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RECENT PUBLICATION

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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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 Ludlam³; Ludlam⁴; Roach²).

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).

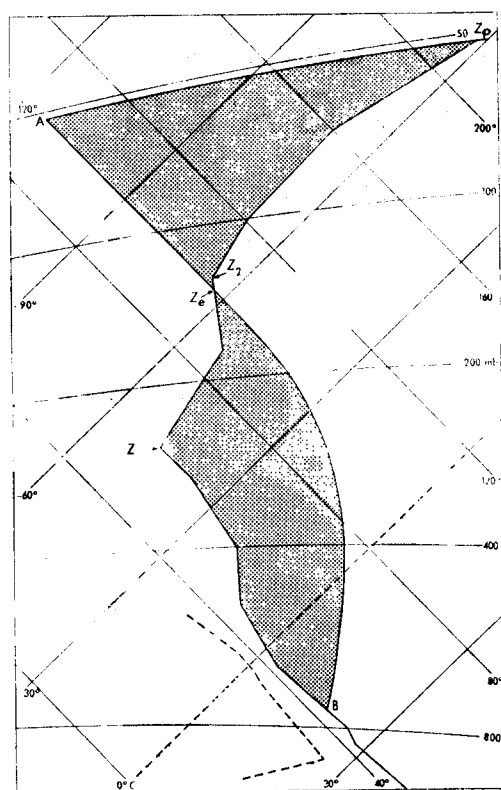


FIGURE 1—TEPHIGRAM SHOWING AN ASCENT OF GREAT POTENTIAL INSTABILITY

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 Kantor⁵; Kantor and Grantham⁶) 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

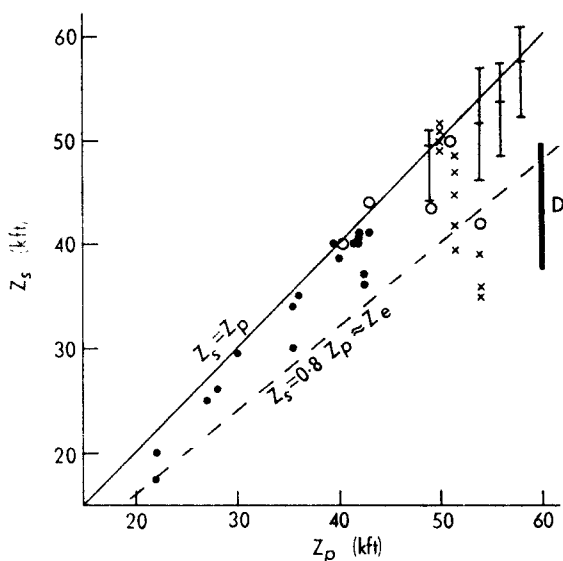


FIGURE 2—CORRELATION OF STORM-TOP HEIGHTS, Z_s , WITH PARCEL HEIGHT, Z_p

- 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 Deshpande¹³ 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 \approx 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.

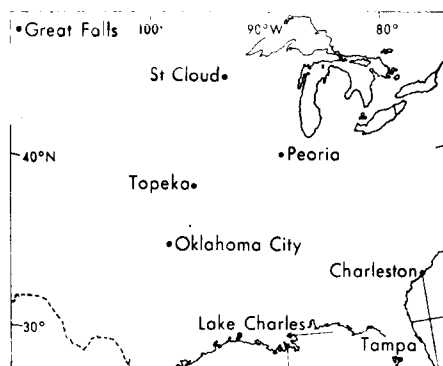


FIGURE 3—MAP OF UNITED STATES SHOWING STATIONS FOR WHICH Z_p WAS EVALUATED

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

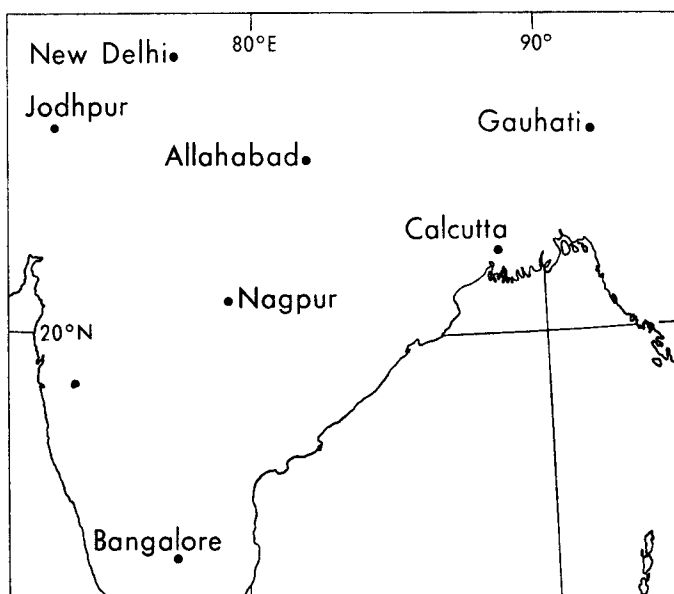


FIGURE 4—MAP OF INDIA SHOWING STATIONS FOR WHICH Z_p WAS EVALUATED

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 5.8 ± 1.2 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).

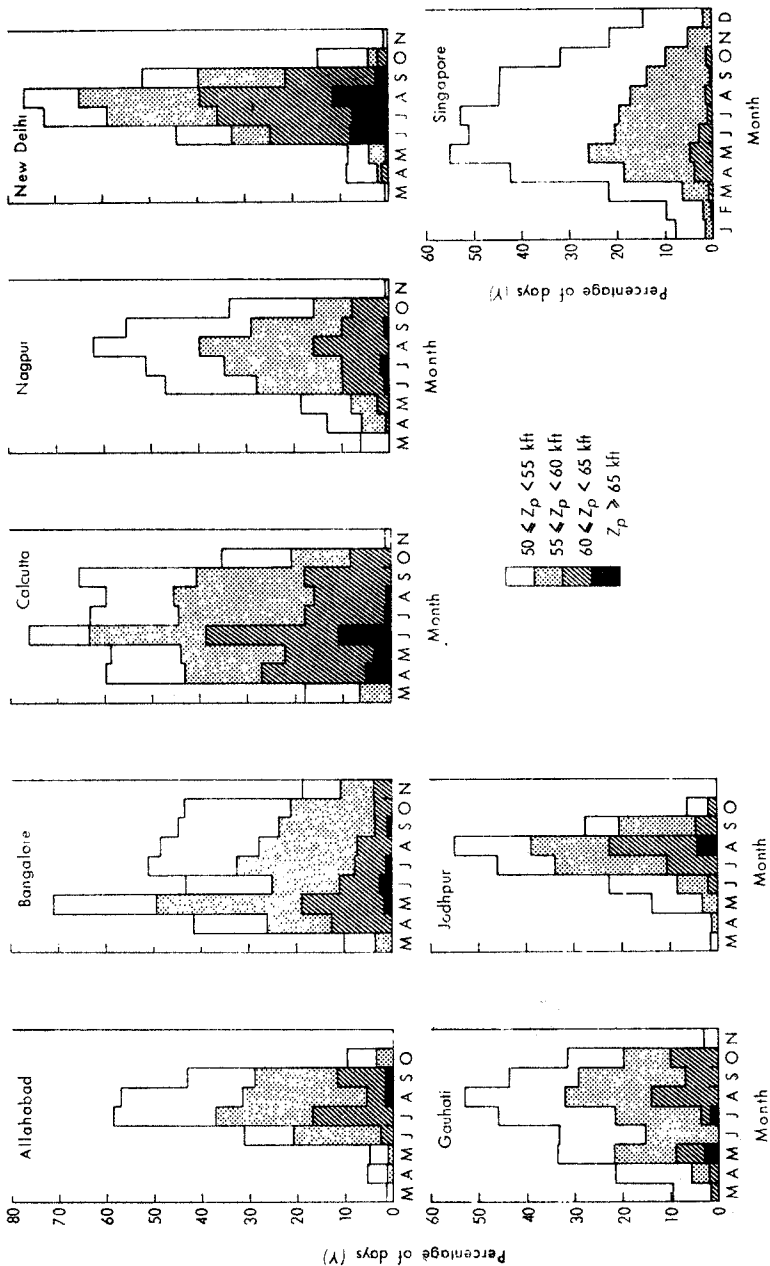
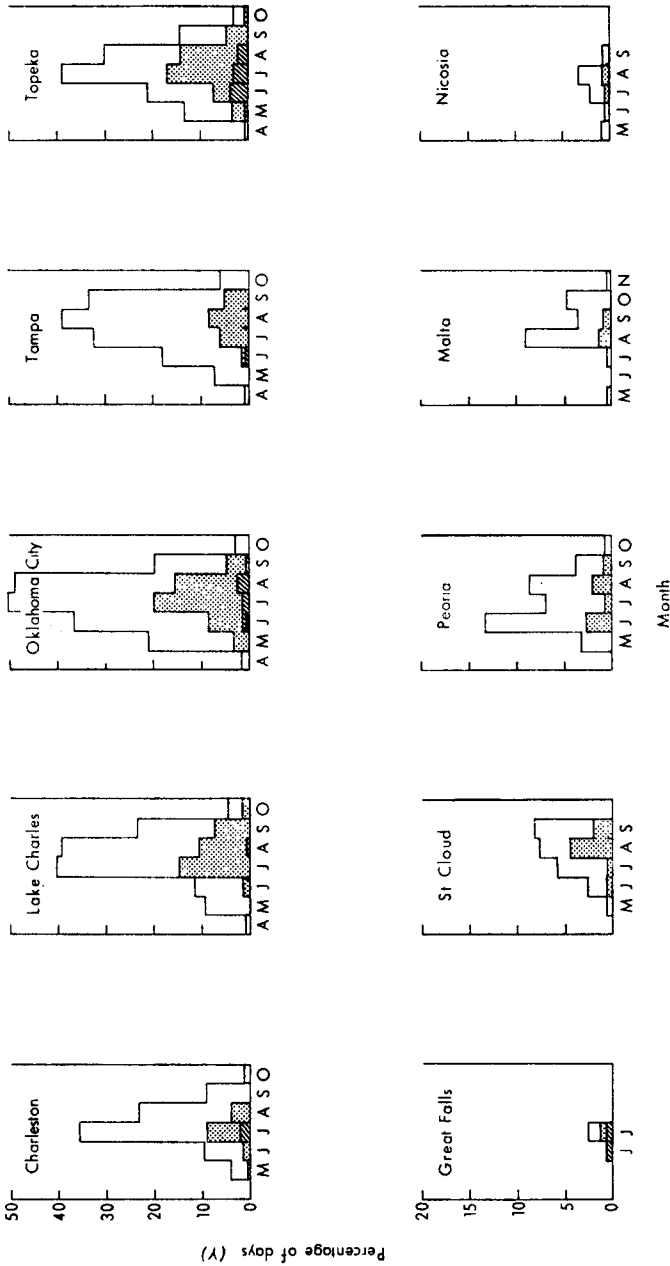


FIGURE 5 (a) Indian stations 1961-66 and Singapore 1959-66



(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.

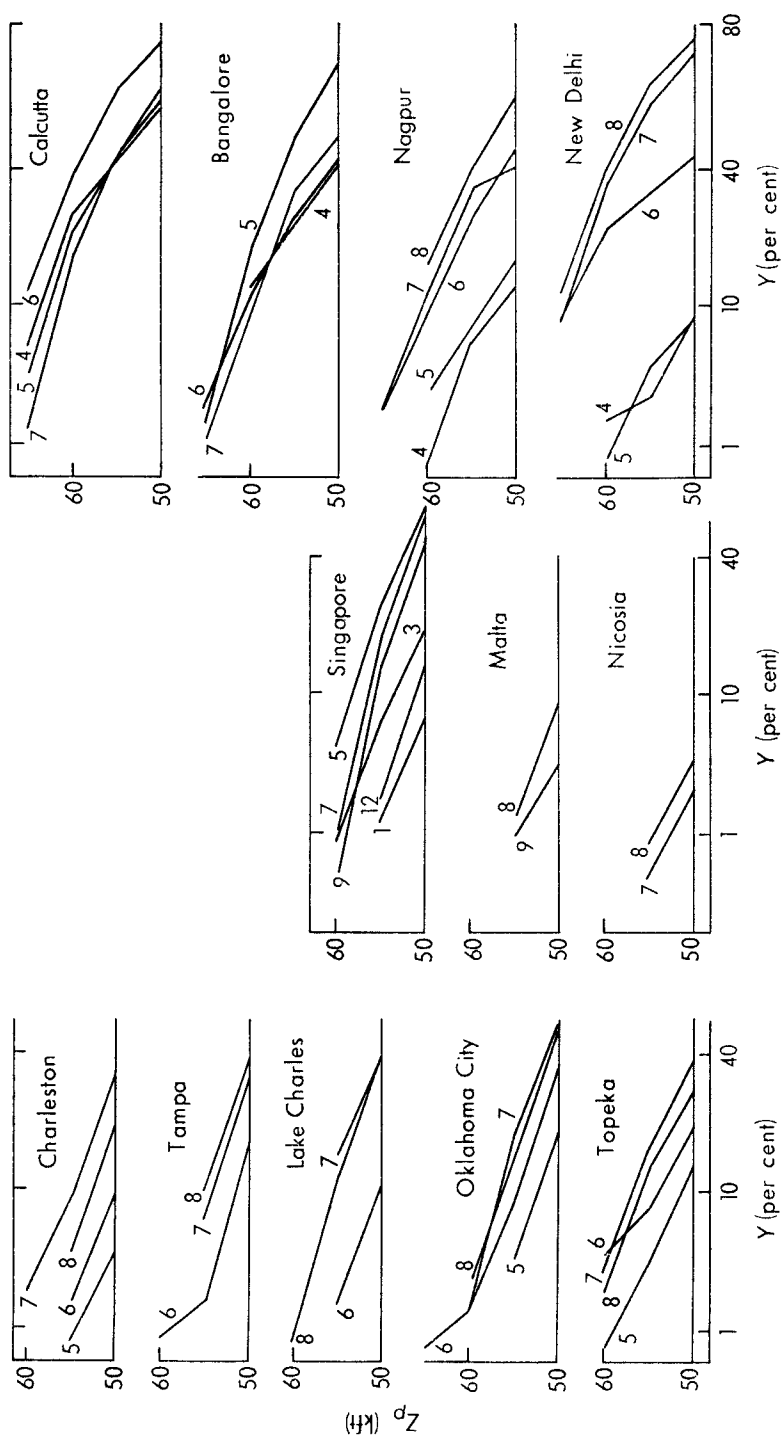


FIGURE 6—SOME OF THE DATA PRESENTED IN FIGURE 5 PLOTTED ON PROBABILITY PAPER
Months identified by 1 = Jan. 3 = Mar. 4 = Apr., etc.

TABLE 1—SAMPLES OF ANNUAL STATISTICS OF Z_p FOR OKLAHOMA CITY (JUNE) AND CALCUTTA (MAY)

Oklahoma City : June				
Year	Lower limit of Z_p (kft)			
	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. WMO¹⁰) 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

$$E = \frac{1}{2}(W_{max})^2,$$

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

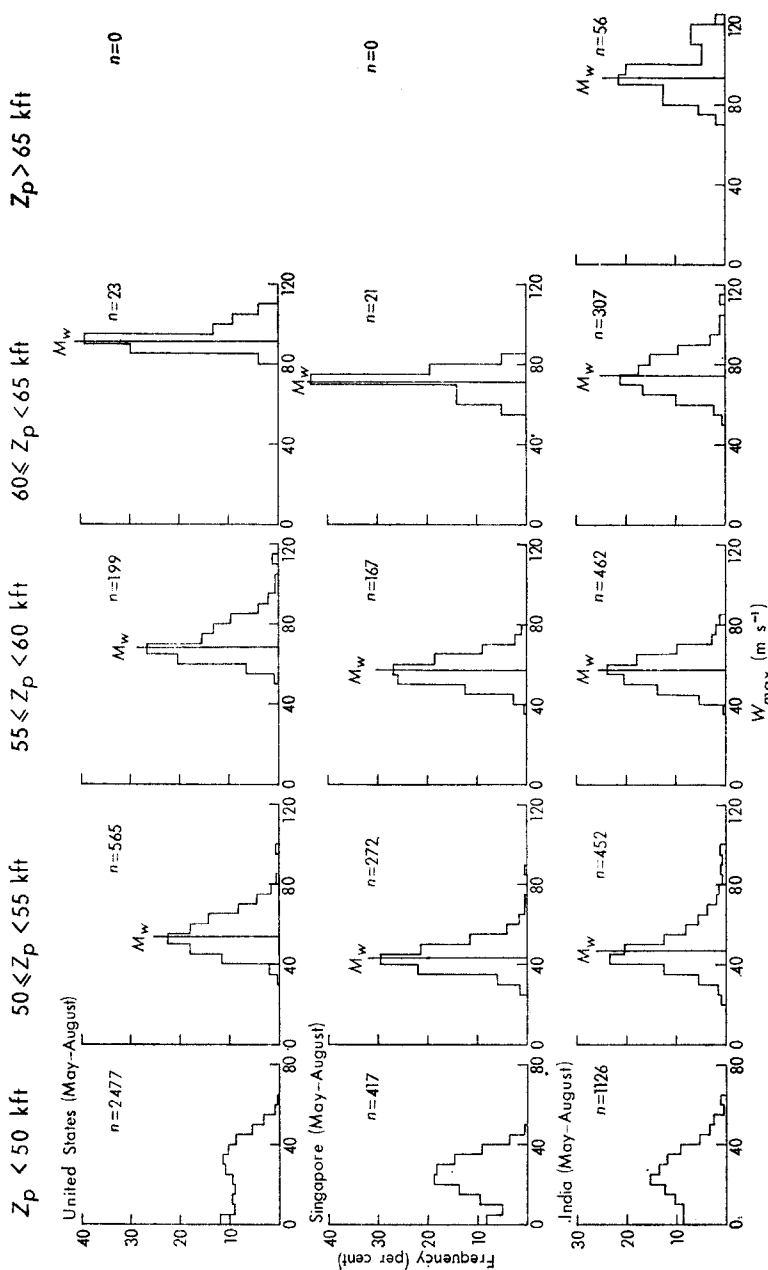


FIGURE 7—HISTOGRAMS OF 'POSITIVE AREA' ENERGY EXPRESSED AS EQUIVALENT MAXIMUM VERTICAL VELOCITY FOR THE UNITED STATES, SINGAPORE AND INDIA

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 $Z_p \leq 50$ 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 (≈ 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. Jordan¹¹) 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 Ronne¹²) 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 $h_j \geq 50$ kft and $h_j \geq 55$ kft, but not for $h_j \geq 60$ 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.

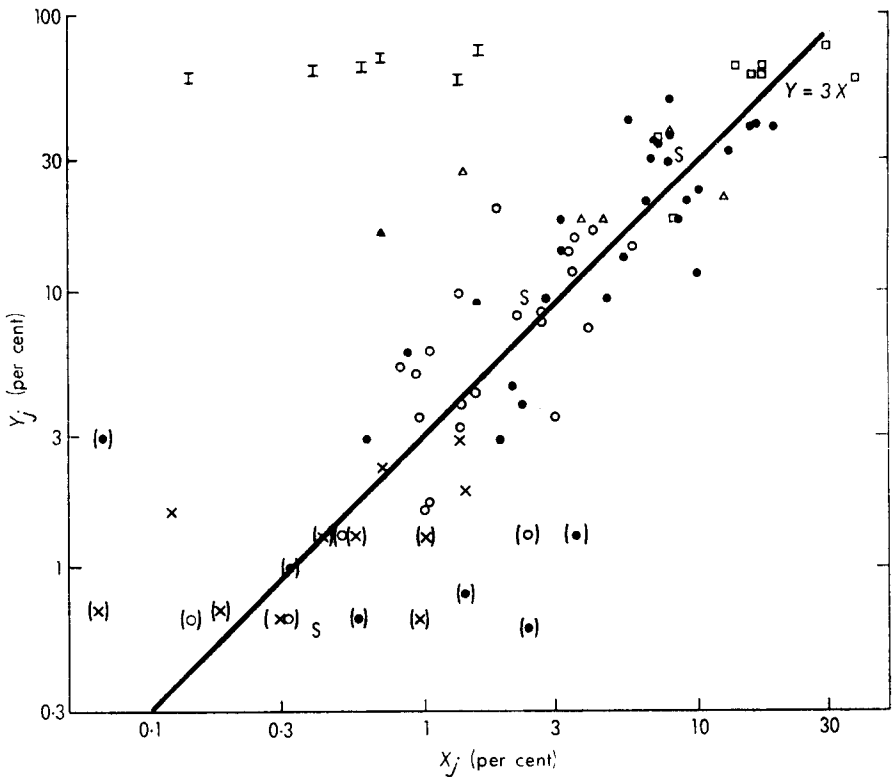


FIGURE 8—A PLOT OF THE PERCENTAGE FREQUENCY OF OCCASIONS (X_j) WHEN THE HOURLY MAXIMUM RADAR ECHO TOP EXCEEDS h_j AGAINST PERCENTAGE FREQUENCY OF DAYS (Y_j) WHEN Z_p EXCEEDS h_j

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 $h_j > 50, 55, 60$ kft

Early Indian data : I $h_j > 50$ kft

Later Indian data (Rakshit⁹) : □ $h_j > 50$ 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 (Kulshrestha⁷) and Calcutta (Bhattacharyya and De⁸) and observations from aircraft (Deshpande¹³) 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 – T 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) Rakshit⁹ 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 than 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

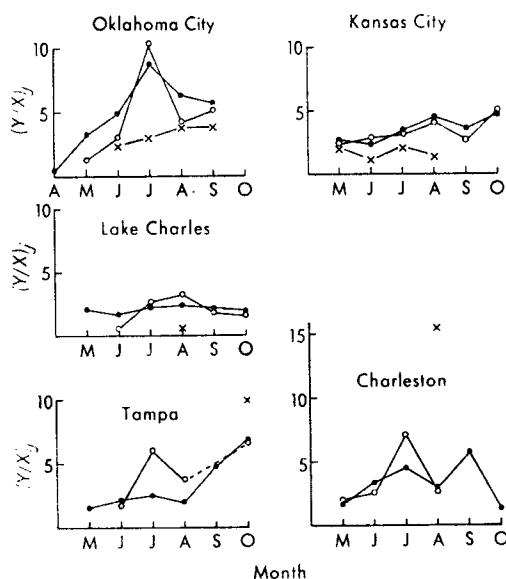


FIGURE 9—SEASONAL TREND OF $(Y/X)_j$ FOR SOME STATIONS (BASED ON FIGURE 8)

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

- 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.
- 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 $\geq Z_p$ at any given time varies from about 1 in 50 to 1 in 10, depending upon the degree of organization.

- This model does not apply to the distribution of maximum heights reached by *individual* storms during their lifetime.
- 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 down-draughts.
- (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 McPherson¹⁴).

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.

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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.

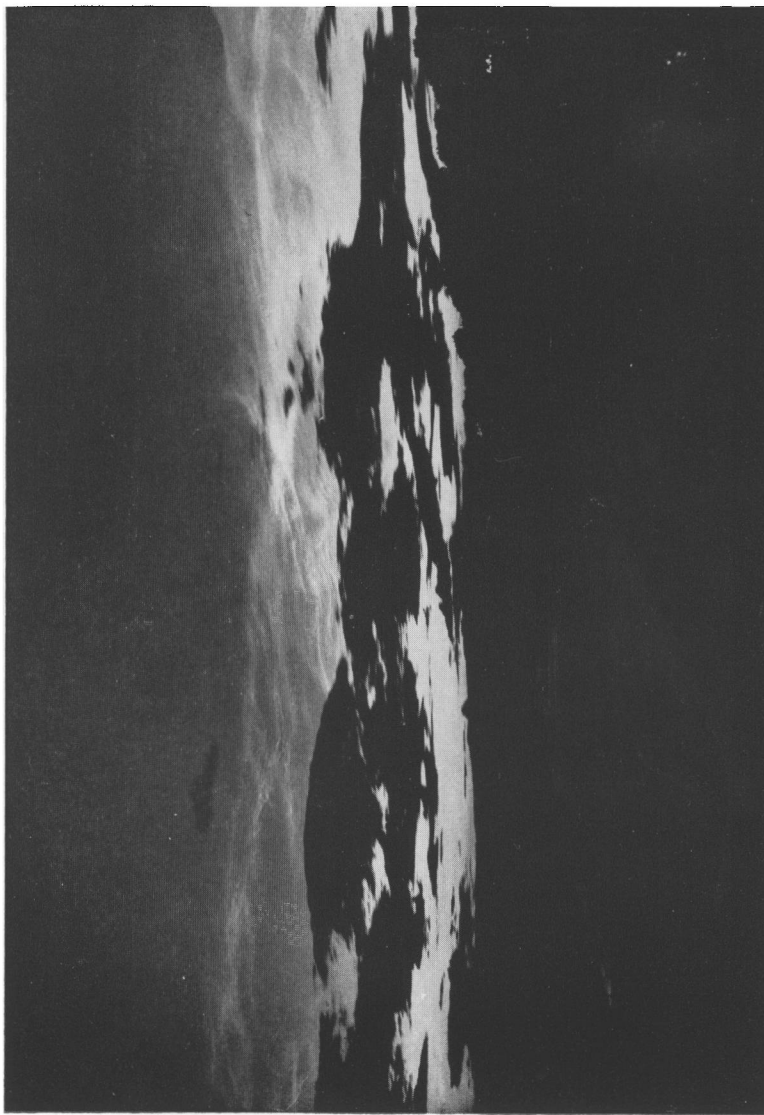


PLATE II (a)---NOCTILUCENT CLOUD OBSERVED FROM PERTH BRIDGE ON THE NIGHT
OF 14 JULY 1971 AT 2350 UT
see page 182.



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. Østergaard Olesen

PLATE IV—NOCTILUCENT CLOUD OBSERVED FROM ALRO, DENMARK, ON THE NIGHT
OF 17 JULY 1971 AT 2150 UT
see page 182.

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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 $\geq 50, 55, 60, 65$ 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

$$\Phi_j = \sum_{i=1}^M [1 - (1 - f_{ji})^{n_i}] , \quad \dots (1)$$

where M = total number of observations in a period of one month,
 f_{ji}, n_i = values of f_j and n on i th occasion,

$$\text{and} \quad X_j = 100 \Phi_j / M, \quad \dots (2)$$

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

$$Y_j = 100 \int_{h_j}^{\infty} P(Z_p) dZ_p , \quad \dots (3)$$

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 i th 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 i th 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 Braham¹⁵ 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, Roach² 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 km². 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 Kessler¹⁶ and Kessler *et alii*¹⁷) shows that as much as 40 per cent (3×10^4 km²) 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 $1 \leq n \leq 30$ 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

$$1 - (1 - f_j)^N = \int_0^{\infty} [1 - (1 - f)^n] P(n) dn, \quad \dots (4)$$

where $P(n)$ is the probability that n lies between n and $n + dn$, 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 $Z_p + dZ_p$ 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 :

$$X_j = 100 \frac{M_e}{M} \int_{h_j}^{\infty} [1 - (1 - f_j)^N] P(Z_p) dZ_p, \quad \dots (5)$$

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	48	6
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	0.8		
VII	0.7	0.15	10			

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

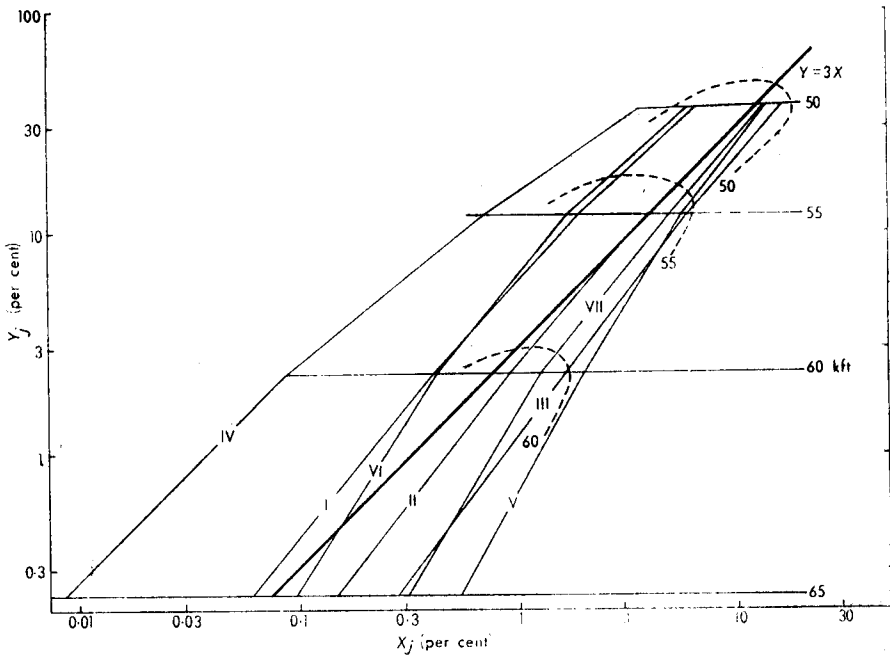


FIGURE 10—PLOTS OF Y_j AGAINST X_j FOR THE MODELS DISCUSSED IN TEXT

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.

NOCTILUCENT CLOUDS OVER WESTERN EUROPE DURING 1971

By J. PATON

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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 UT	Notes	Station position	Time UT	Max. elev.	Limiting azimuths degrees
26–27 May		No NLC				
27–28		No NLC				
28–29	2145–2345	Faint band visible before midnight. The NLC had vanished by 0045 UT.	55.5°N 1.5°W	2245 2345	7 7	320 320–360
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, bands and billows first seen from Stockholm and last from an aircraft over western Atlantic. The bands extended continuously along northern sky and were closely packed showing a greenish tinge in places. Observers in British Isles reported the clouds at their brightest at about one hour before and one hour after midnight.	59.5°N 18°E 56.5°N 7°W 56°N 4.5°W 55.5°N 7.5°W 55.5°N 5.5°W	2205 2235 2255 2345 0045 0145 2250 2250 2344 0045 0120 0210 2345	13 18 18 13 15 20 33 16 12 10 12 20 10	335–360 315–020 315–020 350–020 360–030 010–040 320–020 345–045 315–045 360–045 340–045 315–360 360–045

TABLE I—continued

Date — night of	Times UT	Notes	Station position	Time UT	Max. elev. degrees	Limiting azimuths
			55°N 4·5°W	2320 0040 0115 0200	11 10 15 30	360–045 360–045 360–045 360–045
			54·5°N 6°W	0200 0230 0400	17 16 12	345–040 330–040
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°.	49°N 56·5°W 59·5°N 18°E	0400 2215	12 73	360
7–8 and 8–9 9–10 10–11 11–12 12–13 13–14		No NLC seen in clear skies at Stockholm. Mainly cloudy over British Isles. No NLC No NLC Cloudy No NLC				
14–15 June	2205–2242	Four faint bands seen from Stockholm.	59·5°N 18°E	2205	18	010–020
15–16 16–17 17–18		No NLC No NLC No NLC				
18–19 19–20 20–21 21–22 22–23 23–24 24–25 25–26	2335–0045	Moderately bright display of bands and whirls seen through low cloud. Cloudy Cloudy Cloudy No NLC Cloudy Cloudy Cloudy	55·5°N 1·5°W	2335 2345 0050	18 10 35	330 315–360 320–030
26–27 27–28 28–29 29–30	0052–0203	Bands and billows seen from Ocean Weather Ship <i>Weather Surveyor</i> . Cloudy over western Europe. No NLC Cloudy No NLC No NLC	59°N 19·5°W	0115	49	280–060
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 2–3	2132–0120	No NLC Moderately bright display of bands and billows, brightest and most clearly defined before midnight. Faint whirls appeared after midnight.	59·5°N 18°E 56·5°N 3°W 56°N 4·5°W 55·5°N 4·5°W	2245 0005 0043 0030 0055	90 14 16 22 15	343–055 360–030 010–040 010–040
3–4	2220–2235	Four faint bands seen from Stockholm.	51°N 1·5°E 59·5°N 18°E	2132 2220	28 35	340–010 045
4–5 5–6 6–7	2240–0150	No NLC No NLC Veil and weak to moderately bright greenish bands forming a rather unspectacular display. Reported also from Denmark and Sweden.	57°N 2°W 56·5°N 3°W 56·5°N 7°W 56°N 10°E 56°N 3°W 56°N 4·5°W	2345 0015 0050 2340 0015 0050 0150 2305 2340 2310 2300 0001 0030 0100 0130 2240 0025 0115 2400 0100 2330 2245 2315 2350 0050	12 10 10 11 10 10 8 7 10 7 10 11 11 15 12 9 9 4 11 6 9 5 4 8 6	330–015 290–020 355–015 340–015 290–020 355–015 335–030 315–045 325–050 335–360 335–045 340 340–030 313–035 313–027 311–035 310–050 010–040 320–045 320–010 315–040 320–025 320–360 350–030 340–020 330–010 360–020

TABLE 1—*continued*

Date — night of	Times UT	Notes	Station position	Time UT	Max. elev. degrees	Limiting azimuths
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 1—continued

Date — night of	Times UT	Notes	Station position	Time UT	Max. elev. degrees	Limiting azimuths
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 1970¹ (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 wind-break, 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 authoritative 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.

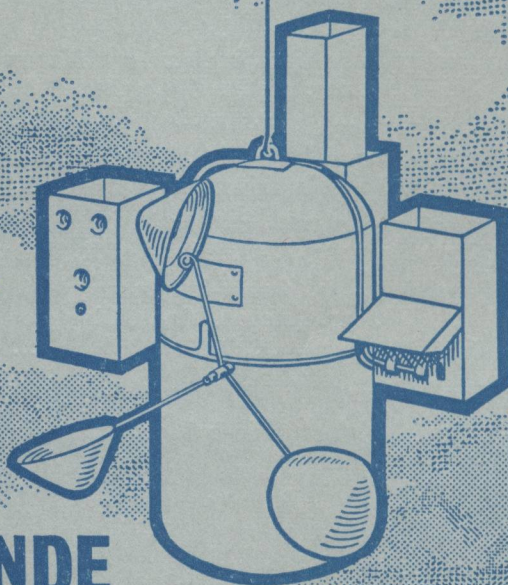
The high-altitude balloon flight was made from Holloman Air Force Base New Mexico in August. A total payload of some 900 lb (≈ 415 kg) was carried to a float altitude of 133 000 ft (≈ 41 km) by a 10.6-million-ft³, helium-filled balloon for one hour before a controlled descent and successful parachute 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 ($1\text{Å} = 10^{-4}\mu\text{m}$)) 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 $1\frac{1}{2}$ 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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NOTICES

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