipitation with apparent and estimated specific discharges are given in Table II.

TABLE II—AVERAGE ANNUAL PRECIPITATION AND ANNUAL SPECIFIC DISCHARGE FOR SPECIFIED AREAS

	Average precipitation	Annual specific discharge
Areas for which flow data were available	*mm*	$m^3/s\ km^2$
Eastern Britain	861	0·0133
Western Denmark	760	0·0125
Rhine to Lobith	822	0·0131
Ems	712	0·0090
Weser	723	0·0085
Elbe	658	0·0055
Meuse to Lith	827	0·0101
Norway	1797	0·0769
		Estimates of annual specific discharge
Residual areas		$m^3/s\ km^2$
Rhine below Lobith	700	0·0060
Meuse below Lith	730	0·0080
Scheldt	815	0·0140
Flanders streams	750	0·0090
Ijsel	720	0·0080

Flow for individual months from the residual areas was then obtained by taking the ratio of specific discharge over each of these areas to that of a neighbouring area and increasing the observed flow in the neighbouring area for the particular month in that ratio. No great accuracy can be claimed for this method but it is considered that the estimated value will at least be of the right order.

Annual flow from each major area. Table III shows the annual flow, 1941–60, in cubic metres $\times$ 10^9 from each of the major areas contributing discharge to the North Sea. The values for the residual areas represent the means of the 12 monthly values rather than the more correct means of daily values.

Monthly precipitation over the North Sea. Table IV shows monthly precipitation in millimetres and Table V the equivalent volume in cubic metres $\times$ 10^9 over the North Sea. The area of the North Sea which has been adopted is that proposed by T. Laevastu* (Fisheries Oceanographer, Food and Agriculture Organization). It is bounded in the north by a line running approximately from Nord Fiord, Norway, to Shetland, Orkney, and the mainland of Scotland, and to the south by a line from Dover to Calais. The Skagerrak and Kattegat are excluded. The extent of this area is given as 575 300 km^2.

* LAEVASTU, T.; Synopsis of information on the oceanography of the North Sea. FAO, Fisheries Division, Biology Branch, 1960. (Unpublished, copy available in the Meteorological Office, Met.O.8a.)

TABLE III—ANNUAL FLOW FROM MAJOR AREAS OF EUROPE CONTRIBUTING WATER TO THE NORTH SEA

Year	Eastern Britain	Western Denmark	Rhine to Lobith	Ems	Weser	Elbe	Meuse to Lith	Norway	Rhine below Lobith	Meuse below Lith	Scheldt	Flanders	Ijsel
	115 472	10 850	160 000	12 480	45 253	144 055	29 500	45 474	5500	3370	21 000	3231	3600 km^2
						cubic metres × 10^9/*year*							
1941	54	3	87	5	17	47	11	70	1	1	11	1	1
42	43	4	60	3	12	26	8	111	1	1	8	1	1
43	43	4	46	3	8	15	8	144	1	1	8	1	1
44	42	4	74	4	13	27	11	117	1	1	11	1	1
45	45	5	69	4	12	24	9	109	1	1	9	1	1
46	51	5	66	4	14	26	9	109	1	1	9	1	1
47	50	3	50	2	9	18	6	92	1	1	6	1	1
48	49	4	77	4	13	26	11	120	1	1	11	1	1
49	38	4	38	2	7	17	5	147	1	1	5	1	1
50	48	5	58	3	11	19	9	129	1	1	9	1	1
51	62	6	70	4	11	17	12	93	1	1	12	1	1
52	52	5	80	3	12	20	14	108	1	1	14	1	1
53	40	5	54	2	9	20	7	130	1	1	7	1	1
54	63	6	61	4	10	19	8	109	1	1	8	1	1
55	44	5	72	3	14	31	8	104	1	1	8	1	1
56	46	4	75	5	18	33	10	109	1	1	10	1	1
57	50	4	65	4	14	28	11	127	1	1	11	1	1
58	59	5	80	5	17	21	13	98	1	1	13	1	1
59	40	4	50	1	7	18	7	92	1	1	7	1	1
60	63	4	68	3	9	21	10	75	1	1	10	1	1
Mean 1941–60	49	4	65	4	12	24	9	110	1	1	10	1	1

TABLE IV—MONTHLY PRECIPITATION OVER THE NORTH SEA (AREA 575 300 SQUARE KILOMETRES)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
						millimetres							
1941	38	62	50	30	35	21	79	119	31	101	64	67	697
42	63	29	31	30	58	34	91	66	93	125	70	97	787
43	92	64	30	58	56	55	42	88	74	69	111	46	785
44	85	42	40	45	48	65	53	53	117	96	124	82	850
45	74	72	30	48	75	56	50	76	69	70	44	88	752
46	58	75	49	46	40	76	90	99	118	47	109	74	881
47	41	31	78	58	28	58	58	14	78	31	113	63	651
48	112	49	31	45	42	66	56	92	95	85	59	78	810
49	88	48	45	63	43	32	36	56	61	104	95	104	775
50	52	80	47	62	38	61	88	110	127	71	110	81	927
51	81	72	68	73	40	43	63	115	68	36	127	87	873
52	74	46	64	37	39	66	61	99	101	85	88	79	839
53	51	53	23	58	54	48	83	103	70	51	78	63	735
54	62	54	50	26	49	68	86	87	103	124	104	101	914
55	59	47	39	35	62	41	20	33	77	103	43	96	655
56	104	36	29	27	38	53	83	110	62	86	60	76	764
57	68	76	62	24	37	44	85	105	107	90	76	72	846
58	82	77	45	42	69	47	93	107	70	89	52	83	856
59	87	18	41	61	19	46	55	48	23	83	102	99	682
60	87	59	26	44	35	42	77	96	68	110	111	96	851
Mean 1941–60	73	54	44	46	45	51	67	84	81	83	87	82	797

TABLE V—MONTHLY PRECIPITATION OVER THE NORTH SEA (AREA 575 300 SQUARE KILOMETRES)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
						cubic metres $\times 10^9$							
1941	22	36	29	17	20	12	45	68	18	58	37	39	401
42	36	17	18	17	34	19	52	38	53	72	40	56	452
43	53	37	17	33	32	32	24	51	43	39	64	26	451
44	49	24	23	26	28	37	30	31	67	55	72	47	489
45	43	42	17	28	43	32	29	44	40	40	25	50	433
46	33	43	28	26	23	43	52	57	68	27	63	43	506
47	24	18	45	33	16	33	33	8	45	18	65	36	374
48	64	28	18	26	24	38	32	53	55	49	34	45	466
49	51	27	26	36	25	18	21	32	35	60	55	60	446
50	30	46	27	35	22	35	51	63	73	41	63	47	533
51	47	41	39	42	23	25	36	66	39	21	73	50	502
52	42	26	37	21	23	38	35	57	58	49	51	46	483
53	29	31	13	33	31	28	48	59	40	29	45	36	422
54	36	31	29	15	28	39	50	50	59	71	60	58	526
55	34	27	22	20	36	23	12	19	45	59	25	55	377
56	60	21	17	16	22	30	47	63	36	49	34	44	439
57	39	44	35	14	21	25	49	61	62	52	44	41	487
58	47	44	26	24	40	27	53	62	41	51	30	48	493
59	50	10	24	35	11	27	32	27	13	48	59	57	393
60	50	34	15	25	20	24	45	56	39	63	64	55	490
Mean 1941–60	42	31	25	26	26	29	39	48	47	48	50	47	458

The estimates were made by taking 17 rainfall stations, more or less evenly spaced round the coasts of the North Sea and adopting a simple arithmetic mean of the monthly totals at these stations to obtain an estimate of areal general rainfall over the Sea. The assumption in this approach is that, in the absence of relief or other factors likely to induce precipitation, linear interpolation is possible. Although the stations were chosen to be as close to sea level as possible, it seems likely that in all cases the land mass on which they stand will have had some effect on the precipitation at the station. Again, it is hoped that the estimates are of the right order, but it seems likely that they are even less certain than those for run-off. The uncertainty is almost certainly in the direction of overestimation.

The stations used were :

	Latitude	Longitude
United Kingdom		
Lerwick	60°08′N	1°11′W
Hellgar Holm	59°01′N	2°54′W
Kinnaird's Head	57°42′N	2°00′W
Carnoustie	56°30′N	2°42′W
Tynemouth	55°01′N	1°25′W
Hornsea	53°55′N	0°10′W
Gorleston	52°35′N	1°43′E
Margate	51°24′N	1°24′E
Netherlands		
Hollum (Amesland)	53°27′N	5°38′E
Den Helder	52°58′N	4°45′E
Naaldwijk	51°59′N	4°12′E
Germany		
Emden	53°22′N	7°13′E
Denmark		
Vestervig	56°46′N	8°20′E
Nordby (Fanø)	55°27′N	8°25′E
Norway		
Lista	58°06′N	6°34′E
Skudenes	59°09′N	5°16′E
Hellisøy Fyr	60°45′N	4°43′E

Total accession of fresh water to the North Sea. Table VI shows the total accession of fresh water to the North Sea, in cubic metres × 10^9, for each month from January 1941 to December 1960. These values are the respective sums of the values in Tables I and V.

TABLE VI—TOTAL ACCESSION OF FRESH WATER TO THE NORTH SEA

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
						cubic metres × 10^9							
1941	49	66	63	44	45	46	69	90	35	77	60	67	711
42	55	31	46	41	57	49	78	59	76	99	61	78	730
43	78	63	37	56	59	68	55	71	62	62	78	41	730
44	74	46	40	47	53	70	62	56	85	77	102	85	797
45	61	84	46	52	72	67	56	62	56	58	38	68	720
46	53	82	57	49	47	74	85	78	92	40	82	62	801
47	41	27	80	63	46	60	51	16	60	38	80	51	613
48	109	62	39	49	48	65	61	73	82	76	54	66	784
49	74	46	45	57	55	53	48	52	51	84	69	78	712
50	47	73	49	52	51	71	79	84	97	69	83	72	827
51	76	62	63	66	49	52	63	91	61	34	95	80	792
52	74	47	63	52	53	61	64	78	77	66	79	81	795
53	51	56	37	50	58	62	75	80	58	51	67	56	701
54	52	44	45	31	54	69	76	74	86	106	87	95	819
55	70	54	43	41	59	54	50	39	63	80	40	77	670
56	88	37	42	34	49	66	82	90	57	82	54	73	754
57	67	77	64	34	43	56	81	84	88	80	66	65	805
58	74	76	55	44	70	62	91	88	59	79	51	71	820
59	82	26	44	55	37	51	52	44	23	59	76	72	621
60	70	53	33	39	44	49	63	76	59	90	93	89	758
Mean 1941–60	67	56	50	48	53	60	67	69	66	70	71	71	748

Acknowledgement. The author wishes to thank the various European hydrological and meteorological organizations which kindly supplied data and, in some cases, valuable comments on the data.

551.577.36(421)

AN INVESTIGATION INTO CONSECUTIVE WET WORKING DAYS AT LONDON WEATHER CENTRE

By H. V. FOORD

Summary. The number of consecutive wet days at London Weather Centre for summer and winter half-years from 1946 to 1971 was analysed to show the chances of completing an outdoor task requiring one dry working day if it were possible to allot one, two or three days to the project.

Introduction. Weather centres receive many requests regarding the possibility of performing a certain task on some days in the future, when the critical weather element is the absence of appreciable rainfall during the working day. Typical examples are: one-day building and decorating jobs, such as concreting, external paintwork or roof repairs; personal sporting activities, such as tennis or golf; outdoor social events, such as garden parties or presentations. Clearly the allocation of two or more days to the project (i.e. the task to be completed on the first day if dry; if not, then on the second day and so on) would result in a much higher probability of successful completion, but a quantitative assessment of probability has not hitherto been made.

Relevant information is not readily available, because most published rainfall data include periods outside the normal working day. An investigation was therefore made into the incidence of consecutive wet working days at London Weather Centre.

Procedure. The rainfall at London Weather Centre was analysed for the 25 years from April 1946 to March 1971 inclusive, yielding 25 summer half-years, from April to September inclusive, and 25 winter half-years, from October to the following March inclusive. The *Meteorological glossary* defines a wet day* as having one millimetre or more of rain in 24 hours, and wet working days for this investigation were classified as days when the rainfall between 09 and 18 GMT was one millimetre or more.

Frequency of consecutive wet working days. Table I shows the frequencies of single wet working days and sets of consecutive wet working days, as defined above, for each month and the total frequencies over the 25-year period. However, in order to decide the chances of achieving dry weather on one day by allotting a certain number of consecutive days to a

London, Meteorological Office. Meteorological glossary. London, HMSO, 1972, p. 314.*

project, sets with a high number of consecutive wet days must be taken to contribute to the sets of lower numbers of consecutive wet days, i.e. three consecutive wet days also count as three single wet days and as two occasions of two consecutive wet days, and so on. These cumulative frequencies are given in Table II for each month, together with the total frequencies for the 25-year period. The cumulative averages are given in Table III together with the annual averages and standard deviations and the monthly cumulative averages for the whole period.

Figure 1 shows the frequency distribution of the annual cumulative totals of single wet working days, whilst Figure 2 shows the frequency distribution for the annual cumulative totals of pairs of consecutive wet working days.

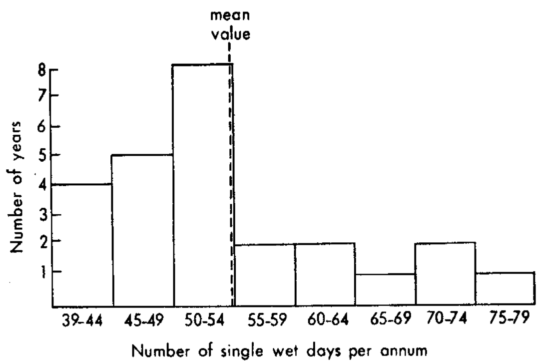

FIGURE 1—FREQUENCY DISTRIBUTION OF ANNUAL CUMULATIVE TOTALS OF SINGLE WET DAYS

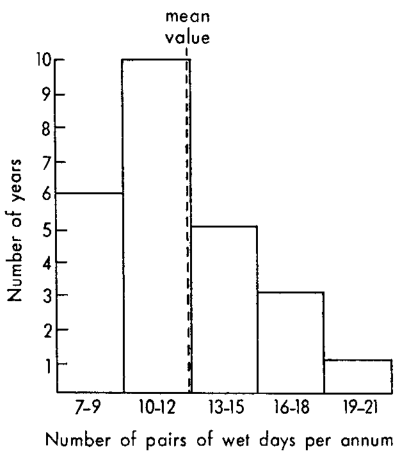

FIGURE 2—FREQUENCY DISTRIBUTION OF ANNUAL CUMULATIVE TOTALS OF PAIRS OF WET DAYS

Figures 1 and 2 both show that about 2/3 of the annual totals were at or below the mean annual value, with the wetter extremes in Figure 1 being thinly scattered. The distributions about the means are therefore not normal.

TABLE I—TOTALS OF CONSECUTIVE WET WORKING DAYS, APRIL 1946 TO MARCH 1971

	Consecutive wet working days					
	1	2	3	4	5	6
Jan.	67	14	4	0	0	0
Feb.	55	13	5	1	1	0
Mar.	58	13	2	1	0	0
Apr.	68	15	5	0	0	0
May	74	15	2	0	0	0
June	69	11	4	1	0	0
July	67	11	3	0	3	0
Aug.	73	18	4	2	0	0
Sept.	74	16	2	1	0	0
Oct.	75	12	5	0	0	0
Nov.	73	16	3	0	0	1
Dec.	75	17	2	1	0	0
Total for 25 years	828	171	41	7	4	1

TABLE II—CUMULATIVE TOTALS OF CONSECUTIVE WET WORKING DAYS, APRIL 1946 TO MARCH 1971

	Consecutive wet working days					
	1	2	3	4	5	6
Jan.	107	22	4	0	0	0
Feb.	105	30	10	3	1	0
Mar.	94	20	4	1	0	0
Apr.	113	25	5	0	0	0
May	110	19	2	0	0	0
June	107	22	6	1	0	0
July	113	29	12	6	3	0
Aug.	129	32	8	2	0	0
Sept.	116	23	4	1	0	0
Oct.	114	22	5	0	0	0
Nov.	120	27	7	3	2	1
Dec.	119	24	4	1	0	0
Total for 25 years	1347	295	71	18	6	1

TABLE III—CUMULATIVE AVERAGES OF CONSECUTIVE WET WORKING DAYS, APRIL 1946 TO MARCH 1971 INCLUSIVE

	Consecutive wet working days					
	1	2	3	4	5	6
Jan.	4·3	0·9	0·2	0	0	0
Feb.	4·2	1·2	0·4	0·1	0·04	0
Mar.	3·8	0·8	0·2	0·04	0	0
Apr.	4·5	1·0	0·2	0	0	0
May	4·4	0·8	0·1	0	0	0
June	4·3	0·9	0·2	0·04	0	0
July	4·5	1·2	0·5	0·2	0·1	0
Aug.	5·2	1·3	0·3	0·1	0	0
Sept.	4·6	0·9	0·2	0·04	0	0
Oct.	4·6	0·9	0·2	0	0	0
Nov.	4·8	1·1	0·3	0·1	0·1	0·04
Dec.	4·8	1·0	0·2	0·04	0	0
Annual mean	53·9	11·8	2·8	0·7	0·2	0·04
Annual standard deviation	8·1	3·4	2·0			
Monthly mean	4·5	1·0	0·2	0·06	0·02	0·003

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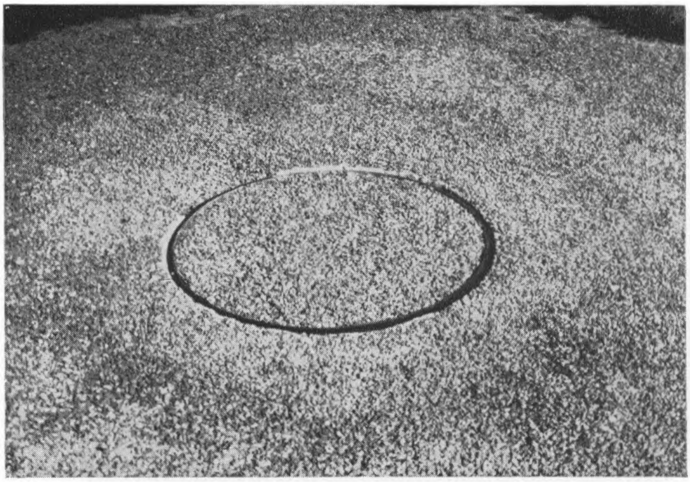

PLATE I—CLOSE-UP OF RAIN-GAUGE AREA SHOWING GRANITE CHIPS COVERING GAUGE AND SURROUND

See page 370.

PLATE II—GENERAL VIEW TOWARDS THE SOUTH-WEST WITH RAIN-GAUGE AREA IN FOREGROUND

See page 370.

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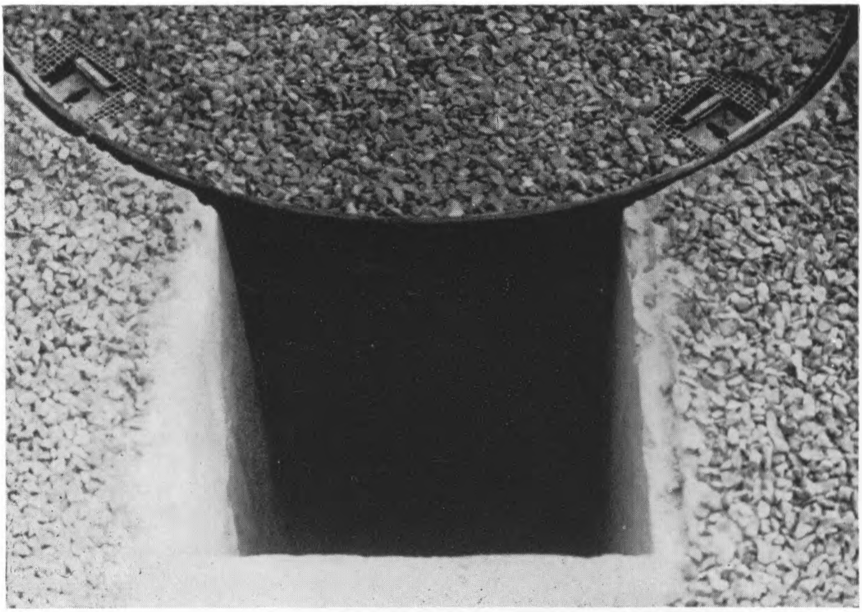

PLATE III—CLOSE-UP OF RAIN-GAUGE SHOWING STAINLESS-STEEL MESH

The access shaft is covered over when the rain-gauge is in use and is hardly visible, see Plate I, See page 370.

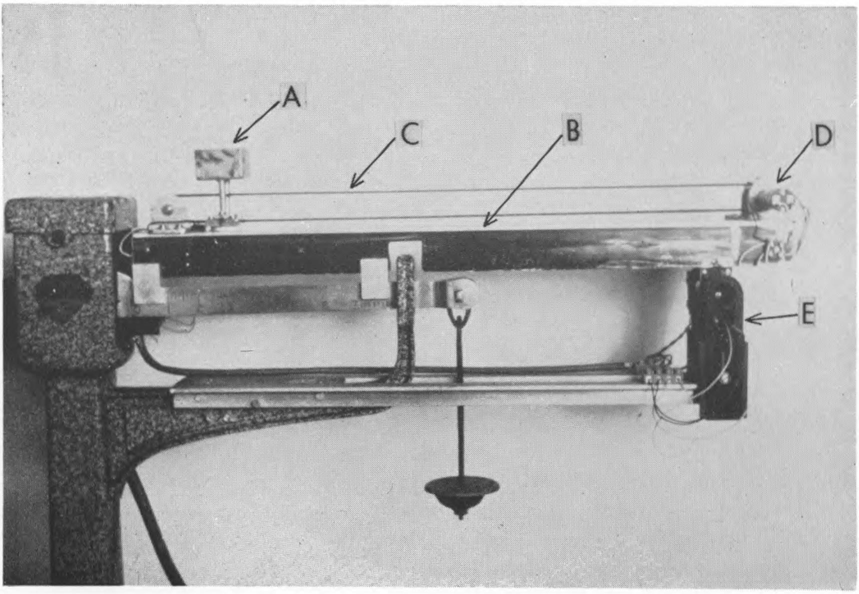

PLATE IV—WEIGHING-MACHINE USED IN GRAVIMETRIC RAIN-GAUGE

For identification of letters see page 370.

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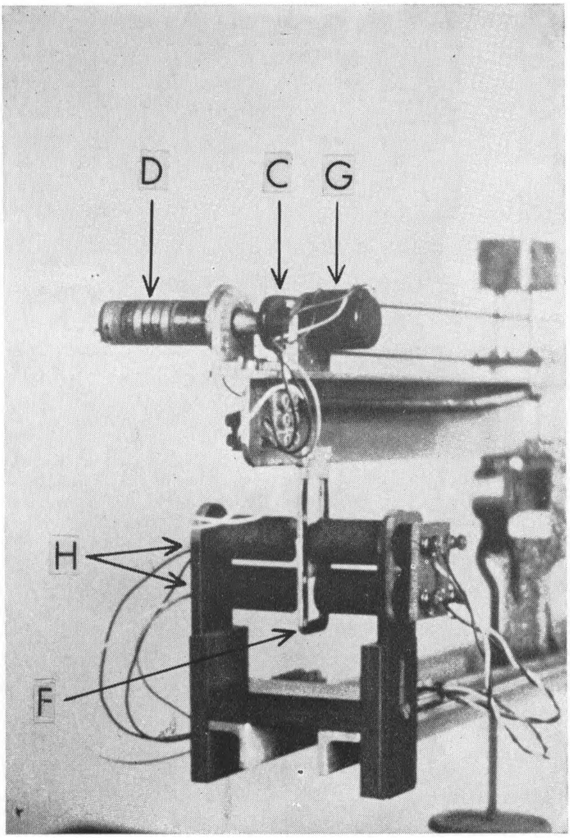

PLATE V—CLOSE-UP OF WEIGHING-MACHINE SHOWING AUTOMATIC BALANCING MECHANISM

For identification of letters see page 371.

Results.

Average annual data. In the period under review Table III shows that there were on average :

54 wet working days in each year (lowest total 39, highest total 78) with a standard deviation of 8·1,
12 pairs of wet working days in each year (lowest 7, highest 21) with a standard deviation of 3·4,
3 trios of wet working days in each year (lowest 0, highest 9) with a standard deviation of 2·0,
1 quartet of wet days approximately every other year,
1 quintet of wet days every 5 years,
1 sextet of wet days every 25 years.

Average monthly data. Similarly there were, on average, during the period under review :

between 4 and 5 wet working days in each month (lowest total 0, highest total 13),
1 pair of wet days in each month (lowest 0, highest 7),
1 trio of wet days in every 5 months (lowest 0, highest in one month 5),
1 quartet of wet days in every 16 months,
1 quintet of wet days in every 50 months,
1 sextet of wet days in every 300 months.

Probabilities. Using these past records therefore, anyone seeking to complete a one-day project in dry weather is :

85 per cent likely to complete if allotting only one day,
97 per cent likely to complete if allotting two consecutive days,
99 per cent likely to complete if allotting three consecutive days,

or, to put it another way, the likelihood of rain preventing completion is :

just under 6 to 1 against if only one day is allotted to a task;
30 to 1 against if two consecutive days are allotted;
122 to 1 against if three consecutive days are allotted.

Discussion. In 3 of the 25 years analysed there were no occurrences at all of three consecutive wet working days; in 15 of the years there were no occurrences of four consecutive wet days.

There were 13 individual months in the total period without any wet working days at all; these were quite evenly distributed through the year, one case occurring in each of February, March, July, August, September, October and December, and two cases in each of January, April and June. However, May and November always had at least one wet working day during this 25-year period.

The cumulative totals show that the monthly distribution is reasonably constant, but the number of wet spells rises to a peak in July, with August having a large number of pairs of wet days. February and November are the other months prone to consecutive wet days. However, one spell of six consecutive wet days in November tends to distort the cumulative figures for that month, which otherwise would have been very similar to October.

Whilst the variation in wet working days from month to month is small, the difference between summer and winter is remarkably small also. In fact the number of wet working days in the period October to March is slightly lower than in the period April to September. This could suggest convective influences giving rise to persistent showery situations in high summer.

During most of the period under review either British Summer Time or Double British Summer Time was in operation and thus for a part of most years the normal working day started and finished earlier than the GMT hours used in the investigation. Perusal of the records revealed that quite often in the summer months the only rainfall was a heavy shower late in the day. The results shown here which refer to 09–18 GMT are therefore likely to be pessimistic compared with a working day of 09–18 BST, so the chances of dry weather in the summer half of the year should be greater than shown.

551.501.3

SI UNITS IN THE METEOROLOGICAL OFFICE

By F. E. LUMB

Summary. This article discusses the use of the International System of Units within the Meteorological Office.

Introduction. It is Government policy to introduce metric units in the United Kingdom by 1975,[1] based on the International System of Units (SI). A recent Government publication[2] indicates the state of progress towards metrication and the various agreements which will be required on entry to the European Economic Community. For the introduction of some units there may be a delay beyond 1975, but the maximum practicable progress towards the metric system is to be made within the next few years.

SI units. The British Standards Institution (BSI) and the Royal Society have for some time been encouraging users (schools, universities, industry) to adopt the SI, which uses the seven base units listed in Table I, in order to establish a familiarity with metre, kilogram, second units in practice before the eventual national change-over, and to avoid any unnecessary confusion with other forms of metric units such as are used in the c.g.s. system. The metre, kilogram, second units are large enough to satisfy general needs for practical measurements as well as for laboratory work and give a coherent system of derived units. Table II lists four important derived units with special names which are of fundamental importance in meteorology.

TABLE I—SI BASE UNITS

Quantity	Unit	
	Name	Symbol
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Luminous intensity	candela	cd
Amount of substance	mole	mol

TABLE II—FOUR IMPORTANT SI DERIVED UNITS WITH SPECIAL NAMES

Quantity	Unit	
	Name	Symbol
Force	newton	N (see below for definition)
Energy, work, quantity of heat	joule	J (see below for definition)
Power	watt	W (1 W = 1 J/s)
Pressure	pascal	Pa (1 Pa = 1 N/m^2)

Definitions

newton: the force that produces an acceleration of 1 m/s^2 when applied to a mass of 1 kg.

joule: work done by a force of 1 newton in moving the point of application 1 metre in the direction of the force.

In addition, several units of great practical importance or useful in specialized fields of scientific research are to be retained. These include the degree Celsius; bar; degree, minute and second (of angle); and the minute, hour and day (of time).

Full details of SI units and of units outside the SI which are to be retained are given in a recent BSI publication.[3]

Between now and the national change-over the Meteorological Office wishes to co-operate in helping to publicize SI units, e.g. by encouraging the use of these units in Office publications. Wherever possible, texts will use SI units alone, but since meteorological work done in co-operation with other authorities may have to be presented in units commonly used in the United Kingdom by the authorities concerned, traditional units may be necessary for a time. If such units are used, SI equivalents or conversion factors will be given to help readers to gain familiarity with SI units before the complete changeover.

Some common meteorological units.

(a) *Millibar.* The millibar will be retained in name though its relation to the SI unit of pressure, the pascal (Pa), should be noted. Since the pascal is defined as the newton per square metre, it follows that the millibar is 100 pascals, or, in symbolic form, $1 \text{ mb} = 10^2 \text{ Pa}$.

In international journals the abbreviation mbar is being adopted because b is the symbol used for a unit (outside the SI) for effective cross-sectional area (the barn), but Meteorological Office publications are continuing to use the abbreviation mb since there is no possibility of confusion with the barn.

(b) *Temperature.* The base unit is the kelvin (abbreviation K), the degree symbol (°) having been dropped as unnecessary. The degree symbol is still required for Celsius temperatures (e.g. 5°C) but degC can be used to express a temperature difference (e.g. 5 degC).

(c) *Radiation flux.* The SI unit is the watt per square metre but the unit recommended by the World Meteorological Organization is the milliwatt per square centimetre, which is equivalent to 10 W/m^2.

(d) *Specific heat.* The joule replaces the various calories as the unit of heat so that in SI units specific heat is expressed in joules per kilogram per kelvin, or, in symbolic form, J/(kg K).

(e) *Distance.* For some time there will be a requirement for nautical miles and statute miles, and appropriate conversion factors will be quoted. Many conversion problems are easily solved by using duplicate scales on diagrams, e.g. feet and kilometres on cross-sections, each scale having its own natural steps of units.

Soil and earth temperatures are usually measured at depths of 5, 10, 20, 30 and 100 cm but some United Kingdom measurements are still made at 122 cm (4 ft). The bulbs of thermometers in the screen should be at 1·25 m above the ground but 4 ft (1·22 m) is acceptable for existing screens.

(f) *Speed.* The knot is the unit recommended by the World Meteorological Organization for horizontal wind speed for the time being, although a change to metres per second is envisaged for the future. The conversion $1 \text{ kt} \approx 0{\cdot}5 \text{ m/s}$ is sufficient for most practical purposes.

It is reasonable to use knots to give speeds of depressions, etc., especially when such speeds are to be compared with wind speeds in knots. If distances are measured in kilometres, the kilometre per hour (km/h) may be appropriate. The abbreviation kt is at present used in Meteorological Office publications but kn is being used increasingly in international publications to avoid confusion with kilotonne (kt), the tonne (t) being 10^3 kg. Vertical speeds will be given in metres per second, except that for a time there may be some requirements in aviation (e.g. for gliders) and perhaps also in balloon calculations for the use of feet per minute.

(g) *Rainfall.* Depth of rainfall is now generally given in millimetres and it may be noted that 5 mm, for example, is equivalent to 5 kg/m^2 in SI units.

Series of data. A major problem arises with series of data over a long period of years including readings in different units. For example a series may contain 50 years of data in inches of rainfall and 5 years in millimetres, but with computer help there is little difficulty in using millimetres as the common unit. There may be other reasons for treating the series as two separate parts but results of calculations should be given in metric units. Similar problems arise with Fahrenheit and Celsius.

Acknowledgement. The author is indebted to Mr W. S. Garriock for much of the content of this paper, which is based on a report prepared by him for the Publications Committee of the Meteorological Office.

REFERENCES

1. London, House of Commons. Parliamentary Debates (Hansard). Vol. 713, No. 121, 24 May 1965, written answers, p. 33. London, HMSO, 1965.
2. London, Department of Trade and Industry. Metrication (Cmnd. 4880). London, HMSO, 1972.
3. London, British Standards Institution. The use of SI units (PD 5686). London, 1972.

551.508.77

A RECORDING GRAVIMETRIC RAIN-GAUGE — TOWARDS AN ABSOLUTE REFERENCE INSTRUMENT

By S. G. CRAWFORD

Introduction. Definitions of rainfall[1,2] usually state or imply that the ideal gauge should catch the precipitation which would have fallen on to an equivalent area of the ground had the instrument not been there. It has long been appreciated that the precipitation gauges commonly in use throughout the world fall short of this ideal mainly because of two principal sources of error.

If the receiving orifice is above ground level the instrument disturbs the natural airflow in a way which results in the deflexion of some of the raindrops, and a consequent loss of catch. Attempts to counteract this effect by the use of special shields appear not to have been successful.[3] Various modifications to the profile and internal shape of the gauge have been tried but inconsistencies in performance have not been eliminated.[4,5] Reynolds[6] has pointed out that even if field trial comparisons of gauges did give reproducible data on their relative accuracy, information about their absolute accuracy would still be lacking, and it is this property which it is most important to establish. McCulloch[7] considers that the question 'How can point precipitation be measured to a known degree of accuracy?' is a fundamental problem of hydrology.

If the receiving orifice of the collector is brought down to ground level there is a risk that splashes from the nearby ground will carry additional water into the gauge. Various measures to subdue splashing or prevent splashes getting into the ground-level ('flush') gauge have been described by Bleasdale[8] who also proposed an ingenious anti-splash surround[9] which is in use at Kew Observatory in conjunction with an experimental comparison of evaporimeters. At Valdaj (the principal hydrological station of the U.S.S.R.) the upper surface of an extensive area of compact bushes, trimmed to a uniform height, surrounds a gauge having its orifice at the same level.[10] Because it is well known that a flush rain-gauge with 'anti-splash surround' collects more than a rain-gauge with its orifice above ground level, there has sometimes been a tendency to suppose that the flush-gauge catch is therefore 'correct'. It should be borne in mind that the various types of anti-splash surround, whether in the form of sloping slats resting on the ground or a grid accommodated in a shallow pit, constitute surfaces different from that of the surrounding terrain. It is possible, therefore, that they, too, may give rise to aerodynamically induced errors. Indeed, even if splashing is proved to be absent by an independent check such as the chemical tracer test used by Green,[11] the fact that the orifice of the collector is a 'hole' while the natural ground is 'solid' may raise doubts about the reliability of such rain-gauges, whether single or nine-hole.

The problem of eliminating disturbances caused by the instrument itself has been encountered in other investigations, notably the direct measurement of evaporation from a natural surface by weighing. Here, the use of the lysimeter is a well-established technique,[12] and it has been suggested[6] that a rain-gauge constructed to work on a similar principle would provide a 'standard' or 'absolute reference' against which other types of rain-gauge could be assessed. A description of such a rain-gauge, as realized at Kew Observatory, follows.

The collector and surround. In order to collect a representative sample of rain the container should be about a square metre in area and have its upper collecting surface identical and level with the surrounding ground. Any splashing should then cancel out across the perimeter. By using a circular collector the perimeter is kept to a minimum for a given area. A container of suitable size readily to hand was an American Class A evaporation pan, diameter nominally 120 cm. Its depth, 30 cm, is rather larger than necessary but not inconvenient. Careful measurements of the diameter indicated that 1 mm of rain over this area would weigh 1·146 kg.

It was anticipated that even if it were possible to simulate the grass-covered terrain of the experimental site there would be practical difficulties in ensuring that rain intercepted by such a surface would drain off rapidly enough into the collecting pan. Whipple[13] had shown experimentally that a surface of gravel was very effective in suppressing splashing. It was therefore decided to use a similar surface composed of small granite chips. In order to minimize changes in aerodynamic roughness which might affect the airflow across the collecting pan, the grass on the immediately surrounding annular area 180 cm wide was removed by weed killer and the area was then completely covered with similar granite chips. Thus, apart from an essential gap a few millimetres wide between the pan and the surrounding 'guard ring', the receiving surface is virtually indistinguishable from the adjacent terrain (Plate I). The experimental site is flat, level and free of obstructions for 50 to 100 metres in all directions. Plate II shows a general view towards the south-west.

Four stout lugs are fixed just below the top of the inner wall of the pan for lifting purposes. About 2·5 cm below the top a strong stainless-steel mesh covering the whole area of the pan is supported on tightly stretched wires. The 18-gauge wire of the mesh is spaced at 8-mm intervals and provides adequate support for the granite chips which are typically 12 mm long (Plate III). The dry weight of the complete collector is about 82 kg. Although nothing is visible through the layer of granite chips, water can flow quite readily between them into the pan. The water which collects in the pan is removed by pumping out from time to time as part of the routine maintenance of the installation.

The weighing-machine and pit. The collecting pan is supported on an aluminium frame which is bolted to the platform of a bench-type weighing-machine of nominal capacity 100 kg. The whole assembly stands in a cylindrical concrete-lined pit, the height of the frame having been adjusted so that the top of the pan is level with the surrounding ground. The dry weight of the pan and frame is balanced by small weights added to the pendent tray.

Preliminary tests showed that the jockey weight on the balance arm ('steel-yard') of the unmodified machine would give an indication of the load reproducible to within 60 g (this is equivalent to 0·05 mm of rain). This sensitivity was adequate for the present purpose. The working length of the original brass balance arm was 18 cm. In order to increase the capacity a longer piece of T-angle aluminium was bolted to it. Overall length was limited by the wall of the pit and after fitting other attachments the working length for the movement of the jockey weight was 38 cm (Plate IV).

The original jockey weight was removed and replaced by one of special design (Plate IV A) which slides along the upper flat surface of the aluminium arm (IV B). A small flat disc of polytetrafluoroethylene fixed to the underside of the jockey secures smooth motion without additional lubrication. The lower part of the jockey is clamped to a driving belt (IV C); the upper part is in the form of a small brass box. By putting the correct amount of lead into this box the overall weight of the jockey can be adjusted so that its maximum displacement along the arm corresponds to a convenient quantity of accumulated rainfall. At present the weight of the jockey is 354 g, equivalent to an accumulated rainfall of 50 mm. By decreasing the weight of the jockey, and accepting a reduced capacity, the sensitivity of the machine could be further increased to a limited extent, depending on the frictional resistance of the pivots.

The automatic balancing mechanism. The jockey is moved by an endless non-slip driving belt which passes over toothed pulley wheels at either end of the beam (Plate V C). One of the wheels is driven by a small d.c. motor (IV and V D) working through a reduction gear-box. This wheel is fixed to the shaft of a high-resolution precision potentiometer (V G) which produces an electrical output proportional to the displacement of the jockey. The combined unit with supporting brackets weighs about 120 g. It is mounted at the outer end of the beam where its weight helps in backing-off the main load. The wires connected to the motor and potentiometer are brought along the side of the beam to a point as near as possible to the pivot end before passing to a terminal block fixed to the pillar of the machine. The polarity of the current to the motor is determined by two relays which are actuated by a simple optical switch (Plate IV E) so as always to be in a direction which causes the jockey to be driven towards the position of equilibrium. This results in a record which is slightly spread about its mean value as a result of the jockey hunting around the balance point (Figure 1). A micro-switch is interposed near each end of the beam so that if the jockey reaches an extreme position it switches off the current to the motor.

The optical switch. At the outer end of the beam, and fixed to its lower edge, is a small thin rectangular metal plate (Plate V F), the vertical movement of which alternately exposes the light directed towards two photo-sensitive cells (V H). The optical arrangement is such that the cut-off is very sharp and the 'dead-space', when neither relay is energized, is minimal. The extreme movement of the beam is limited by a pair of end stops (not shown in Plates IV and V) the separation of which has been reduced to the smallest value compatible with the exposed light being sufficient to operate the photo-cells.

All the electrical components at the weighing-machine are connected to their various supplies via a lead-covered multicore cable laid between the rain-gauge pit and a nearby underground chamber.

The light is from two 3·5-volt torch-bulbs which are under-run at 3·0 volts to prolong their life. They are supplied from a small mains transformer and rheostat. The light-sensitive units are photo-conductive cells whose large change of resistance with illumination triggers transistors controlling the relays. The latter are housed in a small box which also contains the other components required to operate the unit from mains supply.

The motor supply. The current for the motor is from a small mains transformer and rectifier. The voltage to the motor can be varied up to its full rating (28 V d.c.) to give a selection of speeds. For the main purpose of the gauge the tracking speed of the jockey is not important, but if rates of rainfall are to be inferred the speed must be sufficient to cope with the probable maximum. The highest rate of rainfall ever recorded at Kew over one minute is 300 mm/h.[14] The motor supply has been set at 10 V which gives a speed corresponding to about 400 mm/h.

The transducer. A millivolt analogue of the position of the jockey is provided by a precision 10-turn 5000-ohm potentiometer (Plate V G). To drive the jockey the full length of the beam requires $5\frac{1}{2}$ turns of the shaft. The resolution of the potentiometer, 1·4 in 10^4, is more than adequate for this purpose.

The potentiometer is supplied with about 30 mV highly-stable d.c. (better than 1 in 2000) from a mains-operated unit. The actual value is adjusted so that maximum traverse of the jockey produces full-scale deflexion on the recorder.

The recorder. The recorder is a multi-channel self-balancing potentiometer. In order to avoid errors due to possible slight misalignment between the printing type blocks, only one channel is connected to the transducer. It prints a small dot once per minute. Another channel is connected to a clock which produces a time mark every hour and a zero-reference record in between. An example of a rainfall record is shown in Figure 1.

The chart is usually driven at 1 inch per hour but can be run faster for special purposes, e.g. calibration. It has 100 divisions in a width of 25 cm. Using a vernier scale the record can be read to 0·05 division, so that with the 354-g jockey the difference between two readings might be subject to a maximum error equivalent to 0·05 mm of rain. A lighter jockey increases the resolution. The linear response of the recorder itself is separately checked from time to time.

Calibration. The weighing-machine is calibrated by simply adding weights to the collecting pan up to full-scale deflexion on the recorder and then removing them. The buoyancy error in substituting iron weights for the water to be collected (about 0·1 per cent) is negligible. To avoid pressure on the granite chips and their supporting grid, the weights are placed on a board set diametrically across the pan and resting on the rim. The chart is run at 50 mm per hour for clear separation of the dots. It has been found that 10 successive dots provide an average value reproducible to 0·01 division. The graph of displacement against load is linear. For the four calibrations made at intervals during the first two months of operational recording the slope of the line remained at 1·85 divisions per kilogramme, to within 0·1 per cent. This is equivalent to 0·480 mm rain per chart division, which is the factor used in scaling the rainfall record.

Evaporation. There is the question of evaporation from the collecting pan during the time rain is falling. Relative humidity during rainfall is generally below 100 per cent and may be as low as 80 per cent, even in a heavy shower. The gravimetric rain-gauge record shows the loss by evaporation quite clearly after the rain ceases (Figure 2). As would be expected the rate of evaporation during the time the granite chips are still wet is mainly affected by the meteorological conditions, with radiation predominating. The maximum rate observed so far (winter only) has been the equivalent of 0·07 mm/h. Once the stones are dry, a state which is very clearly revealed by their change of colour from almost black to light grey, evaporation from the water inside the pan is extremely slow and is probably mainly dependent on the stored heat. The records of evaporation under various conditions will provide a basis for estimating quite closely the loss during rain.

Any correction for evaporation during rain would usually be very small. There is some doubt, however, whether it should, in fact, be made at all. Rain falling on to the ground is also subject to evaporation, though the rate is likely to differ somewhat for different types of surfaces.

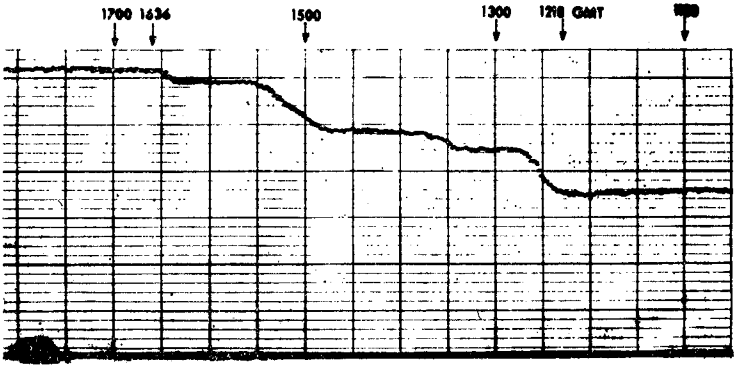

FIGURE 1—EXAMPLE OF A RAINFALL RECORD BY THE GRAVIMETRIC RAIN-GAUGE, 24 JANUARY 1972

The start of the trace shows evaporation after earlier rain. Continuous rain of varying intensity between 1218 and 1636 GMT gave a total of 6·41 mm. (1 large division = 2·4 mm.)

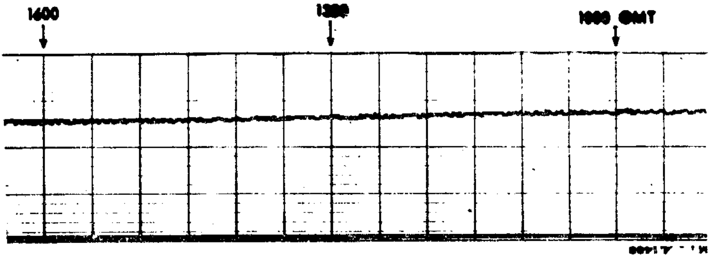

FIGURE 2—EXAMPLE OF EVAPORATION AFTER EARLY MORNING RAIN, 23 JANUARY 1972

Evaporation resulted in a loss of 0·33 mm. Weather was cloudy.

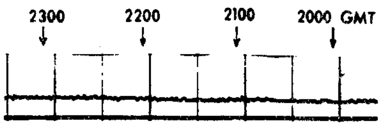

FIGURE 3—EXAMPLE OF CONDENSATION, 15 DECEMBER 1971

Condensation between 2000 and 2300 GMT resulted in 0·14 mm of dew.

Condensation. On clear nights when radiative cooling is pronounced, conditions are favourable for the deposition of dew or hoar-frost. On such occasions the deposit may be abundant on grass while meagre or even absent on bare soil, concrete, tarmac, etc. In the first two months of operation the gravimetric rain-gauge has clearly indicated the weight of the deposit on a number of occasions. In one case the equivalent of 0·14 mm was deposited in 3 h (Figure 3). When a period of rainfall is followed by a period of condensation it is necessary to refer to some other record in order to distinguish the two. At Kew the records from a radiation balance meter[15] or a rainfall chronograph[16] are used.

Experimental programme. The gravimetric rain-gauge is being used as a reference against which to assess the performance of other types of rain-gauge. At present these comprise two 5-inch Mk II gauges set at the standard height of 30 cm and one installed as a flush gauge with anti-splash surround.[9] The time of reading each of these rain-gauges is noted and the gravimetric rain-gauge chart is scaled over exactly the same interval. The limited results over the first two months of operation show, as might be expected, a relation between the gauges similar to that indicated in other work. It will, of course, be some time before sufficient comparison data covering a wide range of meteorological conditions are obtained.

Acknowledgements. The author is grateful to Mr R. H. Collingbourne, Mr D. R. Grant and Mr A. Bleasdale, all of the Meteorological Office, for very helpful discussions and suggestions. The electronics of the optical sensing device were due to Mr T. Stockhill of Action-Video Ltd. The construction and assembly of the modifications to the weighing-machine and collecting pan were skilfully engineered by Mr W. Wright in the Kew Observatory workshop.

REFERENCES

1. London, Meteorological Office. Observer's handbook. 3rd edition. London, HMSO, 1969, p. 131.
2. Geneva, World Meteorological Organization. Guide to meteorological instrument and observing practices. 4th edition. Geneva, 1971.
3. RODDA, J. C.; The rainfall measurement problem. Gentbrugge, International Association of Scientific Hydrology. Geochemistry, precipitation, evaporation, soil moisture, hydrometry. Gentbrugge, IASH Publication No. 78, 1968, pp. 215–231.
4. BLEASDALE, A. and RIDER, N. E.; Rain, wind and the aerodynamic characteristics of rain-gauges. *Met Mag, London*, **98**, 1969, p. 126.
5. CLARKSON, L. S.; On the performance of various types of rain-gauge in the field. *Met Mag, London*, **100**, 1971, pp. 241–255.
6. REYNOLDS, E. R. C.; The accuracy of rain-gauges. *Met Mag, London*, **93**, 1964, pp. 65–70.
7. MCCULLOCH, J. S. G. [McCullouch, J. F. G.]; Lord Rothschild and the Institute of Hydrology. *Nature, London*, **235**, 1972, p. 8.
8. BLEASDALE, A.; Hydrology and British rainfall. *Met Mag, London*, **86**, 1957, pp. 206–210.
9. BLEASDALE, A.; The measurement of rainfall. *Weather, London*, **14**, 1959, pp. 12–18.
10. GOLUBEV, V. S.; The correct measurement of precipitation with a Tret'jakov precipitation gauge. *Trudy Gos Gidrol Inst, Leningrad*, **181**, 1970, pp. 87–97.
11. GREEN, M. J.; Effects of exposure on the catch of rain gauges. *Tech Pap Wat Res Ass, Medmenham*, No. 67, 1969.
12. GRANT, D. R.; Some measurements of evaporation in a field of barley. *J Agric Sci, Cambridge*, **75**, 1970, pp. 433–443.
13. WHIPPLE, F. J. W.; Rainfall as measured by gauges set in turf, gravel and concrete. *Met Mag, London*, **70**, 1935, pp. 32–34.
14. WHIPPLE, F. J. W.; A fifth of an inch in a minute. *Met Mag, London*, **69**, 1934, pp. 157–160.
15. MACDOWALL, J.; Total-radiation fluxmeter. *Met Mag, London*, **84**, 1955, pp. 65–71.
16. London, Meteorological Office. Handbook of meteorological instruments, Part I. London, HMSO, 1956, p. 282.

551.5:06

PLANS FOR TWO MAJOR METEOROLOGICAL RESEARCH EXPERIMENTS

Plans for two major meteorological research projects were discussed at two conferences held in Geneva in September 1972. These experiments fall within the Global Atmospheric Research Programme (GARP) which has been undertaken on a joint basis by the World Meteorological Organization (WMO) and the non-governmental body, the International Council of Scientific Unions (ICSU).

GARP Atlantic Tropical Experiment. The first experiment, known officially as the GARP Atlantic Tropical Experiment (GATE), which is scheduled for 1974, will involve the use of all modern meteorological observing techniques, including satellites, aircraft and ocean vessels. It will enable detailed scientific measurements to be made over about one-third of the world's tropical belt extending from the most western part of the Indian Ocean across Africa, the Atlantic Ocean, South and Central America to the most eastern part of the Pacific Ocean. Ships will be stationed over a large area of the Atlantic Ocean.

Particularly intensive measurements will be taken by radar-equipped oceanographic ships in a concentrated area of about 500 000 square kilometres centred at 25 degrees west and 10 degrees north in the eastern Atlantic. The present indications are that satellite observations will be obtained from American and U.S.S.R. satellites and that, in particular, a stationary satellite will be placed over the experiment area observing it 24 hours a day. About 12 to 15 specially equipped aircraft and about 25 scientific ocean research vessels will take part in the experiment, thus constituting what will probably be the biggest international fleet of ocean-going vessels ever assembled for peaceful purposes. While many of the highly developed countries of the world will be making substantial contributions to the experiment, its success will depend no less upon the active participation of the developing countries in the tropical regions of Africa and South America, and many countries from these regions, recognizing the scientific importance of the experiment, participated in the Conference. Senegal will have a particularly important role to play since Dakar will be the operational centre for the ships and aircraft taking part in the experiment.

An International Scientific Management Group (ISMG) will supervise the detailed arrangements for the planning and implementation of the experiment. The ISMG will conduct most of its activities at the headquarters of the Meteorological Office, U.K., where advanced computer facilities are available, and at the WMO secretariat in Geneva.

The main scientific aims of GATE will be to explore the primary energy source for the atmospheric circulations around the globe. This energy source lies in the tropical oceans which store the heat received from the sun. The mechanism by which this energy is transferred to the atmosphere is obscure, involving disturbances ranging from 10 to 10 000 km in size. These will be intensively observed by GATE, but once this mechanism is understood it is expected that advanced computer models will predict the daily weather not only in the tropics but at all latitudes for periods exceeding two weeks.

The First GARP Global Experiment (FGGE). This experiment, which is scheduled for 1977, will provide a global meteorological data set more complete than at any previous time in the history of meteorology. The scientific aims of the FGGE are to improve the knowledge and understanding of the global circulation of the atmosphere and of the physical basis of weather and climate and to develop more-realistic mathematical models for climate and extended-range forecasting.

The experiment, which will be of limited duration and based on recent technical and scientific advancements, will co-ordinate further work in these fields in all parts of the world.

WMO PRESS RELEASE

REVIEWS

Water balance of monsoon Asia, edited by M. Yoshino. 265 mm × 185 mm, pp. 308, *illus.*, University of Hawaii Press, Honolulu, 1971. Price: $16.

This beautifully printed and produced book is a collection of 15 papers by different authors, all of whom are Japanese. The studies concerned and the production of this book are connected with the International Hydrological Decade, and both were supported financially by the Japanese Ministry of Education. All parties involved are to be congratulated on a fine result, the usefulness of which is enhanced by good indexes both to the subject matter and to the authors cited — features which are far too rare in books compiled from the work of many authors.

The editor is professor of climatology in the Geography Department of the Hosei University, Tokyo, and has written a number of books, including a general climatology and another work devoted to small-scale climatology. He spent three years doing research at the University of Bonn and was later a visiting professor at the South Asian Institute of the University of Heidelberg. He is author or part author of three chapters in the book here under review.

The book is divided into five parts, all the parts and all the individual chapters being directed towards the water-balance theme but all interpreted in terms of a well-informed and up-to-date view of the role of the general atmospheric circulation, including such consideration of southern-hemisphere and complete Pacific patterns as is necessary. Much of the information given in the text and in the maps and diagrams will be new to readers outside Asia. Another unusually valuable feature is the well-balanced use of western (American, British, German, etc.), Russian, Chinese and Japanese sources listed in the 16 pages of bibliographies.

Very few faults were noticed. One, on page 7, is the unjustified assumption that all readers will know that Thornthwaite's 'famous PE index', which is mathematically defined, stands for precipitation effectiveness (not potential evaporation, as some readers of a chapter on 'Water balance problems . . .' are likely to expect). A few of the diagrams have inadequate captions; e.g. Figures 3 and 5 in the otherwise very good chapter on fluctuations of the rainfall in south-east Asia; in Figure 3 'moving average' appears to be a mistake for 'cumulative departure from average'; and in Figure 5 (a) the interesting plot of the rainfall in Peru, greatly varying from year to year in relation to sea temperatures in the equatorial Pacific and the El Niño phenomenon, neglects to mention to which years the rainfall refers.

There are many interesting topics treated in the book, most of all, perhaps, the transport of water vapour over the monsoon regions of Asia which constitute the wettest region of its size in the world and are characterized by a great year-to-year variability in rainfall. This inevitably involves consideration of the proportionately even greater variability of rainfall in the equatorial Pacific (derived from air masses which also affect Asia) and the great anomalies of sea temperature there. However, the main sources of the water vapour are identified as the air-mass sources in the regions of the subtropical anticyclones over the oceans, though there is a contribution from evaporation over land in summer. The mean northward meridional transport of water vapour has its maximum near the 850-mb level at 35°N and exceeds the contribution of the eddy transport. There is also a net southward flux of water vapour from the Arctic Ocean over Asia in summer. There are fascinating maps of frontal frequencies and rainfall by 10-day periods over east Asia from May to July, maps of the position frequencies of the polar front and intertropical convergence and related wind flow in January and July, maps of mean wind velocity, sensible-heat supply, evaporation and Bowen's ratio over the west Pacific in January 1961 and profiles from 0° to 150°E of upper atmospheric pressure levels along the parallels of 30°N and 40°N, the July profile at 40°N being plotted together with the correlation coefficients between 500-mb height at each longitude and the month's rainfall at Bangkok, Hong Kong and Saigon.

Several chapters are concerned with secular change; one of these reviews, with maps and diagrams, the changes of the last 20 000 years over Asia from the maximum phase of the last glaciation through the post-glacial warmest millennia and derives some interesting points in terms of shifts of the general circulation pattern in the Asian sector which were new to this reviewer. The diagram on page 19 showing secular changes since 1885 of the spring rains in China suggested to the reviewer that the 90-year and 22–23-year oscillations might be playing a part in the story, the latter period being mentioned in the text as the strongest feature. The biennial oscillation (and other less-known periods) is said to be present in the annual rainfall record at Seoul, Korea, from 1770. A chapter, interestingly devoted to the regionality of secular variation of rainfall over monsoon Asia, reviews correlation studies between different places, and comes to the conclusion that there are many rainfall regions there with different secular variations. Only in winter some more widespread regions of coherent rainfall variation were found, and the variations were (not unexpectedly) correlated with the Siberian anticyclone and Pacific polar-front activity.

For so much information not readily available elsewhere and a handsome volume the price is not unreasonable.

H. H. LAMB

Introduction to the scientific study of atmospheric pollution, edited by B. M. McCormac. 240 × 165 mm, pp. v + 169, *illus.*, D. Reidel Publishing Company, P.O. Box 17, Dordrecht, Holland, 1971. Price: Dfl. 25 (paperback).

With the enormous increase of interest in pollution of the environment and the corresponding unprecedented growth in literature on the subject, there is obviously a need for reliable and easily read summaries giving both a survey of the broad state of knowledge and a guide to further reading. This short book edited by B. M. McCormac, the editor of the recently inaugurated journal *Water, Air and Soil Pollution,* attempts this task for the multi-disciplinary aspects of air pollution.

There are chapters, contributed by several writers in U.S.A. and Canada, covering the types and sources of pollutants, meteorological aspects, effects on human health and vegetation, and the regular measurement of pollution. The science and technology of all the various aspects have taken on such detail and complexity that substantial condensation and selection has been required to keep within the 150 or so pages. Judged by the section on meteorology this has been carried out with good judgement and a realistic assessment of the present state of the subject. Some omissions and obscurities are inevitable, but these are harmless provided the reader realizes, as the authors clearly intend, that further reference to detailed writings and latest experience will usually be necessary in any detailed practical application. The non-meteorological aspects and the inevitable reflections on the philosophy of air-pollution abatement and control are presented objectively and without the sensationalism which is so easily engendered in the subject. Meteorologists will find these sections informative and a useful background to their own special professional interest.

The book is easy to read, and printing and illustrations are of good quality. In limp but serviceable covers the price is not unrealistic by current standards.

F. PASQUILL

Radar meteorology, edited by V. V. Kostarev, A. A. Chernikov and A. B. Shupyatskii. 245 × 175 mm, pp. v + 277, *illus.* (translated from the Russian by Israel Program for Scientific Translations, Jerusalem), Keter Press Ltd, 15 Provost Road, London NW3 4ST, 1971. Price: £6·30.

This book contains a collection of papers presented at a conference in April 1968 (not 1965 as stated in the Preface). The conference was held at the Central Aerological Observatory whose Radar Meteorology Group is one of the largest of its kind in the world. The papers cover theoretical and experimental aspects and they demonstrate the wide application of radar techniques in the U.S.S.R. in the field of meteorology and hydrology.

The papers are concerned with the application of radar in the following main areas :

(a) the measurement of surface rainfall rate, hail size, and the micro-physical properties of clouds;
(b) the measurement of winds and turbulence in the free atmosphere;
(c) absorption and scattering of radio waves in clouds,
(d) the nature and origin of radar echoes from the clear air;

and

(e) special radar equipment and data-processing techniques.

The papers vary greatly in standard; many, including some of the papers concerned with the quantitative measurement of rainfall rate, are marred by the use of 3-cm wavelength radars which suffer from problems of rainfall attenuation. Of particular interest, however, are papers dealing with the measurement of hail size, and of rainfall intensity, using multi-wavelength techniques. Also of interest are reports of the successful use of polarization techniques for distinguishing between radar echoes from ice crystals and those from raindrops.

Papers concerning Doppler radar techniques are few in number; they mainly deal with the measurement of raindrop size distributions and the structure of turbulence in the planetary boundary layer. There are some interesting measurements of anisotrophy and energy dissipation rate.

The studies of clear-air echoes are disappointing; 3-cm radars of moderate sensitivity were used and many of the clear-air echoes were non-meteorological in origin and were probably due to insects.

There is a notable awareness of the practical value of radar for monitoring and forecasting local weather. An automatic device for the rapid digital processing of radar data is described which it is envisaged by the authors may form the basis for the creation of a unified national weather radar network.

K. A. BROWNING

Fundamentals of aeronomy, by R. C. Whitten and I. G. Poppoff. 233 × 180 mm, pp. xiv + 446, *illus.*, John Wiley and Sons Ltd, Baffins Lane, Chichester, Sussex, 1971. Price: £7.

This book on aeronomy — 'the science of the upper atmosphere' — is one of the latest in the *Space science text series* edited by A. J. Dessler and F. C. Michel in collaboration with a group of distinguished associate editors. The first two chapters contain historical material and brief reviews of some basic ideas in electrodynamics, thermodynamics, kinetic theory of gases, atomic and molecular structure and spectra, collision processes, and chemical reaction kinetics. Chapters 3, 4 and 5 deal, respectively, with problems in physical, chemical and fluid aeronomy, and the remaining chapters with various optical phenomena, electric currents in the upper atmosphere, the structure of the lower, middle, and upper ionosphere, disturbances in the ionosphere, and the propagation of electromagnetic waves in the ionosphere. A set of problems is presented at the end of each of the main chapters, where references are also given.

The book is evidently intended for use in a two-semester course at the senior undergraduate year or first-year graduate level, but with such a wide range of material to cover, the course would inevitably amount to nothing more than a general survey. Nevertheless, the book serves as a useful introduction to a variety of geophysical problems and to several branches of basic physics and chemistry, and as such provides a guide to more advanced work on the subject.

R. HIDE

551.526.6:551.553

LETTER TO THE EDITOR

Coastal winds and cloud development

Mr Hindley,[1] in his description of a clear zone on the coast on 17 July 1971 has indicated that the cold coastal water is the reason for the lack of low-cloud development on the north-east coast (well shown on the satellite picture Plate I). On occasions such as this, when the flow is unstable north-north-westerly the lower surface temperature associated with the cold water anomaly, which is semi-permanent and caused by the strong tidal streams along this coast, is probably the main factor. However, on occasions when the sea-breeze is well developed, subsidence due to inland heating causing a sea-breeze circulation superimposed on the main stream often reduces maritime showers or disperses them altogether in the later morning and afternoon along the coasts. This is often very marked on the south coast of England and also in areas with onshore trade winds and monsoons.

Mr Rowles's[2] streamlines in his Figure 2, whilst naturally concentrating on the English side, would imply that the whole of the mid-Channel was a subsidence area, especially over the narrower portion, with streamlines flowing towards both coasts. This subsidence effect would also help to kill any convection over the middle of the Channel initiated by the slightly warmer water there.

Meteorological Office, B. RAMSEY
RAF Brüggen

REFERENCES

1. HINDLEY, D. R.; The importance of low sea surface temperatures in inhibiting convection along the North Sea coast in summer. *Met Mag, London,* **101**, 1972, pp. 155–156.
2. ROWLES, K.; Sea-breeze front near the south coast of England. *Met Mag, London,* **101**, 1972, pp. 153–154.

OFFICIAL PUBLICATION

The following publication has recently been issued :

Geophysical Memoirs

No. 116. British Isles weather types and a register of the daily sequence of circulation patterns, 1861–1971. By H. H. Lamb, M.A. (London, HMSO. Price: £3.)

The patterns of winds and weather which have occurred day by day over the British Isles each year from 1861 to 1971, i.e. over the last 111 years, are presented in a single volume in the form of a list of seven main types (or 26 types when all possible hybrids are recognized), illustrated by maps and explained by type definitions which describe the weather sequences which each type characteristically brings.

The classification of each day of the 111 years is given in an extensive table. The data so compiled are also analysed in a number of graphs and tables. These give an insight into the natural seasonal changes around the year, as the frequency of each weather type varies, including a fairly well-marked tendency for a recurrence of such changes about the same date in many years.

Other classifications made elsewhere in the world, especially those referring to the northern hemisphere, are also reviewed.

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