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METEOROLOGICAL OFFICE LONG-RANGE FORECASTS: SIX YEARS OF PROGRESS

By R. A. S. RATCLIFFE

The Meteorological Office commenced the issue of long-range (30-day) forecasts in December 1963 and the practice has continued twice a month from that date. Freeman[1] reviewed the success of the first 33 months of forecasts in an article in this magazine in 1966 and this note is intended to bring the reader up to date.

The style of the forecast has not changed very much over the 6 years although over the last year or two it has been the practice whenever possible to start the forecast with a brief description of the salient features of the expected weather over the first 5–7 days. This has become possible with the increasing reliability of numerical forecasts for 2–3 days ahead which has allowed them to be used as a basis for the application of empirical methods of forecasting, thus extending the range by a further 3–4 days. With this exception the main part of the forecast remains unaltered and includes statements on the expected monthly mean temperature and the total amount of rainfall together with additional information on the probable frequency of such elements as snow, frost, gales, etc., during the 30-day period.

As stated in Freeman's article but repeated here for convenience, the expected monthly mean temperature is given as one of five categories: much above average, above average, near average, below average or much below average.

Monthly rainfall totals are quoted as one of three categories: above average, average or below average. The boundaries between the categories in both cases are arbitrarily selected so that in the period 1931–60 each category occurred equally frequently. The category boundaries vary somewhat from month to month and for different areas of the British Isles, examples being quoted in Freeman's paper. The temperature and rainfall forecasts are checked separately for each of the 10 areas of the British Isles shown in Figure 1. These areas have remained unchanged over the 6 years but, in some cases, names have been changed to avoid confusion with similar names used in BBC regional forecasts.

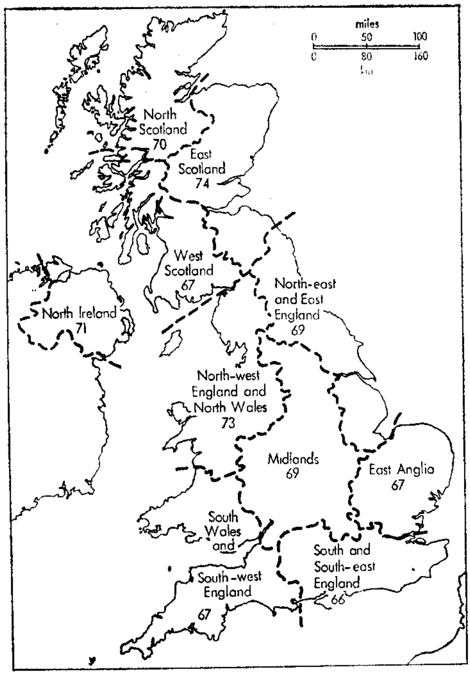

FIGURE 1—FORECAST REGIONS OF THE BRITISH ISLES

The numbers are percentages of correct or nearly correct temperature forecasts in the 6-year period.

For each area there are four to six check stations depending on the area; in this respect a better representation of some areas has been gradually achieved over the years. For example, East Scotland is now represented by Edinburgh and Kinloss as well as by the original check stations Aberdeen and Leuchars, while South and South-east England which previously had no check station near the south coast, now includes both Manston (Kent) and Deal.

The method of calculating the area mean anomalies of temperature and rainfall is entirely objective and was fully described by Freeman in the earlier paper. The calculations are carried out using *Daily Weather Report** stations as far as possible and involve extensive use of the Meteorological Office computer.

A score for each area is calculated from Table I.

TABLE I(*a*)—SCORES FOR TEMPERATURE FORECASTS

Actual	FORECAST Much below	Below	Average	Above	Much above
Much below	4	1	−3	−4	−4
Below	2	4	1	−2	−2
Average	0	1	4	1	0
Above	−2	−2	1	4	2
Much above	−4	−4	−3	1	4

*London, Meteorological Office. *Daily Weather Report.*

TABLE I(*b*)—SCORES FOR RAINFALL FORECASTS

Actual	FORECAST Below	Average	Above
Below	4	−2	−4
Average	0	4	0
Above	−4	−2	4

Over a long period when the frequency of occasions in each category is about equal, the average score by chance will be zero and zero will also be the average score obtained by always forecasting the normal (i.e. climatology). From the scores for each area an average score for the whole country is calculated and is used to assess the accuracy of the forecast in one of the five categories :

A No serious error
B Good agreement
C Moderate agreement
D Little agreement
E No real resemblance

All negative scores are placed in classes *D* or *E*.

The additional information cannot in general be so objectively assessed but each statement made is considered after the event by a panel of meteorologists and a combined mark for all statements is given on the scale *A* to *E*. Some statements can be objectively assessed, e.g. 'frost will be more frequent than usual'. Such a statement would be evaluated by comparing the number of days with frost during the forecast with the normal (1931–60) for the period for all check stations in the British Isles. Similar checks are made for statements about the frequency of snow, gales, thunderstorms, fog, wet days, etc., and also for the monthly total of sunshine which is often forecast in summer as one of three categories : above average, average or below average.

Finally, an overall mark for the accuracy of each forecast is given, compounding the marks for temperature, rainfall and additional information. Freeman's paper quoted the frequency with which the various assessments were made for the first 66 forecasts, ending in August 1966. Table II shows similar frequencies for the 78 forecasts in the period from September 1966 to November 1969.

TABLE II—NUMBER OF FORECASTS IN THE VARIOUS CATEGORIES OF SUCCESS, SEPTEMBER 1966 TO NOVEMBER 1969

Category		Mean temperature	Rainfall	Additional information	Overall marking
A	No serious error	18	5	20	4
B	Good agreement	20	18	30	27
C	Moderate agreement	17	28	21	33
D	Little agreement	13	17	5	11
E	No real resemblance	10	10	2	3

It is gratifying to note that whereas moderate agreement or better was attained in 73 per cent of the earlier sample of forecasts, Table II shows that 64 out of 78 of the more recent forecasts were assessed as being at least in moderate agreement, a figure of 82 per cent. The improvement is perhaps more easy to appreciate from the figures for individual years, which are quoted in Table III.

TABLE III—NUMBER OF FORECASTS SHOWING AT LEAST MODERATE AGREEMENT

Year	Mean temperature	Rainfall	Additional information	Overall marking
1969	19	19	23	22
1968	17	15	24	19
1967	16	15	20	18
1966	14	13	18	18

It would be easy to exaggerate recent success much of which has been due to better 'additional information' rather than to an improvement in the temperature and rainfall forecasts. In particular it must be noted that 'moderate agreement' is not a very high standard. However, *A* and *B* forecasts are good forecasts by any standard and Table II shows that 31 of the 78 more recent forecasts (40 per cent) have been assessed in those categories compared with 38 per cent in the first 66 forecasts, a much more modest improvement. It is interesting and informative to look at the breakdown of poor *(D* or *E)* forecasts by months. It has been known for some years that autumn is a difficult season to forecast for but Figure 2 shows, rather

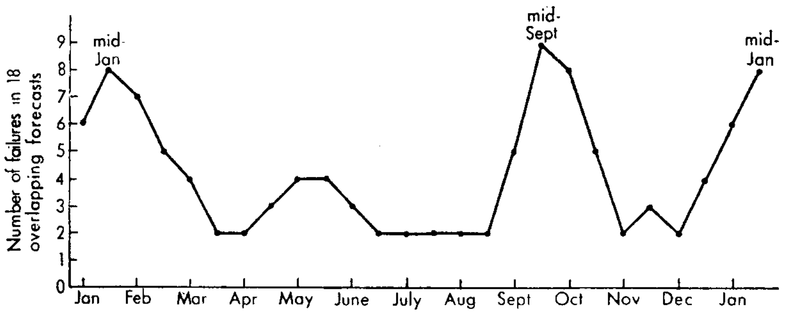

FIGURE 2—VARIATION IN LONG-RANGE FORECAST ACCURACY THROUGHOUT THE YEAR

surprisingly, that there is another peak in failures around the midwinter period and a lesser one about May. This graph is based on a small number of cases (6 forecasts for each of the 24 forecast periods) but each plot is made up from the results of three sets of overlapping forecasts plotted on the centre one, e.g. the figure of 9 for mid-September includes 1 failure in September, 4 in October and 4 in the mid-September to mid-October period. The maximum possible number of failures at any point on the graph is therefore 18. Clearly the long-range forecasts are most likely to be reliable from March to September and also around November and December.

Although Table III shows that rainfall results have improved, good forecasts of temperature are still made more often than good forecasts of rainfall. If the forecasts are broken down into the individual areas shown in Figure 1 the results in Table IV are obtained. Rainfall is forecast as one of three categories so it is not meaningful to quote the percentage of occasions one category out because average rainfall tends to be forecast more often than the two extremes and with a forecast of average an error of more than one category cannot be made.

It is interesting to note that there is apparently a geographical distribution to the success figures, temperature forecasts in particular being better in the

TABLE IV—PERCENTAGE OF CORRECT OR NEARLY CORRECT FORECASTS WHEN THE 10 AREAS* ARE CONSIDERED SEPARATELY, COMPARED WITH CHANCE EXPECTATION

(a) Temperature forcasts

	CHANCE EXPECTATION Assuming 1931–60 distribution	Assuming distribution which occurred 1964–69	First 66 forecasts	Next 78 forecasts	1969
			per cent		
Correct	20	23	26	27	33
One category wrong	32	40	42	43	42
Correct or nearly correct	52	63	68	70	75
(b) Rainfall forecasts					
Correct	33	34	36 (35·9)	36 (36·3)	41

*As shown on Figure 1.

northern and western districts than in the south-east. The percentages of temperature forecasts correct or nearly correct over the whole 6-year period are indicated for each area in Figure 1.

As noted by Freeman,[1] middle categories of both temperature and rainfall were forecast too often and the extreme categories too rarely, but this factor has if anything been over corrected in the more recent temperature forecasts as can be seen from Table V. Average rainfall has occurred a little more frequently than would be expected but the 'over forecasting' of average rainfall has been entirely at the expense of 'above average'. Below-average rainfall occurred 31 per cent and was forecast 30 per cent of occasions. Attempts are being made to correct this bias in rainfall forecasts.

TABLE V—PERCENTAGE DISTRIBUTION OF OCCURRENCES AND FORECASTS FOR THE EARLIER PERIOD (66 FORECASTS) COMPARED WITH THE DISTRIBUTION FOR THE LATER PERIOD (78 FORECASTS)

(a) Temperature

	December 1963–August 1966		September 1966–November 1969	
	Occurrences	Forecasts	Occurrences	Forecasts
	per cent		*per cent*	
Much below average	29	4	15	19
Much above average	9	3	5	9
(b) Rainfall				
Average	35	49	37	59

The modest but real improvement in the last few years in the long-range forecasts has been due to two main causes. Firstly, there has been considerable expansion in the data library used for analogue purposes in the preparation of the forecasts. This now includes historical series of sea surface temperature maps back to 1888, mid-month to mid-month mean surface pressure maps for the period back to 1899 and 500-mb charts for the period back to 1873, the earlier years of which have been produced by the adoption of a statistical technique developed in the Meteorological Office. Secondly, a good deal of research work has been carried out and is continually being integrated into the monthly forecast routine. One of the more successful pieces of research has been the uncovering of relationships between Atlantic ocean temperature anomalies and surface pressure anomalies a month ahead (Ratcliffe and Murray[2]) but there have been other notable advances including work by Ratcliffe[3] relating 500-mb monthly mean patterns to rainfall in England and Wales a month ahead and several papers by Murray[4,5,6] on persistence of monthly mean temperature and sequences of monthly rainfall.

Results still leave a good deal to be desired but it is hoped that further advances can be made. Forecasts would be more useful if a broad description of the expected sequence of weather could be given over the whole period rather than just for the first week. Certainly there is no complacency among the long-range forecasters, but progress will continue to be slow.

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THE EFFECT OF CHANGES OF ATMOSPHERIC STABILITY AND SURFACE ROUGHNESS ON OFF-SHORE WINDS OVER THE EAST COAST OF BRITAIN

By P. E. FRANCIS

Summary. The variation in the ratio of wind speed over the sea to that over the land is examined for various stability conditions and for different initial land winds. An attempt is made to explain the observed variation by reference to the theory of turbulent boundary-layer flow.

Introduction. It is an observable fact that surface winds are affected by changes in surface roughness and in atmospheric stability. In particular, winds blowing across a coastline undergo changes in direction and speed because of the change in the surface roughness characteristics and also because of the changes in the atmospheric stability of the lower layers, due to the different thermal properties of the land and sea surfaces. A knowledge of the winds over the sea is of obvious importance to shipping, sailing enthusiasts and fishermen, who have a direct interest in the wind strength and direction, and in the waves and currents that the winds induce. Not so obvious is the interest of river-authority engineers and coastguards. Their concern in this respect is the generation of storm surges (abnormally high tides) by strong wind fields over the sea. Because it is relatively shallow and partially enclosed, the North Sea is nearly ideally suited for the generation of wind-induced surges. As a result of this interest in the structure of the wind over the sea, the meteorologist is often required to supply relevant information and this, in view of the lack of on-the-spot observations, is a difficult task.

At any given time a coastal observing station on the east coast can supply anemograph data which determine the local wind field. These local winds will differ from station to station because of the varying effects of topography and exposure. The North Sea itself is almost devoid of wind observations except for a few reports from lightships and the occasional report from a commercial vessel. In order to gain some insight into the structure of the wind field over the main sea areas, say up to 50 miles from the coastline, the following investigation was undertaken. A long series of simultaneous wind observations taken at a coastal station and at a lightship stationed in adjacent waters were examined and an empirical relationship between the observed winds at the two stations was arrived at.

A description of some previous work on this subject, together with a review of other, earlier, work may be found in Richards, Dragert and McIntyre[1] referred to in this paper as (A). All the work referred to in (A) was carried out over the Great Lakes of North America, and the findings of that work will be compared to the results arrived at in this account. One major difference must be pointed out from the beginning; since the length of fetch over water was an important factor in investigation (A) it was decided to consider only off-shore winds in this paper so that the variations in fetch for our observations would be small.

Data. The observing stations used in this investigation were Gorleston, on the Norfolk coast, and the Smith's Knoll Lightship. The lightship is positioned about 20 miles off-shore on a bearing of approximately 070° from Gorleston, this direction being nearly perpendicular to the coastline. Observations from the 10 years 1957–66 were used. Off-shore winds were defined as blowing from between 210° and 290° at Gorleston, and to ensure that both observations were made in the same air mass the criterion that the wind directions at Gorleston and Smith's Knoll should not differ by more than 30° was applied. Observations not satisfying this criterion were discarded and in this way the chance of there being an intervening frontal discontinuity was minimized. Under these conditions a total of 3366 simultaneous observations were retained as being suitable for analysis. The data were extracted from punched cards in the Meteorological Office records and put on magnetic tape, each individual observation consisting of the following information :

Year, month, day, hour, wind direction, wind speed, temperature.

For the Gorleston observations the temperature recorded was that of the air, while in the Smith's Knoll observations the sea surface temperature was recorded. Air temperatures before 1961 and all the sea surface temperatures were in degrees Fahrenheit, so this was chosen as the reference scale for temperature, especially as the American work was also in Fahrenheit. Accordingly the air temperatures from 1961 were converted from degrees Celsius. Wind speed measurements were recorded in knots, to the nearest whole knot, and wind directions in tens of degrees.

Method and results. From each pair of simultaneous observations three indices were tabulated :

(i) $R = \dfrac{U_s}{U_L} = \dfrac{\text{wind speed over sea}}{\text{wind speed over land}}$

(ii) D_d = (wind direction over land) – (wind direction over sea)

(iii) T_d = (air temperature over land) – (sea surface temperature)

The index T_d was taken as a measure of the instantaneous stability of the surface layers of atmosphere as they were advected from the land to the sea. Following the method in (A) it was proposed to investigate the variation of R with the wind speed over the land, U_L, and with T_d, and, in addition, to find out whether any information concerning the variation of D_d with U_L and T_d could be obtained.

To facilitate the analysis the range of U_L was divided into four arbitrary sub-ranges called 'wind-speed classes'. These classes and the frequency of observations within them are given in Table I. The range of value of T_d in the observations was from −21 to +24 Fahrenheit degrees. Once again this complete range was split up into sub-ranges, called 'stability classes'. As might have been expected the frequency distribution of T_d values was very peaked, having a maximum near 0 Fahrenheit degrees. The total range was split up in a manner designed to give approximately equal frequencies to the five sub-ranges. Consequently the middle class was narrow while the outer classes were quite wide. Thus these stability classes have no inherent physical basis, but a terminology of the form :

very unstable unstable neutrally stable stable very stable

may be applied as long as it is remembered that no strict definition is being made.

TABLE I—WIND-SPEED AND STABILITY CLASSES, WITH THE FREQUENCY OF OBSERVATIONS IN EACH CLASS

Stability index, T_d degF	Ranges of wind speed over land, U_L (kt) 1–5	6–10	11–15	≥16	All winds
≤−6	157	557	126	55	895
−5 to −2	119	334	140	57	650
−1 to +1	94	230	108	77	509
+2 to +5	81	234	151	101	567
≥+6	86	270	229	160	745
All temps	537	1625	754	450	3366

A total of 20 classifications was then possible, as the combination of four wind-speed and five stability classes. For each of the 20 classifications the mean values of R and D_d were calculated, also the standard deviations of R and D_d and the maximum and minimum values of R. The results of these calculations are tabulated as Table II.

The influence of wind speed and stability on change of direction. Before any use was made of the results set out in Table II it was necessary to justify the classifications of D_d, the change in direction, by wind speed U_L and stability T_d. While such a classification may facilitate the analysis and presentation of results it might also introduce an unnecessary degree of complication. Accordingly an analysis of variance was performed on the mean D_d values of the classification in order to test whether or not there was a significant variation in the mean values among the classes in each of the main classifications. The results were :

$$\frac{\text{variance due to wind-speed classification (3)}}{\text{residual variance (12)}} = 2{\cdot}36$$

and
$$\frac{\text{variance due to stability classification (4)}}{\text{residual variance (12)}} = 36{\cdot}88,$$

TABLE II—MEAN VALUES AND STANDARD DEVIATIONS OF R AND D_d FOR EACH CLASS, TOGETHER WITH THE MAXIMUM AND MINIMUM VALUES OF R

U_L	T_d	Mean D_d	Standard deviation of D_d	Mean R	Standard deviation of R	Maximum R	Minimum R
kt	*degF*	*tens of degrees*					
	−21 to −6	−0·66	1·79	3·39	2·61	18·0	0·4
	−5 −2	−0·24	1·79	3·07	1·85	10·0	0·4
1–5	−1 +1	−0·06	1·81	2·95	2·34	14·0	0·6
	+2 +5	−0·11	1·84	2·59	2·08	12·0	0·2
	+6 +24	0·41	1·79	2·53	1·79	12·0	0·4
	−21 −6	−0·84	1·64	1·90	0·68	4·3	0·2
	−5 −2	−0·41	1·71	1·83	0·61	4·2	0·2
6–10	−1 +1	−0·08	1·72	1·57	0·54	3·5	0·3
	+2 +5	0·27	1·72	1·40	0·43	2·6	0·4
	+6 +24	0·34	1·73	1·31	0·50	3·0	0·2
	−21 −6	−0·64	1·53	1·78	0·45	2·7	0·7
	−5 −2	−0·33	1·63	1·61	0·42	3·5	0·7
11–15	−1 +1	0·11	1·68	1·48	0·32	2·4	0·5
	+2 +5	0·20	1·73	1·29	0·32	2·3	0·1
	+6 +24	0·77	1·57	1·11	0·32	2·2	0·1
	−21 −6	−0·33	1·79	1·55	0·30	2·3	0·7
	5 −2	−0·23	1·41	1·54	0·29	2·4	0·7
⩾16	−1 +1	0·00	1·75	1·35	0·26	2·2	0·6
	+2 +5	0·08	1·68	1·23	0·27	2·2	0·5
	+6 +24	0·68	1·50	1·06	0·27	1·6	0·2

the numbers in brackets being the respective degrees of freedom. At the 95 per cent level of significance $F_{3,12} = 3{\cdot}49$, while at the 99·9 per cent level $F_{4,12} = 9{\cdot}63$. It was concluded from these results that the variation of mean D_d values among the wind-speed classes was not significant while the variation among stability classes was highly significant. In view of this conclusion there was nothing to be gained by classifying D_d according to wind speed, so the mean values and standard deviations for the stability classes were recalculated using data for all wind speeds. The results are shown in Figure 1 together with the 95 per cent confidence limits that were ascribed to the class means.

The change in direction, D_d, was measured in units of 10° of arc. It can be seen in Figure 1 that the mean D_d values for each class were all less than unity, and that the standard deviations (and hence confidence limits) were relatively large. In view of this, only a qualitative interpretation of the results is possible since the actual numerical values can hardly be significant. It is perhaps possible to state that off-shore winds tend to back if initial conditions over the sea are very stable, and tend to veer if initial conditions are very unstable. This change in direction is thought to be independent of the wind speed over the land.

The influence of wind speed and stability on the ratio R. It became apparent from the results set out in Table II that there was more variation in R values in the 1–5 kt wind-speed class than in any of the other wind-speed classes. For the whole class, irrespective of any stability classification, the range in R values was 0·2 to 18·0, the standard deviation of the R values was 2·23 and the mean R value was 2·98; these results are very different from the corresponding statistics of the other wind-speed classes. The 95 per cent confidence limits placed on this mean were $\pm 0{\cdot}19$, and it was concluded that no significant result could be deduced from the data for this class. When winds

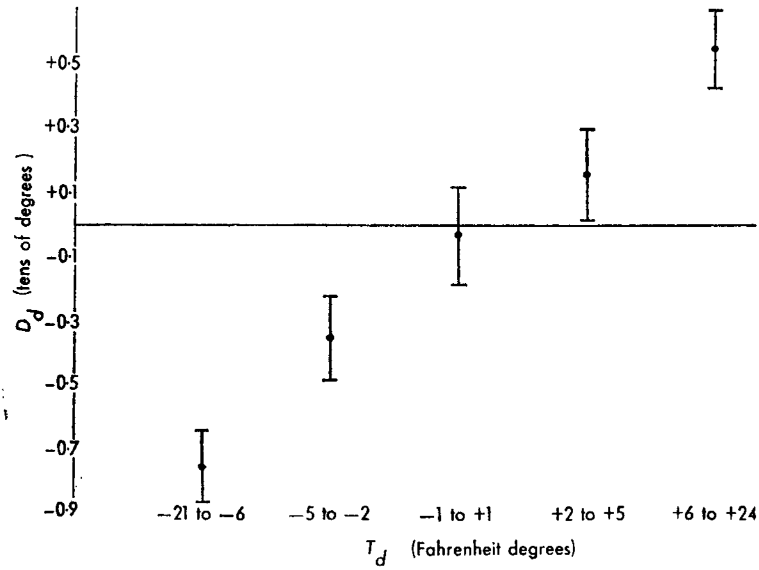

FIGURE 1—VARIATION OF MEAN CHANGE IN DIRECTION, D_d, WITH STABILITY CLASS, T_d

in the 1–5 kt range are being measured, the inaccuracy of the anemometer could perhaps be the main source of the observed peculiarity of the class results, but it is interesting to note that a similar result was recorded in (A) where it was apparently taken at its face value. Because of this suspicion of the results the 1–5 kt class was ignored for the remainder of the analysis.

An analysis of variance was carried out on the class mean R values and the resulting F values indicated that there were significant variations among the classes in each of the main classifications. It was of interest to note that the percentage of the total variance accounted for by the wind-speed classification fell from 86·7 per cent to 19·4 per cent when the 1–5 kt class was omitted, thus confirming the suspicion that the class as a whole was unrepresentative. Figure 2 is a graphical statement of the results for all winds >6 kt over land.

An inspection of the results shown in Figure 2 revealed several general trends in the mean R values. Firstly, however, it was noticed that the 95 per cent confidence limits on all the mean values were small, amounting to a maximum of 5 per cent of the actual values, thus a high significance could be attached to the numerical values obtained for the means. Within each wind-speed class the mean R values decreased as the stability index (T_d) increased, this being clearly shown in Figure 2. Thus, the more unstable the conditions over the sea became the greater was the increase in wind speed. Another general observation was that for all stability classes the stronger land winds were less affected by changes in stability, e.g. even in the most unstable régime the $\geqslant 16$ kt wind-speed class increased by only 55 per cent while in neutrally stable conditions the 6–10 kt class increased by 57 per cent. These trends were reflected in the overall results for all winds and all temperature differences. The mean R value, for all winds $\geqslant 6$ kt, and for all stability indices, was $1{\cdot}53 \pm 0{\cdot}02$.

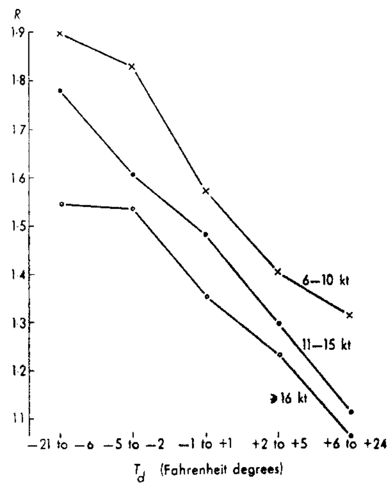

FIGURE 2—VARIATION OF MEAN R VALUES WITH STABILITY CLASS, T_d, FOR EACH WIND-SPEED CLASS, U_L

Comparison of results. The general variations of R with wind speed and stability, noted in the previous paragraph, were also observed in (A). Since the Great Lakes region experiences greater extremes of temperature than the North Sea area, the stability classification in (A) includes a larger total range, i.e. −47 to +42 Fahrenheit degrees. However, the central stability classes are comparable to those in this paper if our central three classes are amalgamated. The mean R values for the extreme stability classes in (A) confirm the relationships observed for the central classes. On comparison of results the general impression is that for the corresponding stability classes the mean R values for the North Sea region are higher than those for the Great Lakes.

TABLE III—MEAN VALUES OF R FOR WIND-SPEED AND STABILITY CLASSIFICATIONS OVER THE GREAT LAKES AND OVER THE NORTH SEA

Stability index, T_d *degF*	Range of wind speed over land, U_L (kt) 6–10	11–15	≥16
(a) Over the Great Lakes[1]			
−22 to −8	1·82	1·40	1·30
−7 to +7	1·49	1·31	1·02
+8 to +22	1·15	0·90	0·94
(b) Over the North Sea			
−22 to −6	1·90	1·78	1·55
−5 to +5	1·63	1·45	1·34
+6 to +22	1·31	1·11	1·06

These results are tabulated for easy comparison in Table III. The results in Table III*(a)* are for an over-water fetch of 16–25 n.miles roughly the same as for the North Sea data. The differences between the two sets of mean R values were tested and found to be significant at the 95 per cent level. The mean R value over the Great Lakes for 16–25 n.miles of fetch, ≥6 kt, and for $-22 \leqslant T_d \leqslant +22$ Fahrenheit degrees was 1·38, significantly different from the value of 1·53 for the North Sea.

As already mentioned the mean R values in the 1–5 kt range recorded in (A) are also very different from the means for other wind-speed classes. Accordingly they are not included in the comparison.

Interpretation of results. The changes in the wind field as the wind blows from the land to the sea arise from two different physical sources. One is the result of the abrupt change in the roughness characteristics of the surface over which the wind is blowing. Some accounts of theoretical and experimental work on this problem are to be found in Panofsky and Townsend,[2] Bradley[3] and Taylor.[4,5,6] The other physical process is effected by the different thermal structure of the atmosphere over the sea. The effect of stability on the velocity profile in lower layers has been investigated at great length by Deacon,[7] Swinbank[8] and Lettau and Zabransky.[9] Other references to associated works may be found in the papers cited, and a general account is given in Priestley.[10]

The work on changes of terrain roughness introduces the concept of an internal boundary layer, arising at the region of discontinuity. From all the accounts, it may be supposed that the over-water fetch in this investigation is of a more than sufficient length to allow the profile of surface wind to attain an equilibrium form again, after passing through the transition zone of this internal boundary layer. The assumption is therefore made that the wind speed profiles at the observing stations are functions of the atmospheric stability at those stations and also of the roughness characteristics of the surface surrounding those stations.

For conditions of neutral stability the wind-speed profile follows the well-known logarithmic law,

$$u(z) = \frac{U_*}{k} \log_e \left(\frac{z}{z_0}\right)$$

where $u(z)$ is the mean horizontal wind speed at height z, U_* the so-called friction velocity, z_0 the roughness length and k von Kármán's constant $\approx 0 \cdot 4$. For non-neutral stability conditions this form is deviated from considerably and many empirical formulations have been made, to fit observational findings. Deacon[7] suggests

$$u(z) = \frac{U_*}{k(1-\beta)} \left[\left(\frac{z}{z_0}\right)^{1-\beta} - 1\right]$$

where $\beta > 1$ for unstable conditions and $\beta < 1$ for stable conditions. This formulation reduces to the logarithmic law as $\beta \rightarrow 1$ and as $(z/z_0) \rightarrow 1$, i.e. for small heights.

A different formulation suggested by Swinbank[8] was

$$u(z) = \frac{U_*}{k} \log_e \left[\frac{\exp(z/L) - 1}{\exp(z_0/L) - 1}\right]$$

$$\text{where} \quad L = -\frac{\rho U_*^{3} c_p T}{kgH}$$

and ρ is the air density, c_p the specific heat at constant pressure, T the air temperature, g the acceleration of gravity, and H the heat flow, defined as positive when directed upwards. Hence negative values of L indicate unstable conditions and positive values indicate stable conditions. For neutral stability L becomes infinite and Swinbank's formulation reduces to the ordinary logarithmic profile.

It is difficult to make use of the theoretical models described above when attempting to interpret and explain the results of this paper, the main reason being that the index T_d is only a measure of the initial stability over the sea. After an interval of time the temperature profile of the air is modified into a state more in equilibrium with the sea surface temperature. However, it is possible to make general statements about the physical processes involved which do explain some of the observations.

The first observation to explain is that the mean R values recorded in this paper are all greater than unity. This phenomenon becomes obvious when it is realized that the value of z_0 is at least 10 times less for the sea surface than for the land. As T_d becomes more positive, i.e. conditions become more stable over the sea, then $\beta_s < \beta_L$ and $L_s > L_L$, where the subscripts denote sea and land values. This effect induces a process in opposition to that brought about by the decrease in value of z_0, so much so that for the extreme conditions of stability recorded in (A) the value of R was observed to be less than unity. This explains why the increase in wind speed is less when conditions over the sea are stable. Finally, there is the fact that for strong winds the velocity profile is dominated by the effect of mechanical turbulence and hence the effect of changes in stability is very small. This fact explains why the stronger land winds are less affected by the changes in stability.

Conclusions. From a series of simultaneous wind measurements made at Gorleston and the Smith's Knoll Lightship it is deduced that :

(i) The ratio between wind speeds over the sea and over land, for off-shore winds, increases as the initial instability over the sea increases.

(ii) This increase is most marked for light land winds.

(iii) When initial conditions over the sea are stable the wind backs, when unstable the wind veers.

Acknowledgements. I wish to thank Mrs M. Mann who carried out the programming work necessary for this investigation, and Mr J. F. Keers who was instrumental in assembling the data.

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551.509.32:629.13

WEATHER FORECASTING FOR SUPERSONIC TRANSPORT

By M. H. FREEMAN, O.B.E.

Summary. The meteorological factors which will affect the operation of supersonic transport aircraft are discussed, and assessments are made of the accuracy which can be expected in forecasting the relevant meteorological elements. The items discussed are wind, temperature, turbulence, cloud, rain and hail. The problems of sonic boom and cosmic radiation are also considered.

Characteristics of Concorde. The appearance of Concorde is now familiar to all (Plate I). It is comparable in size to a Boeing 707 or a VC 10, but with a much smaller wing span. Concorde will be able to carry 128 passengers on stage lengths of 4000 nautical miles (approximately 7400 km) compared with about 140 passengers on legs of 5000 n. miles for a 707 or VC 10. The vital difference is that Concorde will do the London–New York trip in 3½ hours compared with 6–7 hours for the best subsonic jet aircraft.

The flight of a Concorde can be considered in four stages. During the take off and the climb at subsonic speeds to about 25 000 feet (400 mb), the aircraft will behave much as subsonic aircraft (though the rate of climb will be greater); the requirements for meteorological information will be similar. The transonic phase, when the aircraft will accelerate from Mach 0·93 to Mach 1·3, will normally take place between about 400 and 200 mb. This is when sonic boom will be most of a problem, and there may be restrictions imposed as to where the transonic acceleration will be allowed, e.g. only over sea. During this phase sudden manoeuvres are to be avoided, as are turbulence, hail or heavy rain and cumulonimbus generally. Acceleration will continue until Mach 2·2 (1200 kt) is reached at about 53 000 ft (100 mb) when the cruise phase will commence. This will probably be a cruise climb in which the aircraft gradually rises to about 60 000 ft (70 mb); as fuel is used the weight decreases. Later, as the number of supersonic transports (SSTs) increases, Air Traffic Control may require this phase to be operated in a series of steps to higher levels. In the final phase deceleration to subsonic speeds will be at about 50 000 ft, and thence Concorde will operate much as a subsonic jet aircraft during descent and landing.

Meteorological organization for Concorde. Since its maiden flight from Filton to Fairford in April 1969, Concorde 002 has operated from Fairford. Attached to the meteorological office serving the Royal Air Force there is a meteorological officer whose responsibility is liaison with Concorde's personnel and briefing of its aircrew. Forecasts for Concorde are prepared at the meteorological office at London/Heathrow Airport, and are transmitted to Fairford on a special facsimile line. At Heathrow, charts for 100 mb and 70 mb are plotted and analysed twice daily. In addition to forecasts for operational flights, Heathrow prepares forecasts twice daily for BOAC for simulated SST flights to New York and to Anchorage, Alaska. By the time Concorde is in regular airline service (about 1972), in most respects it will be 'just another aircraft' as far as provision of meteorological services is concerned. There will, however, be some differences in the importance attached to certain meteorological elements, and these will be considered in turn here.

Wind. Wind will be less of a problem than it is for subsonic aircraft. Wind speeds in the lower stratosphere (between 100 and 70 mb where Concorde will be cruising) are in general lower than those found in the jet streams of the upper troposphere. The much higher cruising speeds and lighter winds will mean that it is less profitable to deviate from the great circle in order to find a least-time track. The day-to-day variability of wind between 100 and 30 mb is much less than that between 300 and 200 mb and forecasting will be correspondingly easier. In fact the most recent actual chart may well provide the best 12- or 18-hour forecast, and should easily meet the stated requirement for root-mean-square vector error of less than 15 kt over 500-n. mile segments. At 50 mb the standard deviation of 24-hour vector change in wind has been quoted as about 10 kt (1 kt $\approx$ 0·5 m/s).

The Meteorological Office computer (COMET) at present provides objective analyses and forecasts at 100 mb for use at Heathrow. These are on a scale of $1:20 \times 10^6$ and cover the North Atlantic and North America. The 100-mb forecasts use a barotropic model and are produced independently of the 3-level model used for lower heights. Forecasts for 70 mb are produced subjectively at Heathrow, largely by noting the change predicted by the computer at 100 mb and applying a similar change to the 70-mb chart. On the next computer it is expected that the numerical forecasts will use a 10-level primitive-equation model extending from 1000 to 100 mb. Some further technique will be needed for forecasts for higher levels.

Temperature. The provision of accurate temperature forecasts will be of much greater importance to SSTs than it now is for subsonic aircraft. In the cruise phase at Mach 2·2, kinetic heating will raise the skin temperature of parts of the aircraft to near the acceptable limit and if ambient temperature is much above that of the International Standard Atmosphere (ISA) some reduction in speed may be needed, with a consequent increase in total fuel used. Temperature also affects fuel consumption because the higher the ambient temperature, the lower is the thrust produced by jet engines. It is worth remembering, however, that in the early days of jet engines, forecasters were asked to provide much greater precision in temperature forecasts than is now needed, and as SSTs develop the same thing may happen again. Meanwhile the performance of SST engines appears rather sensitive to changes in temperature of the environment, and forecasters will be called on to improve the accuracy of their temperature forecasts.

Temperature forecasts at eight levels from 850 to 150 mb are currently produced by COMET, using regression techniques based on forecast heights at 1000, 500, 200 and 100 mb. A requirement has been stated for temperature forecasts having a standard error not exceeding 3 degC. This is already largely being met at 300 mb and at lower altitudes, but at 200 mb the accuracy is not so good. In summer the required accuracy is just about being achieved, but some errors greater than 10 degC occur especially when the tropopause is low. Winter temperature forecasts at 200 mb are still not good enough. However, Brady* is developing a more sophisticated type of regression technique which attempts to take account of the tropopause and it is expected that when this is introduced operationally there will be a further improvement in upper-troposphere temperature forecasts.

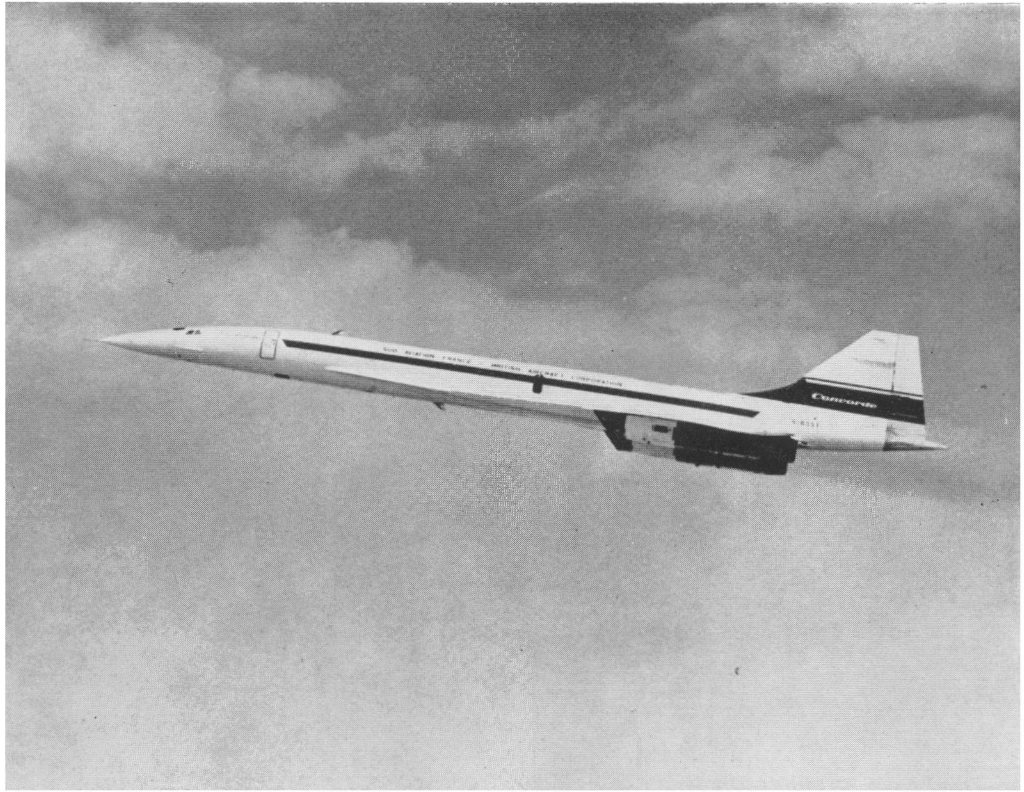
In the lower stratosphere above 100 mb the day-to-day variability of temperature is small for much of the year. At 50 mb over the Atlantic between April and October the use of monthly mean temperatures as forecasts would give standard errors of less than 3 degC, and elementary persistence forecasting would improve on that. During the winter months quite large temperature changes, the so-called 'sudden warmings', can occur. These are not, however, so sudden as to be unforecastable. The effect is often first observed at high levels (30 mb or above) and propagates downwards, and a warm area once found moves comparatively slowly from chart to chart, so that extrapolation methods will produce quite good forecasts for much of the time. If nothing better than a 24-hour persistence forecast were attempted a standard error of 2·7 degC would be achieved at 50 mb, taking the year as a whole.

A factor of importance to the designers of SST aircraft is the occasional occurrence of large temperature changes in short distances. An extreme figure of 10 degC in 1 n.mile has been recorded near cumulonimbus and 21 degC in 1 n.mile in a mountain wave. Temperature changes alter the Mach number, with a consequent need for the geometry of the air intakes to be altered. The design has to be able to cope with rapid changes. There is no possibility of forecasting the occurrence of localized large temperature gradients in advance.

Before leaving temperature it is worth considering the method of presenting the forecast information. Nowadays, forecast documentation for long-distance flights is in the form of several fixed-time constant-level charts with temperatures inserted at representative spots. Probably the part of flight for which temperature will be most critical is the transonic phase, which will normally take place in the upper troposphere. If temperatures in the usual transonic layer are much above standard but higher up there is a layer with standard or below-standard temperatures, then it would be profitable to delay the transonic acceleration to the higher level. Temperature forecasts are therefore presented as difference from ISA rather than as absolute values. Flight planning this phase is simplified if a vertical temperature cross-section along the prescribed climb route is provided. This should be practicable in the early days when routes and flights are fairly limited in number. After that most flight planning is likely to be on a computer-to-computer basis, and meteorological documentation for crews could perhaps be much simplified.

Turbulence. Turbulence will be at least as important to supersonic as to subsonic aircraft and, especially in the transonic phase, may be more so. The existing methods of forecasting clear-air turbulence (CAT) depend largely on locating zones with large vertical or horizontal wind shears or large temperature gradients, with mountain or other waves as additional factors. CAT is commonest below the tropopause but it can occur in the

*BRADY, W.R.; A method of deriving representative temperature profiles, including the tropopause, from the three-level forecast model. *Met. Mag., London*, **98**, 1969, pp. 373–386.



Photograph by courtesy of the British Aircraft Corporation.

PLATE I—CONCORDE 002 ON A TEST FLIGHT FROM ITS BASE AT ROYAL AIR FORCE, FAIRFORD, GLOUCESTERSHIRE

See page 138.

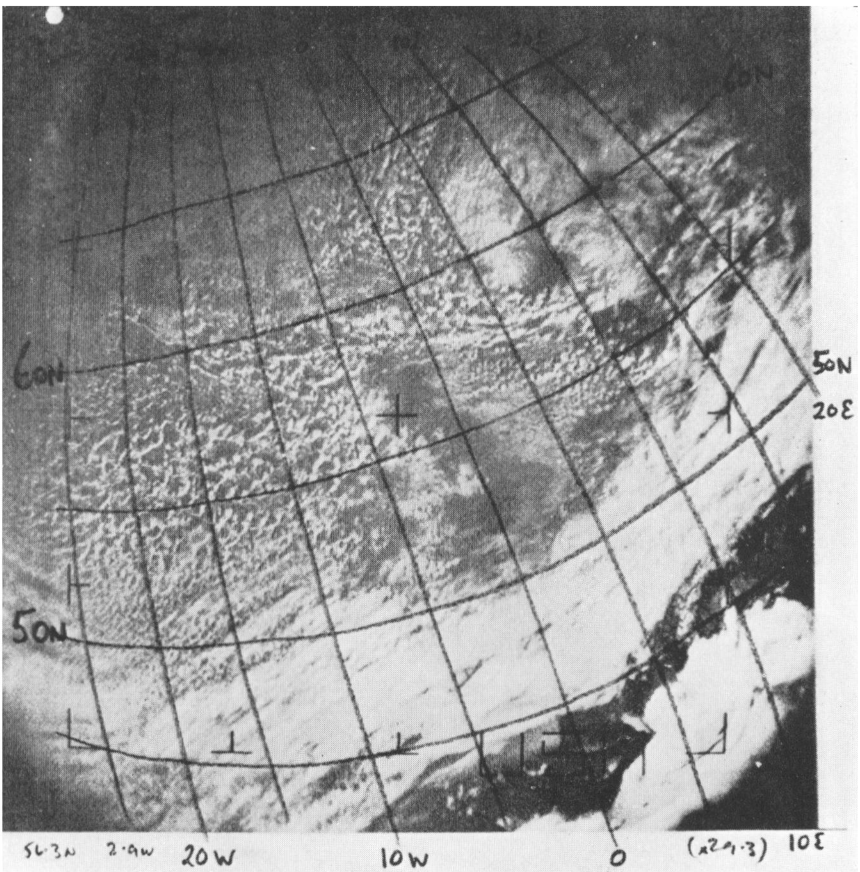
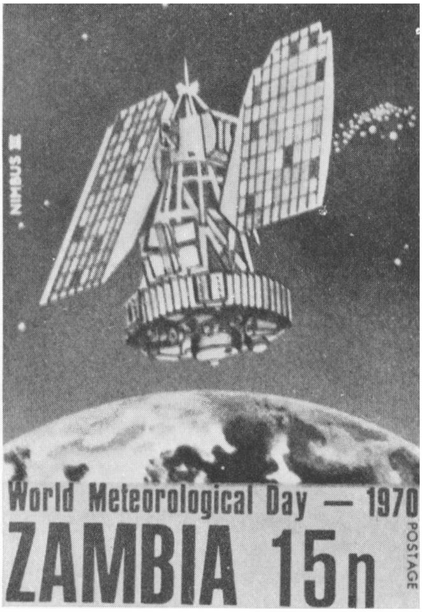


PLATE II—CLOUD PHOTOGRAPH FROM ESSA 8 AT 1041 GMT ON 20 NOVEMBER 1969 SHOWING THE BRITISH ISLES 'DISPLACED' 2° OF LONGITUDE EAST OF ITS TRUE POSITION

See page 152.



Photograph by courtesy of Crown Agents Stamp Bureau

PLATE III—SPECIAL STAMP ISSUED BY THE GOVERNMENT OF ZAMBIA TO COMMEMORATE WORLD METEOROLOGICAL DAY IN 1970

The stamp shows the artist's impression of the U.S. weather satellite NIMBUS III in orbit above the earth's surface.

To face page 141

Reproduced by permission of the Hydrographer of the Navy

PLATE IV—PROTOTYPE SELF-RECORDING METEOROLOGICAL BUOY SYSTEM BEING TESTED DURING THE ATLANTIC TRADE-WIND EXPEDITION IN FEBRUARY 1969

Instruments mounted on the buoy measure air and sea temperatures and run of wind, the data being recorded on magnetic tape. Similar buoys will be used during the preliminary Royal Society air-sea interaction experiment in June 1970, but will carry additional instruments to measure atmospheric pressure.

lower stratosphere, and must be expected in some degree at all levels of supersonic flight. Experience of forecasting CAT at high levels is small and there will be a need to develop further techniques during the proving-flight stage. The effect of turbulence on an aircraft depends on its characteristics and speed, as well as on the state of the atmosphere, so knowledge of the susceptibility of SSTs to turbulence can be built up only gradually. Present forecasts of CAT indicate the areas and heights which are considered favourable for it, but many aircraft fly in these areas without meeting it, and those who do experience CAT are unlikely to find it over the whole segment predicted in the forecast. In other words the forecasts tend to be definitely on the pessimistic side. A good proportion of CAT actually met is covered by the forecasts. Existing techniques can probably be extended to higher levels, but there is not much immediate prospect of significantly improving on the standard of forecasting clear-air turbulence.

During the climb and transonic phases the SST will suffer the same hazards from turbulence in and near cloud as does the subsonic aircraft, though the effects of such turbulence may be of greater importance to the SST as it goes transonic. Cumulonimbus is far the most likely source of severe turbulence in cloud and it will clearly be desirable for SSTs to avoid such clouds. Ordinary forecasting techniques can indicate fairly well the general areas in which cumulonimbus clouds of given extent are likely to occur, but they cannot, nor are they likely to be able to, say exactly where or when a cumulonimbus will occur. Ground-based weather radar can provide useful instantaneous information on the presence of cumulonimbus if suitable communication with the pilot is established. Such equipment is not likely to be available at all airfields and so a good deal of reliance will have to be placed on the evidence from airborne radar. Large temperature gradients and turbulence have been reported in clear air near cumulonimbus clouds, so it is important that any tops detected are avoided by a sufficient margin.

Cumulonimbus in the troposphere, for the climb and transonic stages, will be quite common, but cumulonimbus tops can extend into the stratosphere in favourable conditions. This is not likely to be a hazard to the cruise phase over the Atlantic, but in summer in central U.S.A. and in the tropics heights of 60 000 feet have been exceeded. If airborne radar shows a line of cumulonimbus clouds ahead the pilot has to decide whether to turn or attempt to overfly the tops long before they are reached. Since the radar indication of the height of the tops may not be as accurate as would be desired, good forecasts of the maximum possible heights of tops along the route would be of definite value, and should not be too difficult to provide.

Cloud, rain and hail. Cloud as such will not present any particular hazard. Since an SST will be climbing fairly quickly through any cloud layer, significant amounts of ice are likely to be uncommon, and in general the de-icing equipment will cope with it. The effect of impact of heavy rain and especially of hail is much more serious, and it is clearly desirable that flight through these conditions should be avoided. They are usually associated with cumulonimbus, which may be isolated or embedded in other cloud, and so are in regions which should be avoided anyway because of turbulence. Once again the pilot will have to rely on forecasts indicating the general areas in which the hazards of heavy rain or hail can occur, supplemented by more precise information from weather radar, both ground-based and airborne.

Sonic boom. The intensity of the sonic boom at the ground depends on characteristics of the aircraft such as its size, weight and the way it is being handled and also on the wind and temperature structure between the aircraft and the ground. In order to assess the magnitude of the boom and plan a flight path and speed which will comply with any government regulations on booms, the flight planners will need detailed forecasts of wind and temperature in the region where transonic flight commences, the most critical zone being for Mach numbers between 1·0 and 1·3. A vertical cross-section up to 50 000 ft for the first 200 n. miles from the departure aerodrome may well be the most convenient form of presentation, since the temperature inversions and wind shears which may produce focusing of the boom can readily be depicted by isotherms and isotachs. Local and short-lived variation in the fine structure of temperature and wind will occur, and could produce localized booms much in excess of the general level. There will be no possibility of producing forecasts of these minor, but maybe important, variations.

Cosmic radiation. Cosmic radiation, similar to radiation from radioactive material, is continually entering the earth's atmosphere from space and being absorbed. In normal conditions the level of activity is easily low enough not to present any hazard to passengers in a Mach 2 aircraft, and probably also at the greater heights flown by a Mach 3 aircraft. During periods of maximum solar activity, rare (i.e. 2 or 3 per year) but important outbreaks of cosmic radiation can occur associated with solar flares. Unacceptably high radiation doses may then be experienced, especially at the Mach 3 levels. Fortunately protection can readily be obtained by descent to lower altitudes, where screening by the atmosphere above is adequate. The problem is worst in high geomagnetic latitudes, and on transpolar flights descent to 40 000 ft may be necessary.

Forecasts for some 10 to 100 minutes ahead might be made on the basis of observations of the sun's disc and by monitoring the high-energy protons reaching the ground, but reliable warnings could not be passed to the aircraft in flight because these are just the times when radio communication is likely to be interrupted. It will be necessary therefore for SST aircraft to carry radiation monitoring devices, perhaps including an audible warning, so that suitable avoiding action can be taken. If practicable a warning that an aircraft had experienced exceptional cosmic radiation should be passed to other aircraft as soon as possible.

The Space Disturbance Forecast Center of the U.S. Environmental Science Services Administration makes available its longer-period warnings that conditions are suitable for cosmic outbursts. These are disseminated by the Aeronautical Fixed Telecommunications Network, and serve to alert airlines, pilots and ATCs to the possible need for avoidance action. It has been stated that 70 per cent of solar proton events could be predicted with a 3 to 1 false-alarm rate.

Conclusions. On the whole, meteorological services should be able to meet the operational requirements of SSTs for forecasts. Wind will not be difficult; in the early days the accuracy of temperature forecasts may be only barely good enough but this will become less critical as forecasts and engines both improve. Precise forecasts of the position of turbulence and cumulonimbus will not be generally possible, but the broad indications of the areas in which they are likely to occur should gradually improve. Cosmic radiation is not a matter for which meteorological services will be responsible, beyond perhaps disseminating warnings, and airborne detectors will be the main safeguard.

551.521.11(410):523.74

EXTREMES OF MONTHLY AND ANNUAL SUNSHINE DURATION IN THE BRITISH ISLES

By E. N. LAWRENCE

Summary. Long-period extremes of monthly and annual sunshine duration over the British Isles are studied in relation to general meteorological data for the period 1890 to 1968 and Kew Observatory sunshine data for the period 1881 to 1968.

Results show that (i) the upper extremes occurred in coastal areas of the extreme south, south-east and south-west and (ii) the lower extremes occurred mainly in the north, particularly at high-level sites but also in urban industrial areas. The upper extremes usually occurred with anticyclones and dry easterly and northerly winds but also with north-westerlies in winter: the lower extremes occurred with cyclones and moist westerly airstreams but also with anticyclones and uniform pressure gradients in urban industrial areas in winter and at stations on the north-east coasts exposed to airstreams with a long North Sea track.

The upper extremes of sunshine duration occurred mainly in those years with odd dates, thus confirming the well-known '2-year' periodicity. The time-distribution of monthly extremes over the British Isles and the year-to-year variation of sunshine duration at Kew showed the '11-year' cycle with (i) the sunshine peak occurring with decreasing sunspots, at about two years after the sunspot maximum and (ii) the sunshine minimum occurring with increasing sunspots or near the sunspot minimum.

Introduction. The present note describes the results of a study of some time and space variations of the extremes of monthly and annual sunshine duration in the British Isles.

Data. Table I gives a list of monthly and annual extremes of sunshine duration since 1890. These data are based on records of extremes maintained by the Meteorological Office and refer to networks of sunshine-recording stations mainly as indicated in the *Monthly Weather Report.*[1] The locations of stations listed in Table I are shown in Figure 1. Relevant atmospheric pressure data and details of the synoptic features and surface winds were obtained from the *Daily Weather Report.*[2] Sunshine data (1881–1967 inclusive) used for the statistical analysis of Table II refer to Kew Observatory (51° 28′N, 00° 19′W, 18 ft (5·5 m) above MSL). Figures 2 and 3 are based on annual sunshine summaries.[3]

The data refer to the duration of bright sunshine as measured by the Campbell-Stokes type of sunshine recorder, but for some of the earlier records (for example, at Westbourne, Sussex, in 1893) a Jordan recorder may have been used. Records from these two instruments may show relatively large day-to-day differences but if the two instruments are exposed side by side, their records of total sunshine over a long period are not greatly different.[4] It is assumed, for the present investigation, that over a period of a month, the relatively small proportion of data which is obtained from Jordan recorders can be used to supplement data from the Campbell-Stokes type.

In the most favourable circumstances, sunshine can be recorded when the sun is three degrees above the horizon, say 20 minutes after sunrise or before

TABLE I—EXTREMES OF MONTHLY AND ANNUAL TOTALS OF BRIGHT SUNSHINE IN THE BRITISH ISLES, 1890–1968

	January	February	March	April	May	June	July	August	September	October	November	December	Year
Upper extremes													
Total sunshine (hours)	115·5	167	253	302	353	382	384	325	281	207	145	116·5	2340
% of possible sunshine	44	59	69	73	74	78	77	73	74	62	53	47	53
Year	1959	1891	1929	1893	1909	1925	1911	1899	1959	1920	1923	1962	1893
Year relative to year X*	+2	−2	+1	0	+4	−3	+6	+6	+2	+3	+6	+5	0
Place	Bournemouth	St Helier	Aberystwyth	Westbourne (Sussex)	Worthing	Pendennis Castle	Hastings Eastbourne	Villa Carey (St Peter Port)	Gorey Castle	Felixstowe	Falmouth	Eastbourne	St Helier
Latitude (N)	50° 43′	49° 11′	52° 25′	50° 52′	50° 49′	50° 09′	50° 52′ 50° 46′	49° 27′	49° 12′	51° 57′	50° 09′	50° 46′	49° 11′
Longitude	01°53′W	02° 06′W	04° 05′W	00° 55′W	00° 22′W	05° 03′W	00° 34′E 00° 17′E	02° 32′W	02° 01′W	01° 20′E	05° 05′W	00° 17′E	02° 06′W
Ht of ground above MSL(ft)	125	25	69	30	35	200	240 35	180	0	15	167	35	25
Ht of recorder above ground (ft)	57	5	6	6	55	40	40 100	45	270	5	33	86	5
‡Mean pressure (mb)	1013	1032	1017	1022	1018	1022	1018	1020	1021	1016	1010	1017	1016
‡Mean pressure 1931–60 (mb)	1016	1017	1015	1016	1017	1017	1016	1017	1017	1016	1014	1015	1016
Main synoptic features† and surface winds	C & NW'ly → A	A E'ly	A E'ly to N'ly	A E'ly	A	A N'ly	A	A E'ly	A E'ly	E'ly, SE'ly	NW'ly	A & E'ly, NW'ly	
Lower extremes													
Total sunshine (hours)	3·6	4·3	25·0	35·9	59·6	60·9	50·1	43·9	34·3	8·0	4·9	0·0**	696·2
% of possible sunshine	1·5	1·6	6·8	8·6	12·0	11·4	9·2	9·4	8·9	2·4	1·9	0·0	15·6
Year	1901	1966	1916	1920	1967	1912	1961	1912	1967	1968	1942	1890	1961
Year relative to year N*	0	+2	+3	−3	+3	−1	−3	−1	+3	+4	−2	+1	−3
Place	Morpeth (Cockle Park)	Great Dun Fell	Whitworth Park (Manchester)	Whitworth Park (Manchester)	Great Dun Fell	Crathes	Strathy	Eskdalemuir	Baltasound (Shetland)	Great Dun Fell	Burnage (Manchester)	Westminster (London)	Great Dun Fell
Latitude (N)	55° 13′	54° 40′	53° 28′	53° 28′	54° 40′	57° 02′	58° 31′	55° 19′	60° 46′	54° 40′	53° 26′	51° 30′	54° 40′
Longitude (W)	01° 41′	02° 26′	02° 14′	02° 14′	02° 26′	02° 25′	04° 01′	03° 12′	00° 53′	02° 26′	02° 12′	00° 08′	02° 26′
Ht of ground above MSL (ft)	324	2780	125	125	2780	140	120	794	80	2780	147	27	2780
Ht of recorder above ground (ft)	4	3	11	11	3	6	4	5	5	3	5	80	3
‡Mean pressure (mb)	1013	1000	1006	1005	1007	1008	1011	1006	1008	1012	1025	1013	1013
‡Mean pressure 1931–60 (mb)	1011	1014	1015	1015	1016	1014	1011	1013	1010	1013	1012	1011	1014
Main synoptic features† and surface winds	S & SE'ly →W'ly	C	C NE'ly	C	C	C	NW'ly	C	C	SW'ly	A	A E'ly	

*X and N are the years of the relevant maximum and minimum annual sunspot-relative-number, respectively.
†C = cyclonic A = anticyclonic.
**0·1 h at Bunhill Row, 51° 31′N, 00° 05′W, 80+80 ft; 0·3 h at Kew Observatory, 51° 28′N, 00° 19′W, 18+44 ft.
‡Sea level.

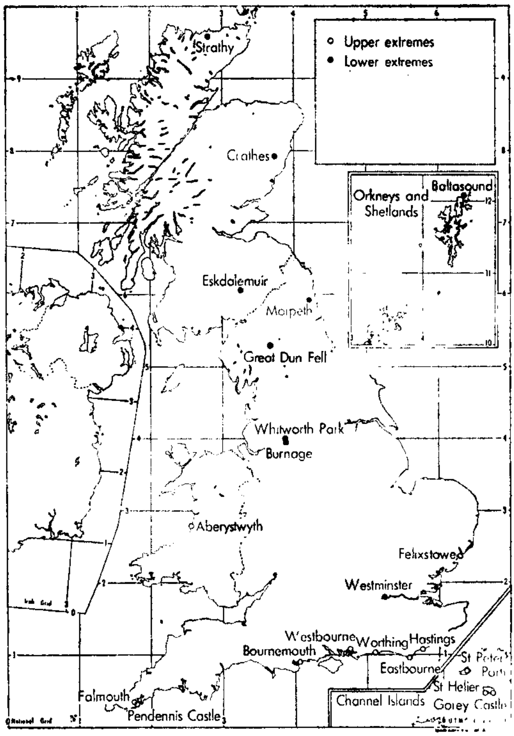


FIGURE 1—STATIONS WITH MONTHLY EXTREMES OF DURATION OF BRIGHT SUNSHINE

Stations are listed in Table I.

sunset; but this implies a very clear atmosphere when the loss of record due to reduction of intensity of transmitted sunlight by atmospheric absorption and scattering is minimal. There is also a slight obstruction by the instrument when the sun's angle of elevation is very low, so that in general for half an hour at either end of a fine day, there is no record trace. Hence, the effective length of the possible duration of 'bright sunshine' may be about an hour less than the total length of daylight which is used to calculate the percentage of possible sunshine duration in Table I. Daylight is defined as beginning and ending when the upper limb of the sun is apparently on the horizon, due allowance being made for refraction and assuming that both observer and horizon are at sea level.[5]

Restriction of the exposure of a sunshine recorder by hills, buildings, etc., should also be taken into consideration. For the stations of Table I, the percentage loss of sunshine for angles of solar elevation greater than three degrees is estimated not to exceed approximately five per cent. In this connection, it must be remembered that the loss of record due to low-angle obstruction is small because within an hour or so of sunrise and sunset, sunshine is limited by cloud, haze or atmospheric absorption even when the horizon is unobstructed (see, for example, Furmage[6] Figure 1 of reference). Many stations in west Scotland have considerable natural obstructions and are consequently excluded from the present investigation.

Geographical distribution and synoptic features. The extreme values of sunshine duration recorded in Table I, though dependent on the local topography of the sites, are generally representative of large areas where the overall conditions are primarily dependent on the macrometeorological or synoptic situation; the statements in *Monthly Weather Reports*[1] draw attention to the occurrence of sunshine duration extremes over extensive areas in the months concerned.

Table I and Figure 1 show that all of the upper extremes of monthly sunshine duration occurred on or near coasts in the south, whereas the lower extremes of sunshine were mainly in the north of the British Isles, particularly at high-level stations and those exposed to moist Atlantic air masses but also in urban industrial areas, exposed to smoke pollution.

The geographical distribution for non-urban stations persists throughout the year and so does not depend solely on the latitudinal variation in the length of daylight. In summer, the north has the lower extremes of sunshine despite the longer days, while the south has the upper extremes. This spatial pattern of extreme sunshine duration is similar to that for sunshine averages[7] and furthermore, the pattern is very similar to that obtained for the extremes of yearly totals of bright sunshine for individual years, as indicated in Figure 2 for 1967 and Figure 3 for 1968.

The geographical distributions of the upper extremes for both 1967 and 1968 (Figures 2 and 3) are strikingly similar to that indicated in Figure 1 for the monthly extremes over the period 1890 to 1968. With reference to the lower extremes, Figure 2 (for 1967) is rather more like Figure 1 than is Figure 3 (for 1968), presumably because in 1967 the difference between the north and south of the British Isles (with more sunshine in the south) was enhanced, whereas in 1968, the difference was reduced. For example, the sunshine in 1967 expressed as a percentage of the 1931–60 average for England and Wales, Scotland, and Northern Ireland was 109, 102, and 97 respectively, but the corresponding values for 1968 were 88, 97 and 107.[1]

The spatial distribution of the stations of Table I suggests that 'continental' sites (or locations with possible short sea track from the continent) are liable to upper extremes of sunshine duration while the more 'oceanic' sites (or locations with possible long North Sea track), especially high-level ones, are much more liable to low extremes of sunshine. Also, the fact that all the upper extremes occurred at coastal sites suggests that inland convection cloud in summer, and radiation fog in winter, play an important role in reducing sunshine.

Further evidence of the effects of topography is found in the results of a synoptic analysis (Table I). The upper extremes of sunshine usually occurred with anticyclones and dry easterly and northerly winds but also with north-westerlies in winter : the lower extremes of sunshine occurred with cyclones and moist westerly airstreams but with some important exceptions which are described later. These relationships between sunshine and the synoptic pattern are clearly reflected in the corresponding values of mean monthly atmospheric pressure. Thus, as indicated in Table I, the upper extremes of sunshine usually occur with above-average pressure and the lower extremes of sunshine tend to occur with below-average pressure, at least for non-urban sites.

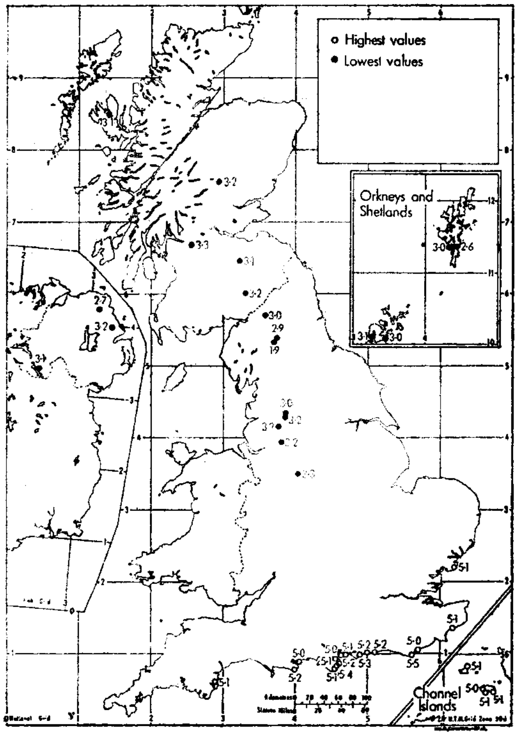


FIGURE 2—THE 20 STATIONS WITH THE HIGHEST VALUES AND THE 20 STATIONS WITH THE LOWEST VALUES OF MEAN DAILY DURATION OF BRIGHT SUNSHINE IN 1967

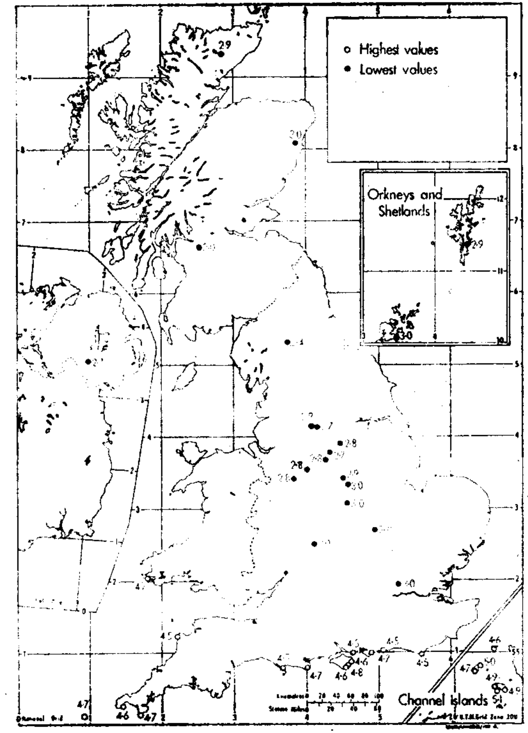


FIGURE 3—THE 20 STATIONS WITH THE HIGHEST VALUES AND THE 20 STATIONS WITH THE LOWEST VALUES OF MEAN DAILY DURATION OF BRIGHT SUNSHINE IN 1968

Excluding stations for which the estimated percentage loss of sunshine because of obstructions exceeds approximately 5 per cent.

A notable exception to the occurrence of low extremes of sunshine with cyclonicity and below-average pressure took place in November 1942 at Burnage, Manchester (Table I). This month was quiet, dry and anticyclonic, and fog and poor visibility developed frequently, especially in large towns. Similar conditions (but with easterlies dominating) prevailed when, in December 1890, Westminster was sunless, and only 0·1 and 0·3 hours were reported at Bunhill Row (in the City of London) and at Kew Observatory, respectively. The low extreme at Kew occurred within five years of the upper extreme at Kew, namely 72 hours in December 1886.[8] The low extremes at Whitworth Park, Manchester, though caused mainly by cyclones, were probably affected by smoke pollution. Following the Clean Air Act of 1956, it would be expected that the chance of air pollution causing low extremes of sunshine duration in the major urban centres would be lessened.

Further exceptions to the association of very low sunshine values with below-average atmospheric pressure occurred at Morpeth (Cockle Park) and Strathy (see Table I). The low extremes of sunshine at these stations were caused by persistent moist airstreams, and at Morpeth at least, partly by North Sea stratus.

Sunshine duration tends to decrease with height above sea level because there is a tendency for increased cloud on hills (see Table 1). A comparison[9] between durations at Fort William (100 ft + 5 ft) and Ben Nevis (4405 ft + 15 ft), which are only about three miles apart, showed that, for the period 1891 to 1902, the duration of sunshine was similar in midwinter but that in midsummer the duration of bright sunshine at the summit of Ben Nevis was only about two-thirds of that at the low-level station, in spite of obstruction at Fort William causing a 15 to 20 per cent loss of sunshine during the summer.

Year-to-year variation. The upper extremes of sunshine, with the exception of those for October and December, occurred in odd-dated years (Table I), thus confirming a well-known periodicity.

All but two of the upper extremes of sunshine occurred in the period from sunspot maximum to sunspot minimum, that is, in the decreasing-sunspot period of the '11-year' solar cycle (Table I). The average date of the upper sunshine extremes is 2·5 years after a sunspot maximum.

The lower extremes of sunshine duration for non-urban sites occurred in the approximately opposite part of the '11-year' solar cycle, namely in the increasing-sunspot period and around the sunspot minimum. Excluding the urban sites in London and Manchester, seven of the eight remaining low extremes occurred from 1 year before the sunspot minimum to 4 years after it, the average date being about 1 year after the sunspot minimum. This position in the solar cycle is equivalent to about 3 years before the sunspot maximum because the increasing-sunspot period is, on average, about 4 years long as compared with about 6 to 8 years for the decreasing-sunspot period. The two urban low extremes of sunshine duration which were associated with anticyclones occurred near the sunspot minimum or rather earlier.

The relationship between sunshine and the '11-year' solar cycle is confirmed by the results of a correlogram analysis between monthly sunshine duration at Kew (using data from 1881 to 1967) and the annual sunspot-relative-

TABLE II—LAGGED CORRELATION COEFFICIENTS BETWEEN THE SEASONAL DURATION (D) OF BRIGHT SUNSHINE AT KEW* AND THE ANNUAL SUNSPOT-RELATIVE-NUMBER (t) EXPRESSED AS A PERCENTAGE OF THE MAXIMUM VALUE OF THE RELEVANT SUNSPOT CYCLE

Season	Period of data from :		** Lag (in years) −5	−4	−3	−2	−1	0	+1	+2	+3	+4	+5	+6	+7	+8
June, July and August	1881	Correlation coefficient × 10^3	−092	−131	−203	−196	−053	+067	+145	+192	+162	+098	−067	−088	−018	−156
		No. of years†	83	84	85	86	87	87	87	87	87	87	87	87	87	87
		Latest year of sunshine data	1963	1964	1965	1966	1967	1967	1967	1967	1967	1967	1967	1967	1967	1967
		p‡			0·07					0·07						
October, November and December	1881	Correlation coefficient × 10^3	−154	−221	−181	−131	−044	+103	+152	+181	+106	+056	−051	−125	−154	−067
		No. of years†	83	84	85	86	87	87	87	87	87	87	87	87	87	87
		Latest year of sunshine data	1963	1964	1965	1966	1967	1967	1967	1967	1967	1967	1967	1967	1967	1967
		p‡		0·04						0·09						
	1900	Correlation coefficient × 10^3	−214	−313	−279	−246	−118	+097	+195	+289	+238	+165	−001	−138	−206	−137
		No. of years†	64	65	66	67	68	68	68	68	68	68	68	68	68	68
		Latest year of sunshine data	1963	1964	1965	1966	1967	1967	1967	1967	1967	1967	1967	1967	1967	1967
		p‡		0·01					0·01–0·02							
		Sign of correlation coefficient	Negative					Positive					Negative			

*Kew Observatory : 51° 28′N, 00° 19′W, 18 ft above MSL.
**Lag used in calculating the correlation coefficients = (year date)$_D$ − (year date)$_t$
†The value of the sunspot-relative-number for 1968 was assumed to be a cycle maximum of 100.
‡p is the significance level.

number, expressed as a percentage of the maximum value of the relevant sunspot cycle. When the sunspot-relative-number is at a minimum it is expressed as a percentage of the mean of the two adjacent sunspot maxima. The use of this solar variable emphasizes the importance of the *position* of a year within a solar cycle. Table II shows that for both summer (June, July and August) and autumn-winter (October, November and December), the sunshine peak tends to occur about two years after a sunspot maximum, while the lower extremes of sunshine tend to occur around the sunspot minimum and during the sunspot-increasing period.

The higher correlations between sunshine and 'sunspots' for the somewhat shorter period (from 1900), shown in Table II, reflect the effects of phase change in the relationship. A suggested explanation of the relationships between sunshine and solar cycle is given elsewhere.[10-12]

Conclusions. Results show that (i) the upper extremes occurred in coastal areas of the extreme south, south-east and south-west and (ii) the lower extremes occurred mainly in the north, particularly at high-level sites but also in urban industrial areas. The upper extremes usually occurred with anticyclones and dry easterly and northerly winds but also with north-westerlies in winter: the lower extremes occurred with cyclones and moist westerly airstreams but also with anticyclones and uniform pressure gradients in urban industrial areas in winter and at stations on the north-east coasts exposed to airstreams with a long North Sea track.

The upper extremes of sunshine duration occurred mainly in those years with odd dates, thus confirming the well-known '2-year' periodicity. The time-distribution of monthly extremes over the British Isles and the year-to-year variation of sunshine duration at Kew showed the '11-year' cycle with the sunshine peak occurring with decreasing sunspots, at about two years after the sunspot maximum, and the sunshine minimum occurring with increasing sunspots or near the sunspot minimum.

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551·509·313:551·515·8:517·9

THE LAPLACIAN AND ITS RELEVANCE FOR ANALYSIS

By T. H. KIRK

The Laplacian operator, symbolically written $\partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2$ or more briefly ∇^2, occurs frequently in meteorology. Examples are the expression for geostrophic vorticity in terms of the geopotential, and the 'omega' equation. Recently, the use of the Laplacian in analysis has been advocated.[1,2]

The purpose of this note is to show that the physical interpretation of the Laplacian, first given by Maxwell[3] and recently re-emphasized,[4] can lead to a wider appreciation of its function and to a more general concept of meteorological analysis.

If φ is any scalar continuous function of position, having a value φ_0 at a point o, then it can be shown[4] that the average value of φ in the immediate neighbourhood of o, denoted by φm, is given by

$$\varphi m = \varphi_0 + \frac{h^2}{24}(\nabla^2\varphi)_0$$

where h is a small measure of distance and $(\nabla^2\varphi)_0$ is the value of the Laplacian at the point o.

Rearrangement of this equation gives

$$(\nabla^2\varphi)_0 = \frac{24}{h^2}\ (\varphi m - \varphi_0)\ .$$

The important result of immediate physical interest is therefore :

(i) The Laplacian of a function at a point o is a measure of the local anomaly of that function relative to the function's average in the immediate neighbourhood of o.

It follows directly from (i), or it may be deduced independently, that if the distribution of φ is *linear* then $\nabla^2\varphi = 0$. The second important interpretation may therefore be expressed as follows :

(ii) The value of the Laplacian of a function is a rough indication of the *non-linearity* of its distribution. In particular, the vanishing of the Laplacian denotes a *quasi-linear* distribution of the function.

These results may be used to clarify the concept of 'air mass', hitherto only qualitatively defined in terms of a quasi-constancy of property. If the property is S, e.g. potential temperature, then a constancy of S implies $\nabla^2 S = 0$. In practice, more generally, the term 'air mass' comprehends a uniform variation of property rather than a constancy. It is therefore still possible to conceive of an air mass as specified ideally by $\nabla^2 S = 0$.

At the present time, when numerical methods are being employed to produce distributions of most meteorological elements, it might appear somewhat anomalous that subjectively analysed fronts are still a feature of surface charts. It is conceded that these are useful at a level below the synoptic scale, although their positions are subject to some uncertainty and there is occasionally doubt about what, in fact, is being depicted. It might be argued that the pristine simplicity of the frontal concept has been lost and that its use will be unnecessary in the future at a time when all meteorological elements can be calculated and printed out at will. We may ask the question, 'What is the essence of the frontal concept as far as the *synoptic* scale is concerned ?' In other words, what is worth while depicting on the charts interchanged between nations ? Is it possible to retain the essential character of the concept and at the same time achieve a greater objectivity consistent with the use of numerical methods ?

An immediate solution suggested by the above results is to recognize non-linearity of property as the fundamental characteristic worthy of representation in addition to the distribution of the property itself. This is consistent with the use of the vorticity chart in relation to the contour chart.

In the application to frontal analysis, it must be recognized that the different aspects of fronts and frontal activity[2] may be expressed by a suitable choice of parameter. Traditionally, fronts have been associated with the non-linearity of the thermal field and this aspect finds expression in the use of the thermal vorticity chart. This type of chart is in current use at Bracknell for the interpretation of frontal zones.

In recent years, fronts have come to be identified in terms of their dynamical properties, in particular the vertical velocity. This is derived as a product of the computer programme and is also implicit in the cloud photographs from satellites. In the light of the foregoing argument, a chart of $\nabla^2 dp/dt$, expressing the non-linearity of the distribution of the vertical velocity, is suggested as an appropriate method of depicting fronts on the synoptic scale. Although, with present models, the grid lengths are too large for the optimum calculation of Laplacians, this state of affairs is rapidly changing. New models will soon be available, employing much shorter grid lengths, and new techniques of objective analysis[5] will permit calculation to a higher degree of accuracy.

This method of analysis is independent of the details of current frontal theory and practice — a very desirable characteristic !

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THE DISPLACED BRITISH ISLES

By G. C. JOHNSON

The satellite picture reproduced in Plate II was taken by ESSA 8 at 1041 GMT on 20 November 1969. It appears to show the displacement of the British Isles some 2° of longitude to the east of its true position.

An obvious possible explanation is that the grid was incorrectly drawn, but close scrutiny showed that this was not so. The calculated centre fiducial point value of 56·3°N 02·9°W is correct, and further checks on identifiable geographical features of Norway (the coast, and Sognefjord at 61°N) the French coast at 44°N, and the Alps, confirm this.

The explanation of the apparent displacement is thought to be as follows. At the time of the picture pressure was low over Scandinavia with the British Isles lying in an unstable west-north-west airstream which followed the passage of a cold front on the 19th. Cumuliform cloud forming in the unstable airstream was carried across western coasts, in general only as far as the main high ground barrier presented by the Welsh Mountains, Pennines, etc., though some degree of penetration is evident even over high ground. This is particularly noticeable over the southern Pennines into Lincolnshire. The apparent western coastline at 3°W is therefore not the true coastline, but indicates the eastern limit of penetration of the cloud.

On the eastern side of the high ground the air was a little too dry and temperatures too low for marked convection to occur. After leaving the coast, however, the air would pick up moisture from the sea, and also be affected by the higher temperatures of the water surface; convection would then be expected to become increasingly vigorous with length of sea track, i.e. after sufficient moistening and warming had taken place. This, together with the fact that the newly formed cloud would only become visible on the picture upon attaining the size and amount capable of detection by the automatic picture transmission system, means that the cloud edge would therefore be found at roughly the same distance from the east coast for most of the length of the British Isles, and thus have the same shape as the coastline, but be displaced further to the east.

The fact that the true coastline cannot be seen, even where cloud free, is due to the very similar reflective qualities of land and sea throughout the British Isles under most conditions. Only when favourable conditions exist, enhancing the reflective nature of either the sea (sun–satellite relationship giving 'sun glint') or the land (snow), can the true coastline of the British Isles be seen.

REVIEW

Essentials of meteorology (Volume 3 of the *Wykeham Science Series*), by D. H. McIntosh and A. S. Thom. 215 mm × 140 mm, pp. 239, *illus.*, Wykeham Publications (London), Cannon House, Macklin St, London WC2. Price : £1 (paperback).

This book by two meteorologists on the staff of the Department of Natural Philosophy at Edinburgh University, is one of a series which, according to the publishers, is intended 'to broaden the outlook of the senior grammar school pupil and to introduce the undergraduate to the present state of science as a university study'. The approach is therefore that of the scientist rather than that of the geographer; as the authors roundly declare in their opening words, 'Meteorology is a branch of physical science'.

The book follows the conventional order of teaching the subject to meteorologists. After a brief but cogent statement of what meteorology is about, there are chapters on the physical properties of the atmosphere, heat transfer, condensation and precipitation, the tephigram, winds, instruments and observations, synoptic meteorology, micrometeorology, the general circulation and weather forecasting.

It is a very good book, clearly and concisely written. There are useful exercises at the ends of chapters. The diagrams are well drawn. The index is sufficient. The book is well printed and attractively produced. An experienced synoptic meteorologist to whom the reviewer lent his copy thought that synoptic meteorology was a little less thoroughly treated than some of the other topics, but it must always be a matter of opinion how deeply one should go in writing about a subject.

Will the book serve its purpose ? The mathematics and physics should present no difficulties to a senior sixth-form student, though the book probably goes into more detail than the average sixth-former requires (in devoting, for example, a whole chapter to the tephigram) — more especially as the publishers offer six other books for sixth-formers to read in the same series. But it will undoubtedly serve as a very useful introduction to the subject for the university student or the budding professional meteorologist. At the rate at which the subject is progressing, especially in such fields as World Weather Watch and numerical forecasting, the book will need revision with each new edition (for it certainly deserves to run to several editions), but at the price of £1 anyone who wishes to keep up to date ought to be able to afford to discard an old edition after a few years and buy a new one.

S. E. VIRGO, O.B.E.

LETTER TO THE EDITOR

551·509·314:551·509·323

Forecasting night minimum air temperature by a regression equation

Gordon, Perry and Virgo* developed a regression equation between $(T_{12}+D_{12})$ and $T_{\min}$ for Mildenhall, based on data for 1967 and 1968. T_{12} and D_{12} are, respectively, the screen temperature and dew-point recorded at 1200 GMT and $T_{\min}$ is the screen minimum temperature recorded on the succeeding night. Excluding nights on which the dew-point changed by more than 2 degC and nights when fog formed or when there was a noticeable front in the area, they found the equation

$$T_{\min} = 0{\cdot}395\ (T_{12} + D_{12}) - 1{\cdot}334$$

to be valid throughout the year, the correlation between $T_{\min}$ and $(T_{12}+D_{12})$ being 0·87 and the root-mean-square error 2·34 (temperatures are in degrees Celsius throughout).

Temperatures at Yeovilton in 1967 and 1968 have been examined. In 1968, 102 days were identified as satisfying the above criteria. Temperatures on these days produced the regression equation

$$T_{\min} = 0{\cdot}482\ (T_{12}+D_{12}) - 2{\cdot}67$$

*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.

with a correlation of 0·91 and a standard error of estimate of T_{min} of 2·18. The scatter diagram exhibits no tendency to non-linearity and, by chance, the extreme values of T_{min} lie close to the regression line. In 1967, 103 days were identified and the temperatures of the 205 days of 1967 and 1968 produced the regression equation

$$T_{min} = 0{\cdot}463\ (T_{12}+D_{12}) - 2{\cdot}30$$

with a correlation of 0·88 and a standard error of estimate of T_{min} of 2·34, these latter two figures being similar to those obtained by Gordon, Perry and Virgo. The composite scatter diagram exhibits no tendency to non-linearity.

On the assumption that the actual T_{min} will be normally distributed about the value predicted by this regression line, it is a short step to produce the following table for forecasting air frost, that will be applicable at Yeovilton on those days, on average two days a week, which are in the category under consideration. Similar tables could, of course, be produced for forecasting the probability of T_{min} falling below any other given value which may be of particular interest.

$T_{12} + D_{12}$ (degC)	>11·1	11·1	9·0	7·5	6·2	5·0	<5·0
Probability that T_{min} will be ≤0°C (per cent)	<10	10	20	30	40	50	>50

RNAS Yeovilton INSTRUCTOR COMMANDER J. MARSH, M.A., A.F.I.M.A., R.N.
Ilchester, Somerset

OBITUARY

It is with regret that we have to record the death of Mr K. R. Suche (Senior Scientific Assistant) on 16 January 1970.

RECENT PUBLICATION

Artificial modification of clouds and precipitation

World Meteorological Organization *Technical Note* No. 105* discusses the difficulty of evaluating the results of rain-making experiments and emphasizes the fact that more research is required before any technique could be recommended for operational purposes.

The case is much the same for the suppression of hail and lightning, which are also considered, but as regards dissipation of supercooled liquid fog over airports, for example, techniques are now known well enough to warrant operational use.

This publication, which is mainly a revision of the *Technical Note* No. 13 issued in 1955, shows that research and operational experience in the intervening 14 years have given no grounds to alter the basic conclusions reached at that time.

Professor Morris Neiburger of the U.S.A., who undertook the task of bringing this information up to date, has produced a lively treatment of the subject which will interest a range of readers much wider than professional meteorological circles.

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*NEIBURGER, M.; Artificial modification of clouds and precipitation. *Tech. Notes Wld met. Org., Geneva,* No. 105, 1969. (Available from WMO Secretariat, Geneva. Price: 16*s*.)

OFFICIAL PUBLICATION

SCIENTIFIC PAPER

No. 30. Orthogonal polynomials as a basis for objective analysis. By R. Dixon, B.Sc.

In current meteorological practice computer analyses of meteorological fields are done by grid-pointwise techniques in which the analytical process is repeated at every one of a large number of grid points. This paper presents an alternative approach in which a high-power bivariate polynomial is fitted to the data over a large area; the results for several such areas are joined together to form the complete analysis. Orthogonal polynomials are used to overcome certain computational difficulties in the fitting of high-powered polynomials.


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