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A NOTE ON THE AVERAGE ANNUAL MEAN OF DAILY EARTH TEMPERATURE IN THE UNITED KINGDOM

By R. W. GLOYNE

Summary. An average annual mean daily earth temperature of 46°F (8°C) is considered to be relevant to aspects of soil formation, and an attempt has been made to display the run of the 46°F isopleth over the United Kingdom. A diagram is given which shows the 46°F isotherm at a height of about 2400 ft above mean sea level along the south coast of England, falling to about 1000 ft at 54°N and to 200–400 ft in north Scotland and the northern Islands.

In the course of the work several useful relations also emerged, viz. :

(i) That an addition of between 0·5 and 1·0 degF to the annual mean earth temperature (based on observations at 09 GMT) at 8 in (20 cm) depth and one of 1·0 to 1·5 degF to the corresponding observation at 4 in (10 cm), would suffice to produce average annual values appropriate to mean values computed on a 24-hour basis.

(ii) That the lapse rate of the annual mean earth temperature is about 1 degF/290 ft (0·63 degC/100 m) in south-east England and in a wide coastal band up the east coast to south Scotland, and 1 degF/330 ft (0·55 degC/100 m) elsewhere.

Introduction. A request for a map showing the run of the isopleths of average annual earth temperature of 8°C (46°F) — a level believed by pedologists to be an important discriminant in relation to soil formation — involved a reassessment of available data on soil temperatures at levels down to 4 ft below the surface.

Three groups of difficulties arose; the first concerned the adjustment needed to obtain from readings made once daily at a fixed hour an acceptable estimate of the daily mean value of an element subject to diurnal variation; the second arose from the irregularity of the network of reporting stations, and in particular the dearth of stations in hilly areas; and the third group of difficulties had to do with the presentation of the results in map form.

Annual mean earth/soil temperature at different depths. In a homogeneous soil, the annual mean temperature from the surface to a depth of several metres is equal at all levels. However the amplitude of the seasonal wave, and of any superimposed diurnal variation, increases towards the surface. Broadly speaking the seasonal fluctuation will be reduced to a fraction of a degree Celsius at a depth of 10 metres and any diurnal fluctuation will be similarly reduced at a depth of about 1 metre — indeed during most of the year in the generally cloudy climate of Great Britain the daily fluctuation at 1 ft (30 cm) under short turf is rarely more than a degree Celsius or so; for pertinent data see Meteorological Office,[1] Gloyne[2] and Rambaut.[3]

Data available for the current study are :

(i) Mean values of readings at 09 GMT of earth temperature under short turf at depths of 1 ft (30 cm) and 4 ft (122 cm), together with some additional short-period results (Gloyne[4]).

(ii) Mean values of soil temperature at depths of 4 in (10 cm) and 8 in (20 cm) under bare soil and at 2 ft (60 cm) under turf for certain agrometeorological stations (thrice-daily readings at 09, 15 and 21 GMT for 1924–31 and once-daily readings at 09 GMT from 1932 onwards*).

Sarson and Applegate[5] used the thrice-daily readings at 4 in and 8 in to establish a 'true' daily mean and computed its deviation from the mean value for 09 GMT. The first seven columns of Table I are extracted from their data and the means for depths of 1 ft and 4 ft have also been included.

The data indicate that an addition of between 0·5 degF and 1·0 degF to the mean 09 GMT value read at a depth of 8 in is needed to obtain a mean daily value; the corresponding figure for a depth of 4 in ranges from 1·0 to 1·5 degF. There is a tendency for the lower figures to be appropriate to stations in the north of England. Furthermore (Reference 1, pp. 18–24), it is apparent that the 1931–60 averages are a few tenths of a degree Celsius above those for 1921–50. Upward adjustments of the type described, when applied to the 1926–55 means for 09 GMT at depths of 4 in and 8 in, will render these latter values close to the 1931–60 means for depths of 1 ft, 2 ft and 4 ft, and so provide a further set of estimates of the values of average annual earth temperature.

Variation of average annual earth temperature with height above mean sea level. The second type of difficulty mentioned in the introduction can be partially surmounted by deriving some estimate of the rate of change of earth temperature with height. Many references were scrutinized, amongst them Geiger,[7] Hann,[8,9] Maurer,[10] Scultetus[11] and some recent work by Alcock.[12] Details of such an examination are set out in Gloyne.[4] The outcome of this study may be summarized as follows :

(i) In most parts of continental Europe average annual earth temperature decreases at rates between about 0·5 and 0·6 degC for an increase in height of 100 m up to a level of about 500 m and thence more slowly, at about 0·4 to 0·5 degC per 100 m. Average air temperature falls off rather more rapidly by approximately an additional 0·1 degC per 100 m, accordingly the difference (average earth temperature minus average surface air temperature) increases with height, and all the continental authors quoted comment on this result. It must however be realized that whilst in the United Kingdom cloudiness tends to increase from sea level to the tops of our highest peaks, in many continental regions the upper parts of the mountains are frequently above much of the cloud. It is therefore to be expected that the difference between the temperature on and under a snow-free, sun-irradiated mountain surface, and that of the ambient air will increase with height.

(ii) Stations in the United Kingdom, judged subjectively as being within the same climatic régime but at different elevations, were grouped and the decrease of average earth temperature with height was computed.

* Unpublished summaries of meteorological observations at agro met stations prepared by the Meteorological Office for the Agricultural Meteorological Scheme of the Ministry of Agriculture and the Ministry of Agriculture, Fisheries and Food.

TABLE I—AVERAGE ANNUAL VALUES OF SOIL AND EARTH TEMPERATURES AT SEVERAL DEPTHS, AND DEVIATION OF MEAN OF 09 GMT READINGS FROM TRUE MEAN

	Four inches*			Eight inches*			Two feet**	One foot†	Four feet†	Period‡
	True mean	09 GMT mean	Difference	True mean	09 GMT mean	Difference	True mean	09 GMT mean	09 GMT mean	
	degrees Fahrenheit							*degrees Fahrenheit*		
Aber*(a)*	50·1	49·1	1·0	50·0	49·4	0·6	50·4	N/A	N/A	
Aberystwyth	49·9	49·0	0·9	49·8	49·4	0·4	49·9	N/A	N/A	
Cannington	51·6	50·6	1·0	52·1	51·0	1·1	52·1	N/A	N/A	
East Malling	50·6	49·5	1·1	50·7	49·5	1·2	51·0	51·1	N/A	1931–60
Ellbridge	52·8	51·0	1·8	52·9	51·8	1·1	N/A	N/A	N/A	
Gulval	53·4	52·1	1·3	54·3	52·9	1·4	N/A	N/A	N/A	
Houghall*(a)*	48·0	46·8	1·2	48·1	47·6	0·5	48·5	N/A	N/A	
Long Ashton*(a)*	50·3	49·3	1·0	50·9	49·7	1·2	51·8	51·4	N/A	1931–60
Long Sutton*(a)*	50·4	49·6	0·8	51·0	50·3	0·7	51·1	51·0	49·5	1921–50
Cockle Park*(a)*	46·8	46·1	0·7	47·3	46·3	1·0	N/A	46·9	47·7	1931–60
Newport	49·2	48·1	1·1	49·3	48·3	1·0	N/A	N/A	N/A	
Newton Abbot	51·6	50·3	1·3	52·0	50·9	1·1	N/A	N/A	N/A	
Newton Rigg*(a)*	47·4	46·7	0·7	47·9	47·3	0·6	N/A	N/A	N/A	
Rothamsted	49·4	48·1	1·3	49·7	48·5	1·2	49·7	49·7	49·4	1921–50
								49·8	49·3	1931–60
Sprowston	49·2	48·4	0·8	49·6	48·6	1·0	N/A	N/A	N/A	
Sutton Bonington	49·2	48·2	1·0	49·4	48·4	1·0	N/A	49·6	49·6	1921–50
								49·3	50·2	1931–60
Wisley	50·4	50·0	0·4	51·2	50·3	0·9	51·6	51·2	51·2	1921–50
								51·8	52·5	1931–60
Woburn	50·0	48·7	1·3	50·6	49·4	1·0	50·9	50·3	50·5	1921–50
								50·4	50·4	1931–60
Wye	50·7	49·8	0·9	50·9	49·9	0·8	51·1	N/A	N/A	

* Adjusted to a 1926–55 basis.
** Data available on a 1926–55 basis from Sarson and Applegate.[5]
† Data available from published normals for 1921–50[6] and 1931–60.[1]
‡ The periods apply to the one-foot and four-foot data.
(a) Stations regarded as relevant to the situation in northern Britain.
N/A = not available.

(iii) A further constraint was imposed by the spatial pattern of observed differences between average annual earth temperature and average annual air temperature. Zero or negative differences up to 1 degC occurred in a narrow zone of the west Midlands which broadens north-eastwards into Lincolnshire and Yorkshire and reappears along parts of the immediately coastal strip of east Scotland. Excesses of up to 1 degC or a little higher were found south of a line from London to Bristol, and the highest values occurred along the Channel coast; similar, or rather greater differences were registered at several high-level stations in Wales, northern England and Scotland. Elsewhere in Wales, north-west England and most of Scotland the excess was 0·75 degC or less.

The evidence having been reviewed, it was decided to adopt two estimates for the lapse rate of average annual soil temperature with height, namely :

(*a*) 1 degF/290 ft (0·63 degC/100 m) and

(*b*) 1 degF/330 ft (0·55 degC/100 m).

In general rate (*a*) was found appropriate to stations in south and south-east England and the eastern Midlands and along a broad coastal strip from the Thames to Aberdeen, and rate (*b*) elsewhere. The final run of the isopleths was also constrained as described in (iii) above and a somewhat irregular transition from east to west was therefore unavoidable.

The graphical presentation of the data. Obviously the straightforward solution of mapping the run of the 8°C (46°F) isotherm would result in a pattern with all the complexities of a contour map. Accordingly an alternative solution was adopted in which, at each station, the estimated height above mean sea level of the isothermal *surface* for 46°F was noted, and this led to the pattern represented in Figure 1.

To facilitate direct use with existing contour maps the heights above mean sea level of the 46°F surface were given in feet. The user would therefore only need to compare the absolute height *above* mean sea level with that of the computed 46°F surface to ascertain firstly whether or not the value appropriate to his site was above or below 46°F, and secondly the approximate vertical distance (positive or negative) from the site to the 46°F surface.

Some comments on the results (Figure 1). Over the United Kingdom the height of the surface at which the average annual earth temperature is 46°F ranges from 2400 ft along the coast of southern England to 1000 ft at about 54°N to 600–800 ft in the Fourth–Clyde valley and to a minimum of about 200 ft inland in northern Scotland. There it rises towards the coast to about 400 ft — a figure valid also for the Orkneys — and resumes its general decrease northwards, reaching a little over 300 ft above mean sea level in the Shetlands.

If, as has been suggested by pedologists, the 46°F isotherm of average annual earth temperature is an important discriminant in relation to soil formation, then certain soil characteristics common to large areas of Scotland will probably not be encountered in southern England (i.e. south of the Wash), except on the highest parts of Dartmoor. Much of the high ground of Wales and northern England, however, rises above the 46°F surface, and, except in parts of south and south-west Scotland, an average annual earth temperature of less than 46°F can be expected over all but the low coastal plains of northern Britain.

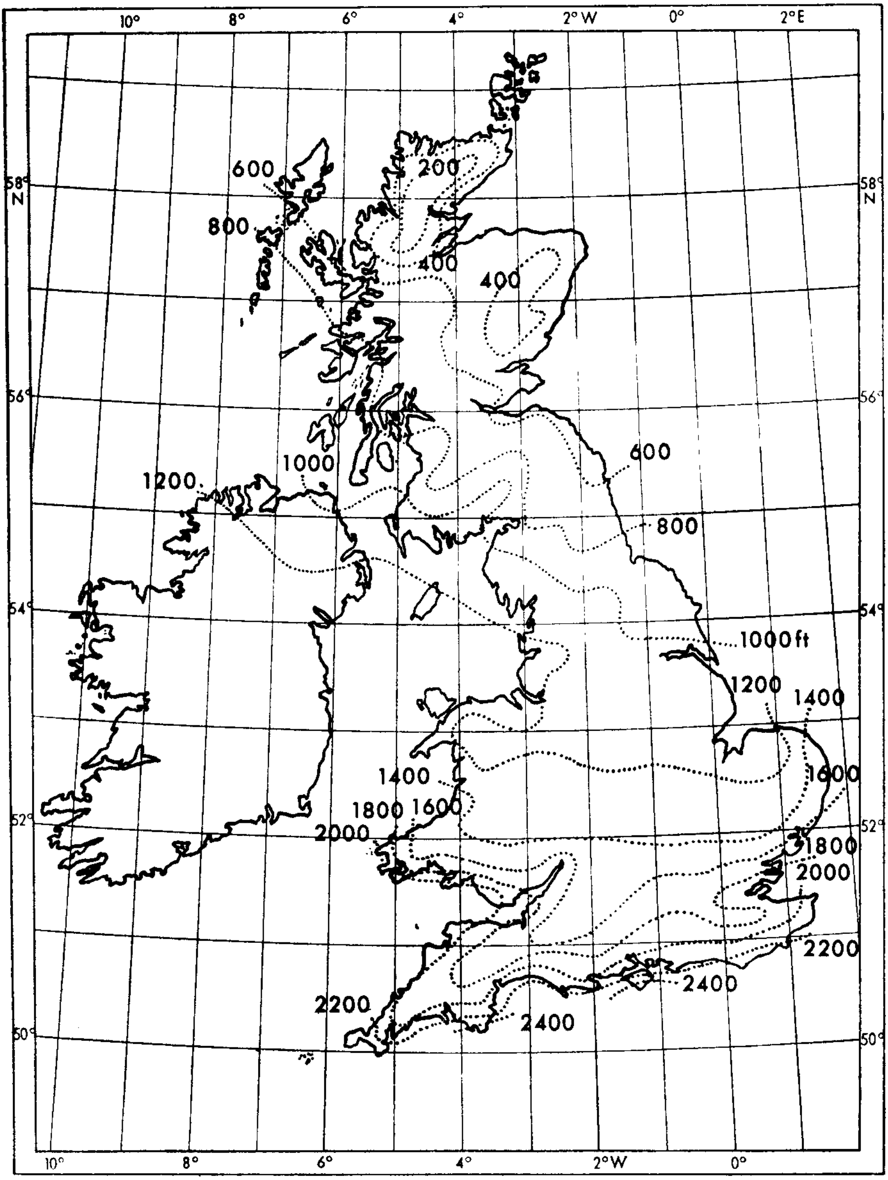

FIGURE 1—COMPUTED CONTOUR HEIGHT AT WHICH A MEAN ANNUAL EARTH TEMPERATURE OF 46°F (8°C) WOULD BE EXPECTED TO OCCUR

Heights are shown in feet.

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551.524.3:629.12

DAY-TIME TEMPERATURE MEASUREMENTS ON WEATHER SHIP 'WEATHER REPORTER'

By C. K. FOLLAND

Summary. This report discusses the influence of screen position on the observation of dry- and wet-bulb temperatures taken aboard a British Ocean Weather Ship. Particular attention is paid to the 'standard' screen exposures on the bulwarks of the bridge deck. The temperatures in the leeward screen were often lower than in the windward screen. Several other screen positions were tried, and one on the roof of the balloon shed gave decidedly lower temperatures than either of the standard positions and would be suitable at least for remote readings on a routine basis.

Introduction. The most suitable position for a thermometer screen on board ship is one where the air will come directly to the screen from over the sea before passing over any part of the ship. The ship is a local source of heat; radiation takes place from the hull and from sunny decks, deck-houses, etc., especially in the tropics. Warm draughts of air may be felt from galleys, engine and boiler rooms, stokehold and funnel. The thermometer screen in use normally stands as far as possible forward and outboard from all such sources of local heating since these tend to give false indications of the true air temperatures, particularly on days when the relative wind is light. The choice of a screen mounting position on the bridge avoids some of these sources of heating. Nevertheless, the bridge-deck screens on large bulk carriers are often many feet inboard of the boat-deck bulwarks. On weather ships the bridge-deck bulwarks are directly above the main-deck rail (Plate I).

The standard practice on British Ocean Weather Ships is to fit two screens to the bridge, and to use that on the windward side (see p. 8) together with an aspirated psychrometer placed near the main-deck rail, also on the windward side of the ship.

PLATE I—GENERAL VIEW OF *Weather Reporter*

See page 6

PLATE II—STANDARD PORT-BRIDGE SCREEN WITH 'OUTER' PORT SCREEN TO THE LEFT

See page 7

Recently Edwards* has demonstrated that the differences in temperature observations obtained from aspirated psychrometers and from screens exposed in the standard fashion on British Ocean Weather Ships and on R.R.S. *Discovery* probably depend on the precise details of exposure of both the aspirated psychrometers and the screens. A limited number of readings taken in light winds during the present investigation suggest that the psychrometer dry- and wet-bulb temperatures are at least as low on almost all occasions as the lower of the temperatures recorded by either of the bridge-deck screens. The problem which arises when different instruments are used as well as different exposures becomes very complex, so further consideration of aspirated-psychrometer observations will not be attempted here.

The investigation. The readings were made in the summer and autumn of 1969. Dry- and wet-bulb temperatures were taken on *Weather Reporter* on voyages 86 (July–August) and 87 (August–September) at a number of non-standard screen positions on the ship at the same time as the standard measurements. Mercury-in-glass thermometers were used throughout and readings were confined to the period 08–21 GMT. At these times of the day the ship may be regarded as a source of heat and the effect of the ship, if any, is to increase the local air temperature.

In daylight the screens themselves may be at higher than ambient temperature owing to the interception of solar radiation. The measurements were taken at ocean weather station 'I' (59°N 19°W). The ship was drifting freely or travelling at a slow speed. The standard screen position on the port bridge-deck bulwarks can be seen in Plate II and Figure 1 (there is a corresponding screen on the starboard bridge-deck bulwark).

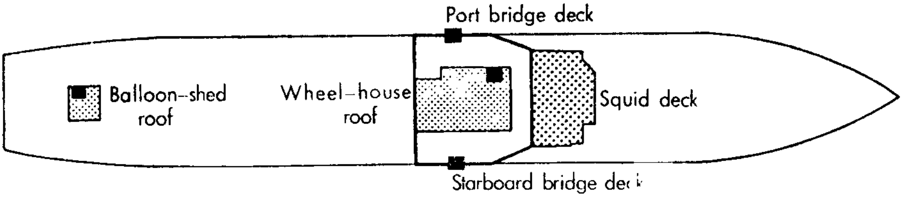

FIGURE 1—PLAN OF *Weather Reporter* SHOWING POSITIONS OF THE THERMOMETER-SCREEN EXPOSURES REFERRED TO IN THE TEXT

The screens are attached to vertical stanchions inboard of the bulwarks, with the bases of the screens level with the tops of the bulwarks. The screens are 10 feet (approximately 3 m) from the wheel-house walls, which extend about 20 feet forward and 8 feet aft from these points. The wheel-house wall is 10 feet high while the wheel-house itself is 20 feet wide. The standard positions are a little nearer the bow of the ship than the stern and about 35–40 feet above the sea.

Seven non-standard exposures were tried, three of them deliberately chosen as 'bad exposures'. The three bad exposures were : above the 'squid deck', near the bow on the starboard side and near the bow on the port side. The

* EDWARDS, P.; Temperature measurements in ships. *Q J R Met Soc, London*, **96**, 1970, pp. 130–131.

temperatures measured in these positions were mostly higher, as expected, than those measured in the standard screens and will not be discussed further. The other non-standard positions were the balloon-shed roof, the 'outer port' position (Plate II), a similar 'outer starboard' position and a position on the wheel-house roof.

The following measurements were also made :

(i) Relative wind speed and direction, to the nearest 5°.

(ii) Intensity of short-wave radiation on a horizontal surface, averaged over the hour previous to the time of observation of the temperature.

A total of 683 pairs of readings of dry- and wet-bulb temperatures have been analysed. The results have been divided according to whether the wind was incident on the port side of the ship or on the starboard side. The majority of observations were taken while the ship drifted slowly. This resulted in a preponderance of observations with wind from the port beam as this particular weather ship tends to drift sideways with the wind blowing directly on to the port side. The few occasions when the wind blew from within 10° of bow or stern have been neglected as they represent a different wind–ship interaction régime from that occurring with other directions and too few observations exist for analysis.

The following comparisons are presented :

(i) *Wind incident on the port side of the ship.*

(a) Comparison of the port and starboard standard screens (228 occasions), Figures 2 and 3.

(b) Port-bridge screen compared with a screen on the wheel-house roof (176 occasions), Figures 4 and 5.

(c) Starboard-bridge screen compared with a screen on the wheel-house roof (176 occasions), Figures 4 and 5.

(d) Port-bridge screen compared with balloon-shed screen (33 occasions), Figure 6.

(ii) *Wind incident on the starboard side.* A comparison of the standard positions (32 occasions), Figures 2 and 3.

Results. To facilitate the comparison, the relative wind speeds and radiation intensities have been grouped to give an approximately equal number of observations in each group.

Relative wind speed categories	Radiation intensity categories (on a horizontal surface)
(1) 0–11 kt	(1) 0–7 mW/cm²
(2) 12–16 kt	(2) 8–26 mW/cm²
(3) 17–20 kt	(3) ⩾27 mW/cm²
(4) ⩾21 kt	

Note. The lower limit of bright sunshine as measured by the solarimeter is near the lower limit set for category (2), and ⩾27 mW/cm² is referred to in the text as 'strong insolation'.

Case (i) *(a) — Wind from port side (comparison of standard screens).* Figure 2 illustrates the mean dry-bulb temperature differences. The vertical lines represent the standard error of the mean differences. On average the port dry- and wet-bulb temperatures are higher than the starboard ones. In fact when the wind was light (⩽11 knots) the port-bridge screen excess averaged

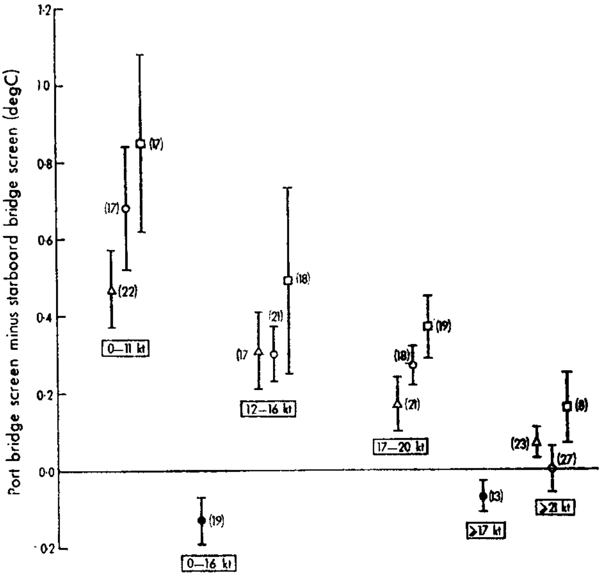

FIGURE 2—COMPARISON OF DRY-BULB TEMPERATURES IN PORT AND STARBOARD STANDARD SCREENS FOR VARIOUS WIND AND SUNSHINE CONDITIONS

□ ≥27 mW/cm²
○ 8–26 mW/cm² } Port to windward (case (i)*(a)*)
△ ≤7 mW/cm²
● All sunshine conditions : Starboard to windward (case (ii))
Vertical lines represent standard errors of the mean differences.
Numbers in brackets are the numbers of observations.

0·47 degC in dull conditions and 0·85 degC in strong insolation. On several occasions the port screen was 2·0 degC higher than the starboard one when the sun shone brightly, with a difference as big as 2·8 degC on one occasion. The port bridge-deck screen and the port wheel-house wall were probably more exposed to direct sunlight in the middle of the day than the starboard screen as the prevailing wind was from the south-west and the port side was facing into wind. The main cause, however, is probably the formation of a windward-side eddy on the bridge deck. The starboard screen was warmer than the port on occasion but the largest starboard excess was less than half that of the largest port-screen excess. Thus pockets of warmer air can also collect, as one might expect, on the leeward side, but not very frequently. A close look at relative wind directions suggests that many occasions of higher temperatures on the lee side occur when the winds are blowing within 30° of the bow direction or stern direction. This suggests a sharp change in the nature of the airflow over the bridge screens near this angle of incidence. A few occasions are accounted for by the sun shining more directly on to the starboard side of the ship than the port.

When the air is not well mixed the port screen is usually warmer. In really windy conditions (≥21 knots) the two screens are likely to agree exactly about half the time and are unlikely to disagree by more than 0·5 degC whether the sun is shining or not.

Figure 3 illustrates that the differences in wet-bulb temperature are similar though slightly smaller than those found in Figure 2 for dry bulbs. The relative humidities deduced from the screen measurements may differ by over 5 per cent on occasion but over a period of time there would be almost no difference in the average values. For relative humidities between 60 per cent and 100 per cent the average wet-bulb temperature excess of the port screen over the starboard would have to be about 90 per cent of the corresponding dry-bulb temperature excess for no net difference in relative humidity to be observed.

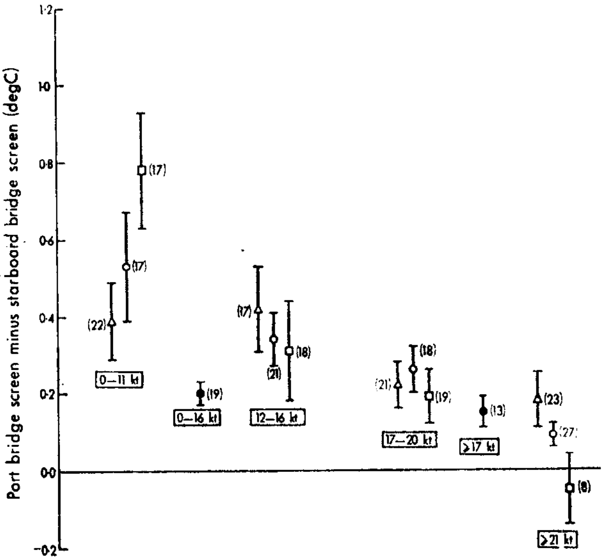

FIGURE 3—COMPARISON OF WET-BULB TEMPERATURES IN PORT AND STARBOARD STANDARD SCREENS FOR VARIOUS WIND AND SUNSHINE CONDITIONS

□ ≥27 mW/cm² } Port to windward (case (i)*(a)*)
○ 8–26 mW/cm²
△ ≤7 mW/cm²
● All sunshine conditions : Starboard to windward (case (ii))
Vertical lines represent standard errors of the mean differences.
Numbers in brackets are the numbers of observations.

Case (ii) — *Wind from starboard (comparison of standard screens).* The low frequency of winds from the starboard quarter is illustrated by the fact that only 32 observations were noted. In Figures 2 and 3 the observations have been divided into occasions when the wind was ≤16 knots or ≥17 knots respectively. On average the dry bulb in the port screen read 0·15 degC lower than in the starboard in the winds ≤16 knots and 0·10 degC lower in the winds ≥17 knots. The wet bulb in the port screen read higher than the standard readings, though the differences were small. The majority of case (ii) occasions resulted from the ship being on passage at a slow speed across the area of station 'I' and so are not strictly comparable with case (i) *(a)*. On one of these occasions the starboard screen dry-bulb reading was 1·1 degC higher than the port reading but both wet bulbs agreed so that relative-humidity differences of over 10 per cent are possible between the two screens.

Cases (i) *(b) and (c) — Wind from port side (standard screens compared with screen on wheel-house roof).* See Figures 4 (dry-bulb temperatures) and 5 (wet-bulb temperatures). The wheel-house-roof dry-bulb temperatures were decidedly lower than those in either of the standard screens. The mean difference between the dry bulb in the starboard-bridge screen and the dry bulb in the screen on the wheel-house roof was 0·50 degC in light winds (⩽11 knots) and strong insolation, and there was a difference of as much as

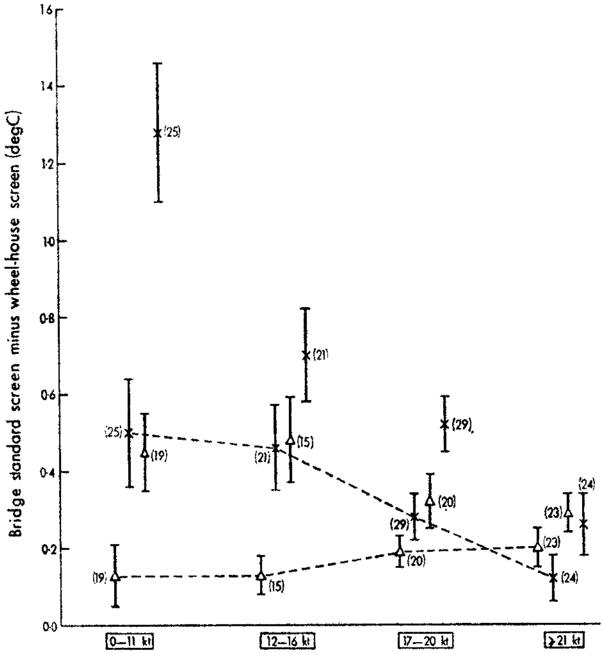

FIGURE 4—COMPARISON OF DRY-BULB TEMPERATURES IN STANDARD SCREENS WITH THOSE IN WHEEL-HOUSE SCREEN FOR VARIOUS WIND AND SUNSHINE CONDITIONS (PORT TO WINDWARD)

X ⩾8 mW/cm² } The observations of case (i)*(c)*, i.e. starboard minus wheel-house, are
△ ⩽7 mW/cm² } distinguished from those of case (i)*(b)*, i.e. port minus wheel-house, by being joined by a dashed line.

Vertical lines represent standard errors of the mean differences.
Numbers in brackets are the numbers of observations.

1·28 degC when the port screen was similarly compared. The wet-bulb temperatures show similar results. The stronger the wind the less the differences between the screens so that in dull windy conditions the mode of the differences between all three screens is zero. Nevertheless, in these conditions the mean wheel-house dry-bulb temperatures are 0·2 degC less than those of the bridge screens, which is more than can be accounted for by the difference in height.

On one occasion in strong insolation and light winds the port-bridge screen dry bulb read 3·3 degC higher than the wheel-house screen while the wet bulb was 2·6 degC higher.

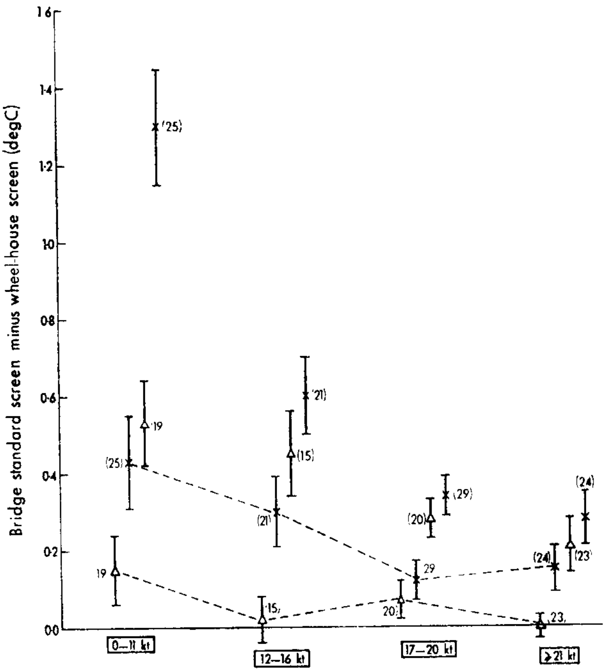

FIGURE 5—COMPARISON OF WET-BULB TEMPERATURES IN STANDARD SCREENS WITH THOSE IN WHEEL-HOUSE SCREEN FOR VARIOUS WIND AND SUNSHINE CONDITIONS (PORT TO WINDWARD)

X ≥ 8 mW/cm² ⎫ The observations of case (i)*(c)*, i.e. starboard minus wheel-house are
Δ ≤ 7 mW/cm² ⎬ distinguished from those of case (i)*(b)*, i.e. port minus wheel-house, ⎭ by being joined by a dashed line.

Vertical lines represent standard errors of the mean differences.
Numbers in brackets are the numbers of observations.

Case (i) *(d) — Wind from port side (port screen compared with balloon-shed screen).* Only 33 occasions were noted and the results are illustrated in Figure 6. On the whole the balloon-shed screen shows itself to be cooler than the wheel-house-roof screen, though no direct comparisons were made. This is shown by the very large excess of the mean port-bridge screen dry-bulb temperature in winds ≤ 16 knots of 1·70 degC and in winds ≥ 17 knots of 1·18 degC. The mean wet-bulb excesses were 0·97 degC and 0·74 degC respectively. The effect of stronger winds is thus to reduce the day-time port-bridge screen temperature much more than either the balloon-shed or wheel-house-roof readings. In fact in every instance the balloon-shed temperatures were as low as or lower than the lowest values from the standard screens. The fact that the mean difference of wet-bulb temperatures between port-bridge screen and balloon-shed screen was considerably less than the dry-bulb temperature difference is important. If the balloon-shed values are accepted as being near the truth and if it is remembered that both standard screens give similar average relative humidities the real effect of using bridge-screen measurements is to give estimates of relative humidity which are below the true value by about 8 per cent for wind speeds ≤ 16 knots and 5 per cent for speeds ≥ 17 knots.

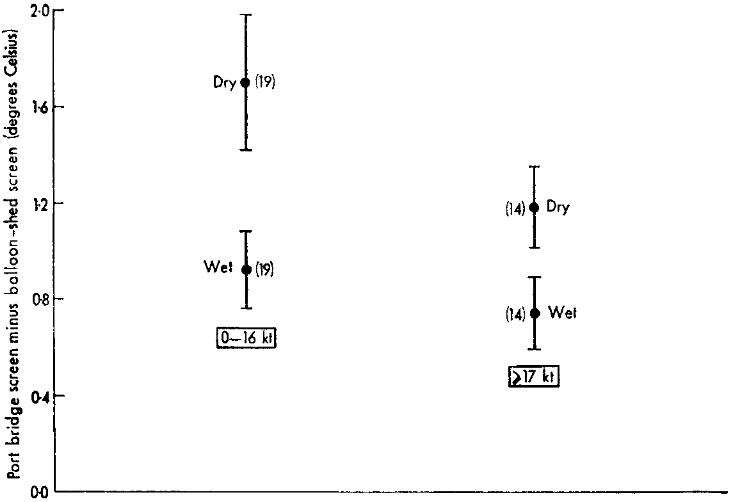

FIGURE 6—COMPARISON OF TEMPERATURES (DRY- AND WET-BULB) IN PORT SCREEN WITH THOSE IN BALLOON-SHED SCREEN FOR VARIOUS WIND CONDITIONS (PORT TO WINDWARD)

● All sunshine conditions : case (i)*(d)*, i.e. port balloon-shed roof.
Dry-bulb and wet-bulb temperatures are annotated accordingly.
Vertical lines represent standard errors of the mean differences.
Numbers in brackets are the numbers of observations.

Discussion. The roof of the balloon shed seems to give a much better exposure for marine screens than does the bridge. The balloon-shed screen was attached to a rail which presented little resistance to the airflow. Furthermore there were no large obstacles to leeward to give rise to eddies. The wheel-house-roof exposure was next best and better than either standard bridge screen on the whole, though this screen does read higher than the leeward standard screen from time to time. If it were placed higher above the wheel-house deck the results might improve but it would be inconvenient and might be more affected by funnel smoke.

Analysis of nine pairs of readings from the 'outer port bridge-deck' and 'outer starboard bridge-deck' screens was inconclusive. The results suggested that the windward 'outer' screen was cooler than the standard windward exposure in 8 cases out of 9. The windward 'outer' screen was often cooler than the standard leeward screen but not always. This re-emphasizes the complex flow patterns, influenced in part by the screens themselves, which must be occurring.

The balloon shed would be a practical position for a screen if remote-indicating temperature equipment were used. It would then be necessary to visit the screen only at intervals of a few days for checking purposes and to change the wet-bulb wicks. However, further work is needed to determine the best compromise between ideal and practical positions, not only on the weather ships but also on merchant ships of different types.

It is clear from the foregoing that present observational practices are wrong and that significant improvements in the readings would result from the adoption of the following procedure for entries in the official returns.

(i) Select the lower of the two dry-bulb temperatures read in the standard bridge screens (usually the leeward screen) as the dry-bulb observation.

(ii) The wet-bulb temperature should be taken from the same screen.

(iii) When the dry-bulb temperatures are the same in both screens, select the windward wet-bulb temperature.

The effect of this procedure (at least in summer in the North Atlantic) would be to reduce the mean dry- and wet-bulb temperatures by 0·3 degC, but by 0·6 degC in sunny conditions and moderate winds. The above procedure assumes (for the present) that aspirated-psychrometer readings will continue to be taken when the wind speed is light and the sun is shining.

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A CASE STUDY OF THE SPECTACULAR DEVELOPMENTS AND MOVEMENT OF A FEBRUARY STORM

By R. M. MORRIS

Summary. An example of synoptic evolution is described, using the routine twice-daily computed analyses at the Central Forecasting Office (CFO), Bracknell. The study reveals, with the aid of the omega and vorticity equations, how the various terms in the equations are functional in determining the translation and development of the isobaric contour and thickness fields. In particular the importance of latent heat release and sensible heat flux from the sea surface is demonstrated in the generation of cyclonic vorticity in the lower layers of the troposphere.

Introduction. Between 10 and 12 February 1970 a frontal wave depression moved east-north-eastwards across the Atlantic Ocean towards south-west England. The depression deepened considerably and subsequently moved up the English Channel with an intense circulation in the lower layers of the troposphere. The evolution of this system illustrated in a clear manner the role played by the different terms in the equations relating to dynamical evolution in tropospheric motion. The theoretical aspects of the case study will be based upon the vorticity equation (see, for example, Petterssen[1]) and the omega equation.[2]

The equations are briefly described as follows :

$$\left[\nabla^2 - \frac{f^2}{\sigma}\frac{\partial^2}{\partial p^2}\right]\omega = -\frac{f}{\sigma}\frac{\partial}{\partial p}\left[\mathbf{V}.\nabla Q\right] - \frac{g}{p\sigma}\nabla^2(\mathbf{V}.\nabla h_{TT}) \quad \ldots (1)$$

$$\frac{\partial}{\partial t}Q_5 = -\mathbf{V}_5.\nabla Q_5 - \omega\frac{\partial Q}{\partial p} + \frac{\partial \mathbf{V}}{\partial p}\times\nabla\omega.\mathbf{k} \quad \ldots (2)$$

$$\frac{\mathrm{d}}{\mathrm{d}t}Q_{10} = -(\mathbf{V}_5.\nabla Q_5 - \mathbf{V}_{10}.\nabla Q_{10}) - \omega\frac{\partial Q}{\partial p} + \frac{\partial \mathbf{V}}{\partial p}\times\nabla\omega.\mathbf{k} -$$

$$-\frac{R}{f}\nabla^2\left[\frac{-g}{R}(\mathbf{V}.\nabla h_{TT}) + S + H\right]. \quad \ldots (3)$$

The various symbols have the following meaning :

ω (omega) $= \frac{dp}{dt}$ the total time derivative of pressure representing the vertical velocity in pressure co-ordinates.

V = the quasi-horizontal velocity vector on an isobaric surface.

$Q = (\zeta + f)$ = the absolute vorticity about a vertical axis, i.e. the sum of the relative vorticity ζ and the earth's vorticity f.

∇, ∇^2 = the operators denoting respectively the gradient and Laplacian of a function on the isobaric surfaces.

k = a unit vector in a direction normal to the isobaric surfaces and approximately vertical; the dot and cross products have their usual vector meaning.

S = the static stability term, $\omega(\Gamma_a - \Gamma) \log \frac{1000}{500}$ meaned over the layer from 1000 mb to 500 mb.

Γ_a, Γ = adiabatic lapse rate, actual lapse rate in terms of pressure.

H = the adiabatic heating term, $\frac{1}{c_p} \frac{dW}{dt} \log \frac{1000}{500}$ meaned over the layer.

$\frac{dW}{dt}$ = the heat, other than latent heat, supplied to, or removed from, unit mass in unit time.

σ = a static stability parameter which in practice is usually negative, $\frac{1}{\rho\theta} \frac{\partial\theta}{\partial p}$.

θ = potential temperature.

ρ = air density.

g = gravitational acceleration.

R = the gas constant.

h_{TT} = the thickness of the 1000–500-mb layer.

Subscripts 5 and 10 refer to the 500-mb level and 1000-mb level respectively.

The omega equation (1) has been derived by Thompson[2] but was adapted in the present form by Sanders[3] who has extensively investigated the interpretation and uses of the equation in relation to synoptic charts. The equation relates the three-dimensional Laplacian of vertical velocity in a layer to the vertical derivative (through the layer) of vorticity advection on the isobaric surfaces and the Laplacian of thickness advection within the layer. By restricting the analysis to areas of maximum vertical motion it follows that :

$$\nabla^2\omega \approx -\omega,$$

and also, confining interest to qualitative estimates of magnitude only, equation (1) becomes

$$\omega \approx -\frac{\partial}{\partial p} (\mathbf{V}.\nabla Q) - \nabla^2 (\mathbf{V}.\nabla h_{TT}). \qquad \ldots (1a)$$

Thus descending air (ω positive) occurs in association with relatively strong negative (anticyclonic) vorticity advection aloft and/or a maximum of cold advection in the layer. If equation (1*a*) is applied to the 1000–500-mb layer the mean vertical velocity in the layer depends upon the difference between the vorticity advection at 500 mb and at 1000 mb and the advection of the thickness by a mean wind in the layer. In this study equation (1*a*) is used to assess the sign of vertical motion in the middle and lower troposphere.

Equation (2) expresses the balance of vorticity transfer at 500 mb assuming negligible divergence.[1,4] The first term on the right-hand side represents the quasi-horizontal advection of vorticity at 500 mb, the second term represents the vertical transfer of vorticity to and from different levels and the third term is the twisting term. In other words the horizontal advection of vorticity represents the transfer of existing resources at 500 mb whereas the other terms represent the relatively small additions to and subtractions from other levels of the fluid.

Equation (3) relates the changes of vorticity in the moving system at 1000 mb to the various functions in the 1000–500-mb layer.[1] The first term on the right-hand side (in brackets) is synonymous with the first term on the right-hand side in equation (1) and the second and third terms are equivalent to the corresponding terms in equation (2). The fourth term (in brackets) contains a thickness advection term similar to that in equation (1) and also static stability and non-adiabatic heating terms. The stability term expresses the thickness changes due to adiabatic warming or cooling associated with vertical motion whilst the non-adiabatic term expresses changes of thickness due to latent heat, sensible heat and radiative transfer, etc.

Vorticity changes at 500 mb are closely related to the contour-height changes at this level. If the horizontal advection of vorticity at 1000 mb is temporarily neglected in equation (3) it follows that the changes of vorticity at 1000 mb (left-hand side) can be expressed as a balance between the 500-mb contour-height changes and the 1000–500-mb thickness changes.

The basic data. The operational numerical forecast procedure at CFO, Bracknell, includes an objective analysis of the synoptic data at 00 GMT and 12 GMT. The computed output includes surface, 500-mb, and 1000–500-mb thickness analyses and a distribution of vertical velocity in the 1000–600-mb layer.[5,6] These charts are scrutinized by forecasters at CFO and, if necessary, additional information is fed into the computer to improve the objective analyses. Thus there is available a reasonably accurate objective analysis of the synoptic situation twice daily and these data have been used to illustrate the case study.

Although the computer does not solve equation (1) to derive the field of vertical motion, the omega equation is one of the few that offers a satisfactory basis for estimating the large-scale vertical motion. An analysis of the 1000–500-mb layer will be presented and comparisons made between the objectively derived vertical-motion field and subjective estimates using equation (1*a*). Equations (2) and (3) will be used to describe the evolutions that have occurred and will also be the basis of any tentative and consistent predictions that can be made at each stage.

The analysis.

(i) *Synoptic analysis at 00* GMT, *11 February 1970.* Figure 1*(a)* depicts the 1000–500-mb thickness and superimposed 1000-mb contour-height flow at the time; arrows indicate the recent 12-hour movement of ridges and troughs in the thickness field. An intensifying large anticyclone was moving east close to Newfoundland with well-marked thickness advection fields on its eastern and western flanks. A small frontal wave in the 1000-mb flow was detectable about 49°N 25°W and was associated with a thermal ridge moving eastwards. Figure 1*(b)* depicts the 500-mb contour flow with superimposed isopleths of thickness advection ($\mathbf{V}.\nabla h_{TT}$) calculated from Figure 1*(a)* and using $\mathbf{V}_{10}$ as the advective component of wind in the 1000–500-mb layer and a grid length of 100 nautical miles.* (1000-mb contours were drawn at intervals of 30 gpm to improve the accuracy of $\mathbf{V}_{10}.\nabla h_{TT}$.) Arrows indicate the movement of 500-mb contour troughs and ridges during the previous 12 hours.

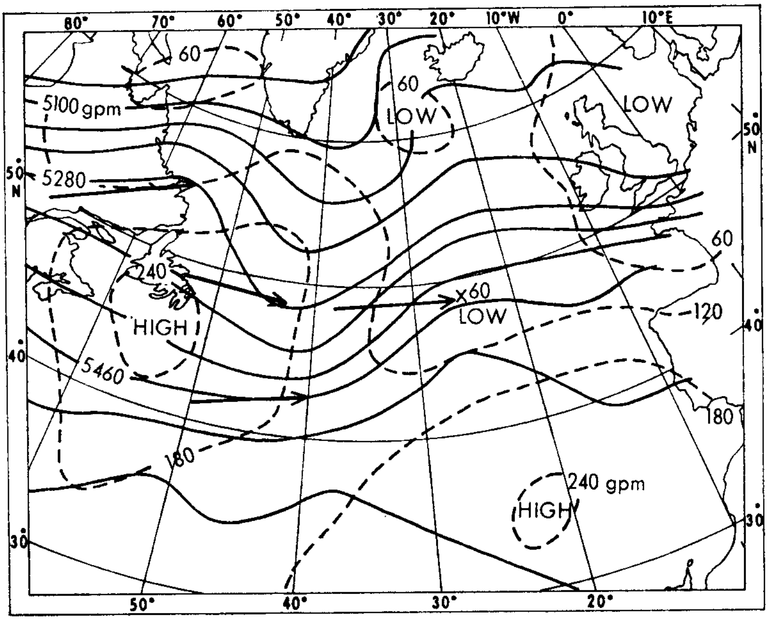


FIGURE 1*(a)*—1000–500-mb THICKNESS AND 1000-mb CONTOURS AT 00 GMT, 11 FEBRUARY 1970

——— Thickness - - - Contours

The 500-mb flow consists of two distinct flow patterns. In the north a trough was advancing across Labrador with a downstream trough axis near ocean weather station 'C'. In the south an upper ridge was amplifying over and to the south of Newfoundland and a downstream trough had become more sharply defined (i.e. cyclonic curvature had increased at the trough axis) near ocean weather station 'D', which was reporting a wind of 290° 90 kt at the time. The two patterns merged into a confluent ridge over the eastern

* The units for grid length have been quoted in nautical miles because knots were used as speed units. Thus the final units for thickness advection are geopotential metres per hour. For speeds measured in metres per second the appropriate grid-length units would be metres and the thickness advection units would then be geopotential metres per second (1 knot ≈0·5 m/s; 1 nautical mile ≈1850 m).

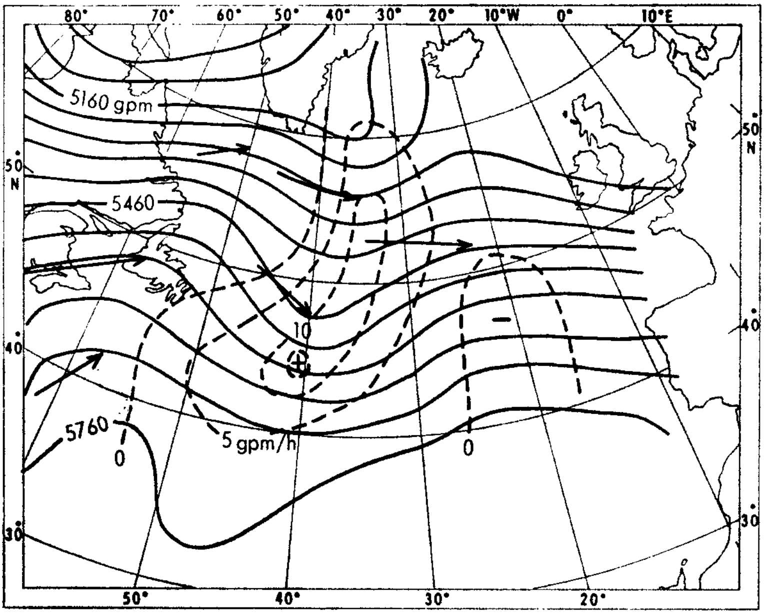


FIGURE 1(*b*)—500-mb CONTOURS AND ISOPLETHS OF THICKNESS ADVECTION AT 00 GMT, 11 FEBRUARY 1970

——— Contours - - - Isopleths of thickness advection

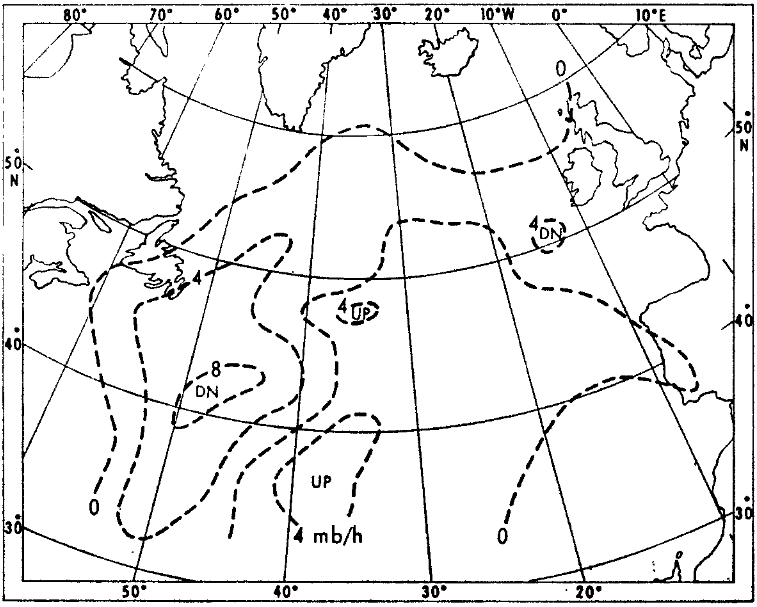


FIGURE 1(*c*)—MEAN VERTICAL VELOCITY IN THE 1000–600-mb LAYER AT 00 GMT, 11 FEBRUARY 1970

DN = down

Atlantic. It will be seen that a tongue of maximum cold advection extends from just east of the northern upper trough axis across the base of the southern trough. Referring to equation (1*a*), if the vorticity advection at 1000 mb is neglected in comparison with the vorticity advection at 500 mb, it can be seen that the vorticity advection term is negative just ahead of the northern trough axis (advection of cyclonic vorticity) and therefore opposes the thickness advection term (positive), which implies that the vertical velocity will be small. The cold advection maximum is centred just behind the axis of the southern contour trough and extends south-westwards; the vorticity advection term vanishes in the axis of the contour trough but is strongly positive west of the trough. Thus it may be inferred that descending motion is occurring beneath the upper trough axis and is occurring strongly to the west of the trough axis. The vorticity advection term is only weakly opposed by the thickness advection term ahead of the upper contour trough, which implies ascent of air in this region.

Figure 1*(c)* depicts the distribution of mean vertical velocity in the 1000–600-mb layer as produced by the computer.[5,6] Most of the subjective assessments are clearly substantiated, with a broad area of descending air embracing the central and rear region of the southernmost trough and a small significant area of ascending air just ahead of this trough. A broad area of weaker ascent embraces the thermal ridge (frontal wave) presumably associated with the advection of cyclonic vorticity near the confluent upper ridge.

A comprehensive assessment of the analysis above is the basis for tentative predictions about the contour and thickness fields in accordance with equations (2) and (3). The movement of troughs and ridges at 500 mb is largely in response to the quasi-horizontal advection of vorticity at that level but for the present it can simply be noted that the two 500-mb troughs in mid-Atlantic are moving eastwards. The tongue of cold advection extends across areas of ascending and descending motion from which it can be deduced that a marked lowering of thickness should occur north-east of ocean weather station 'D' whereas relatively small changes are likely to the west. An area of weak ascent embraces the thermal ridge associated with the frontal wave so that adiabatic cooling should lower the thickness unless latent heat is released to offset the cooling. The ascending motion may increase in the vicinity of the frontal wave in association with the advancing 500-mb trough since there appears to be an area of stronger upward motion near 48°N 35°W (Figure 1*(c)*).

(ii) *Synoptic analysis at 12* GMT, *11 February 1970.* Figures 2*(a)*, *(b)* and *(c)* depict the analysis at 12 GMT on the 11th. The upper contour pattern has transferred eastwards at a consistent rate and the southernmost trough has become confluent under the influence of the thickness advection field. The thickness pattern has also been transferred eastwards largely in accordance with expectation except that thickness values have not fallen in the thermal ridge, from which it may be inferred that non-adiabatic heat has been added at some stage during the previous 12 hours. This heat has clearly produced the necessary imbalance in equation (3) to increase the circulation at 1000 mb. The increase in circulation has intensified the cold advection field and also created a warm advection field. In fact the warm advection field must have been the only mechanism able to transfer the thermal ridge eastwards since 00 GMT on the 11th.

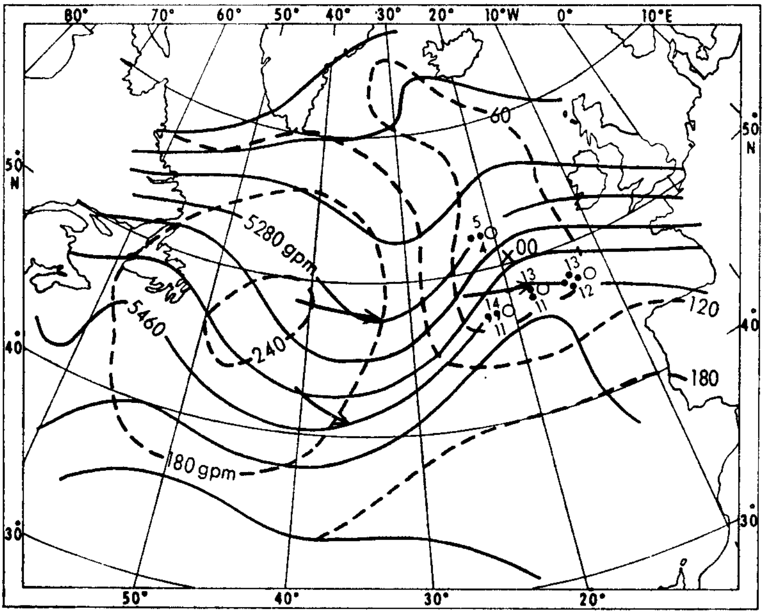


FIGURE 2(*a*)—1000–500-mb THICKNESS AND 1000-mb CONTOURS AT 12 GMT, 11 FEBRUARY 1970

——— Thickness - - - Contours

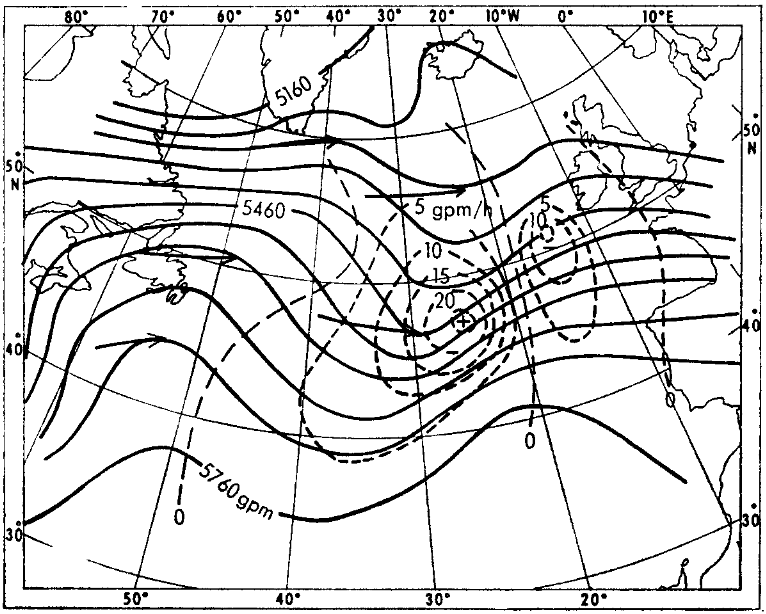


FIGURE 2(*b*)—500-mb CONTOURS AND ISOPLETHS OF THICKNESS ADVECTION AT 12 GMT, 11 FEBRUARY 1970

——— Contours - - - Isopleths of thickness advection

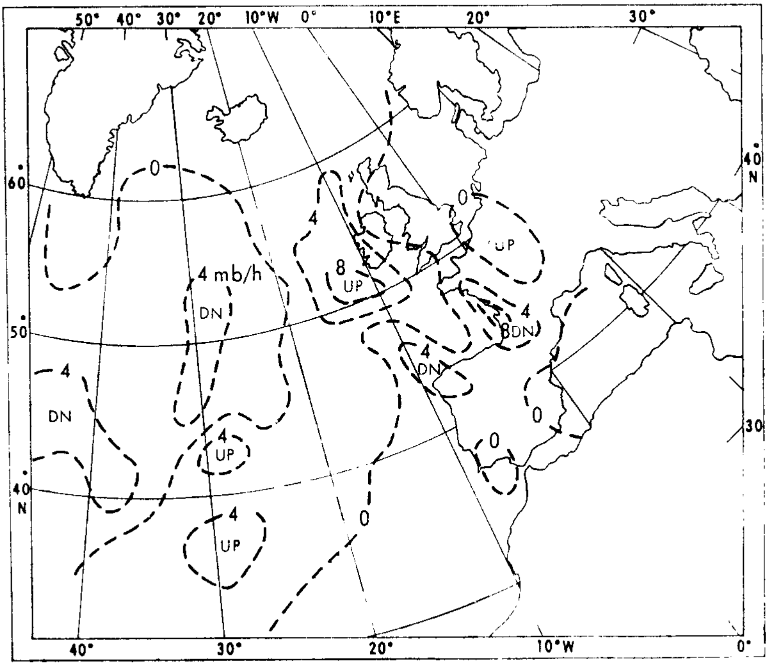


FIGURE 2(c)—MEAN VERTICAL VELOCITY IN THE 1000–600-mb LAYER AT 12 GMT, 11 FEBRUARY 1970
DN = down

Figure 2(b) shows that the core of strong cold advection is located just ahead of the upper contour trough and therefore opposes the vorticity advection term, which suggests that the vertical velocity will be small (see Figure 2(c)). It is of considerable interest to compare the position of maximum warm advection with the area of ascending air. Comparison of Figure 2 with Figure 1 reveals that the most significant development has been the greatly enhanced upward motion associated with the intensifying warm advection field.

The analysis shows that cold advection and descending motion are located west of the thermal ridge whilst warm advection and ascending motion are located east of the thermal ridge. This symmetry about the axis of the thermal ridge means that the thermal ridge should tend to be translated eastwards without significant distortion. At the same time relatively weak ascending motion is occurring in the thermal ridge south of 49°N, which implies a lowering of thickness values by adiabatic cooling. On the other hand it appears that heat is already being supplied to the thermal ridge as a result of condensation, which suggests that adiabatic cooling may be insignificant in the region around the 1000-mb centre. The upper contour trough is confluent, and cyclonic (positive) vorticity advection tends to be concentrated in the southern portion of the trough forward of the trough axis (the so-called right-hand entrance region) and implies ascending motion. Anticyclonic (negative) vorticity advection tends to be concentrated in the northern portion of the trough (the so-called left-hand entrance region) and implies descending motion; Figure 2(*c*) tends to support these assertions. The strong cold advection field is situated in a region of weak descending motion so that substantial cooling by advection is likely towards the south-east.

(iii) *Synoptic analysis at 00* GMT, *12 February 1970.* Figures 3(*a*), (*b*) and (*c*) depict the analysis at 00 GMT on the 12th. The thickness pattern has been transferred eastwards at about twice its speed during the previous 12 hours, furthermore thickness values have actually increased in the ridge in the region of the 1000-mb centre. It can be deduced that the warm thickness advection field and non-adiabatic heat supply must have over-compensated the adiabatic cooling due to ascending motion. The role of the terms for thickness advection and non-adiabatic heat in equation (3) is particularly striking since a rapid increase in circulation at 1000 mb has occurred beneath the thermal ridge. At the same time the upper contour heights have fallen about 120 gpm above the low-level centre, which represents a substantial change in the evolution of the 500-mb flow. Further inspection of Figure 2(*b*) suggests that it was hardly possible for the quasi-horizontal vorticity advection field to account for the changes at that level.

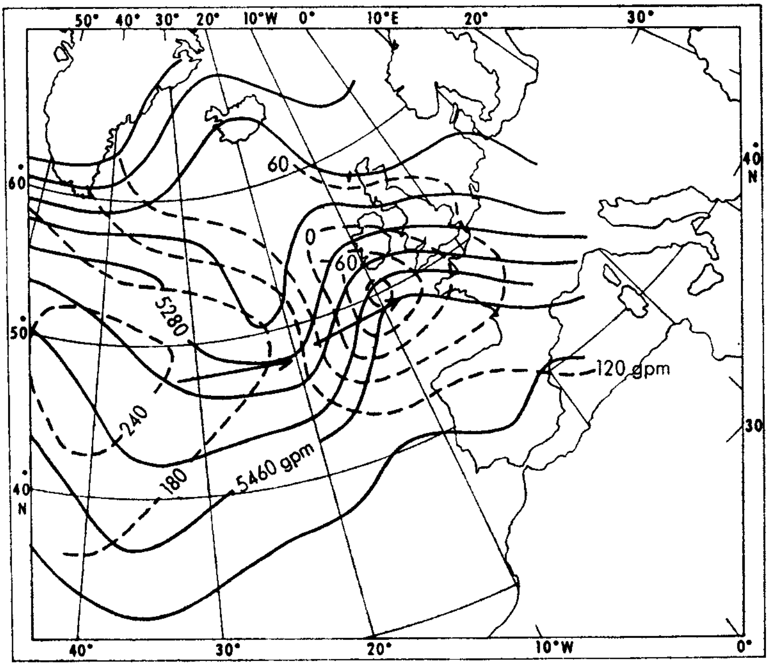


FIGURE 3(*a*)—1000–500-mb THICKNESS AND 1000-mb CONTOURS AT 00 GMT, 12 FEBRUARY 1970

——— Thickness - - - Contours

If the whole of the first term on the right-hand side of equation (3) is assumed to be small at 12 GMT on the 11th near the centre of the depression, then the subsequent large positive value of the left-hand side must have been due to the combined effects of thickness advection and non-adiabatic heat in excess of the opposing stability term plus any contribution from the vertical-advection term and the twisting term. It follows also that the increase in

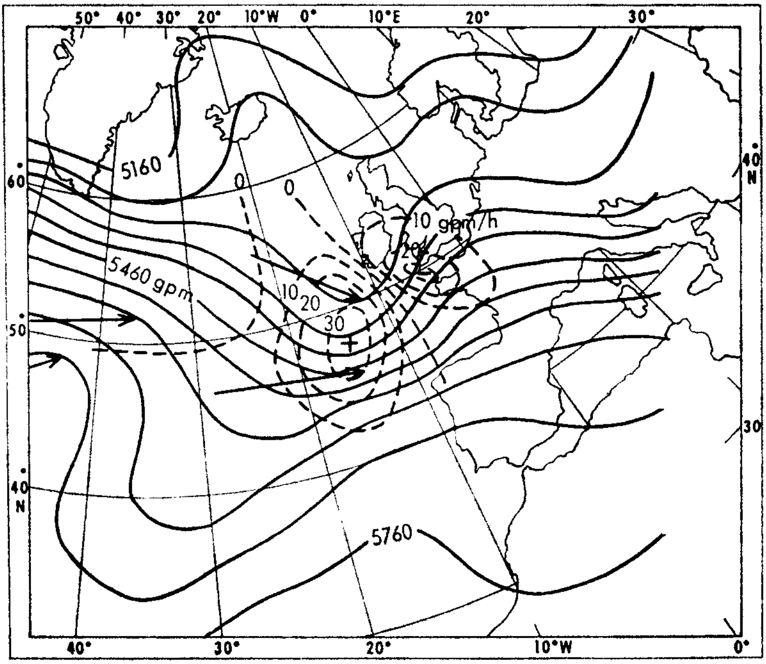


FIGURE 3(*b*)—500-mb CONTOURS AND ISOPLETHS OF THICKNESS ADVECTION AT 00 GMT, 12 FEBRUARY 1970

——— Contours - - - Isopleths of thickness advection

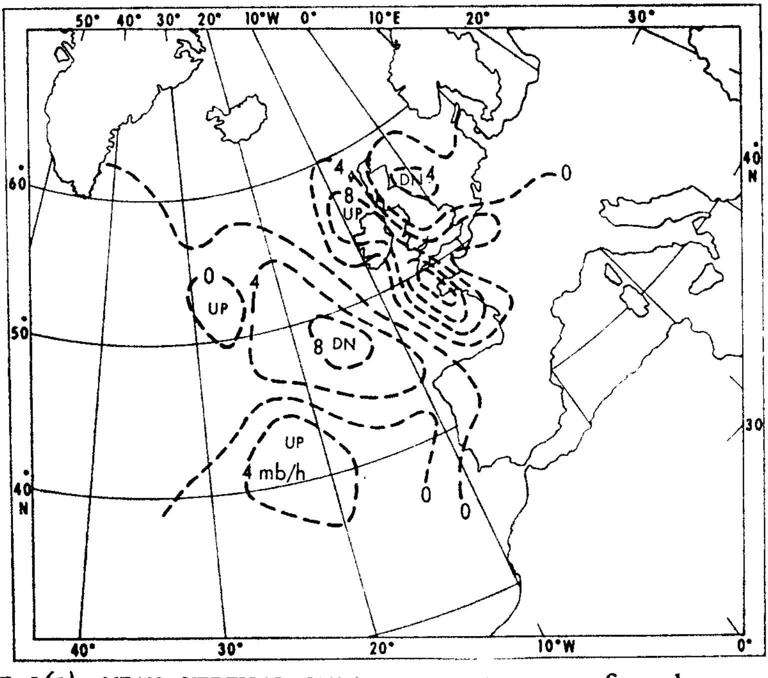


FIGURE 3(*c*)—MEAN VERTICAL VELOCITY IN THE 1000–600-mb LAYER AT 00 GMT, 12 FEBRUARY 1970

DN = down

500-mb vorticity above the low-level centre must have been largely due to the vertical-advection term and the twisting term, as required by equation (2). Comparison of Figures 2*(a)* and 2*(c)* with 3*(a)* and 3*(c)* suggests that the upward transfer of cyclonic vorticity has increased from small values near 15°W at 12 GMT on the 11th to fairly large values over Ireland and the South-west Approaches at 00 GMT on the 12th. This is simply because the upward motion and low-level cyclonic vorticity have increased together. Comparison of Figures 2*(b)* and 3*(b)* reveals that it is in this region that the greatest fall has taken place in the 500-mb contour heights in the trough during its eastward progress. The fall in contour height is most probably synonymous with an increase of cyclonic vorticity at this pressure level. The twisting term will be zero where the vertical velocities are at a maximum ($\nabla\omega = 0$) and also zero where the thermal wind vector is parallel to the horizontal gradient of vertical velocity ($\partial \mathbf{V}/\partial p \times \nabla\omega = 0$). Comparing Figures 2*(a)* and 2*(c)* suggests that $\partial \mathbf{V}/\partial p$ is almost parallel to $\nabla\omega$ in the thermal ridge between 50°N and 55°N but there is probably a significant angle between the vectors just south of 50°N between 10°W and 20°W. The rotation is such that cyclonic contour vorticity is being increased in the latter region with a corresponding decrease of thermal wind. It will be seen in Figure 3*(a)* that a decrease of thermal wind only occurred south of 49°N. Thus it seems fair to conclude that the warm thickness advection and non-adiabatic heat terms were the prime functions responsible for the development of the intense low-level circulation with subsidiary contributions from the vertical-advection term and the twisting term.

The intensity of the low-level circulation at 00 GMT on the 12th makes it more difficult to assess the vertical derivative of the vorticity advection term; nevertheless subjective estimates can be made. The 1000-mb field (Figure 3*(a)*) consists of three troughs radiating south-east, north-north-west and south-westwards from the cyclonic centre. Thus it appears that positive vorticity advection over the western English Channel (ahead of a trough) lies beneath a region of positive vorticity advection at 500 mb (Figure 3*(b)*) so that the vertical derivative is probably small. The maximum of warm thickness advection in this region therefore probably determines the sign of vertical motion, as suggested in Figure 3*(c)*.

The 1000-mb trough which extends north-north-westwards just west of Ireland lies beneath negligible flow at 500 mb so that the vorticity advection term suggests ascending motion east of the low-level trough and descending motion to the west. The thickness advection field tends to support the vorticity advection term since a tongue of warm advection extends north across Ireland and a tongue of cold advection extends north to the west of Ireland. These deductions are consistent with Figure 3*(c)*.

The vorticity advection term is clearly most difficult to assess in the region between the low-level centre and ocean weather station 'K'. The upper and low-level troughs appear to lie close together but there is a marked difference in orientation, which accounts for the strong cold thickness advection field. Although it may be presumptuous to assert that the vorticity advection term is probably weak, there can be little doubt about the striking connection between the pattern of cold advection (Figure 3*(b)*) and descending motion (Figure 3*(c)*).

Since the vertical velocity maxima and the thickness advection fields are still almost symmetrical about the thermal ridge, a continuation of the eastward translation of the system is to be expected. The close conjunction of the upper and lower centres means that further deepening of the low-level centre can only occur through excessive latent and sensible heat release in the ascending air east of the thermal ridge. The warm thickness advection field cannot advect any air warmer than that already present above the surface centre. It is worth noting however that the thermal ridge is more pronounced than it was 12 hours previously and comparison of Figures 3*(a)* and 3*(c)* suggests that the twisting term may be significant in the narrow zone between the axis of the thermal ridge and the axis of maximum upward motion extending from north of Ireland to north-west France. The direction of vectors $\partial \mathbf{V}/\partial p$ and $\nabla\omega$ suggests a 'twisting' of the thermal wind into cyclonic vorticity in the contour flow.

(iv) Figure 4 depicts the 1000-mb and thickness fields at 12 GMT on the 12th. The low-level circulation has remained fairly constant in association with an undistorted thermal ridge. It is interesting to see that the thermal wind has decreased significantly above the low-level circulation; this may be attributed to the effect of the twisting term.

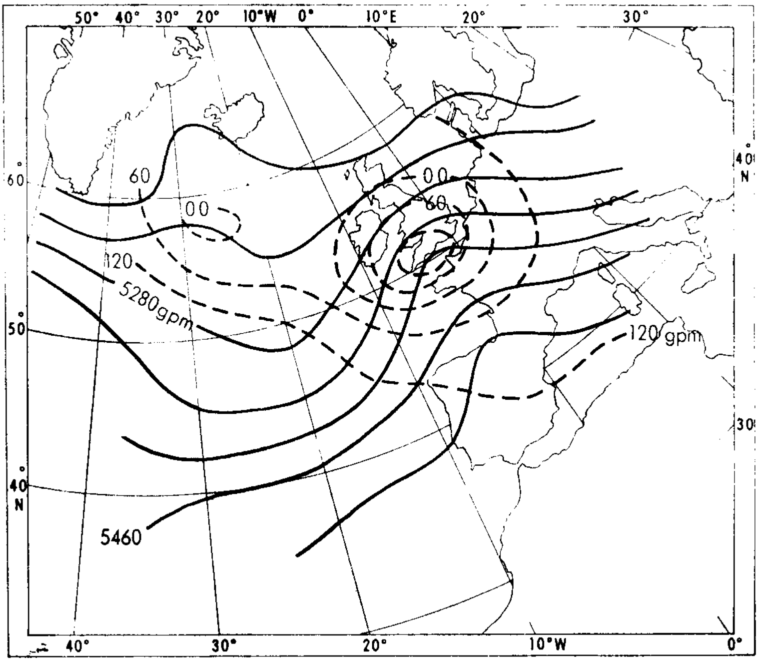


FIGURE 4—1000–500-mb THICKNESS AND 1000-mb CONTOURS AT 12 GMT, 12 FEBRUARY 1970

——— Thickness - - - Contours

Evidence for the release of latent and sensible heat. The track taken by the frontal wave makes it difficult to reach firm conclusions based upon an analysis of the upper air soundings from the various weather ships; however at 12 GMT on 11 February the frontal wave seemed to have passed just south of ocean weather station 'J' and was located about 200 nautical miles south-east of the station. The 12 GMT sounding from OWS 'J' is shown in Figure 5 and it can be seen that the air is moist and marginally unstable to surface temperatures. It is rather surprising to find no evidence of warmer air at medium levels so close to the frontal wave. This suggests that the thermal ridge (Figure 2*(a)*) consisted largely of warm air in the lowest 200 mb of the troposphere. SHIP reports are plotted in Figure 2*(a)* and give the temperature, dew-point and present weather. Saturated air at 12–13°C was present in the warm sector close to the wave tip and the reports of moderate to heavy rain verified the upward motion deduced earlier. If the lowest 200 mb of the sounding in Figure 5 is modified to the form of a saturated lapse from

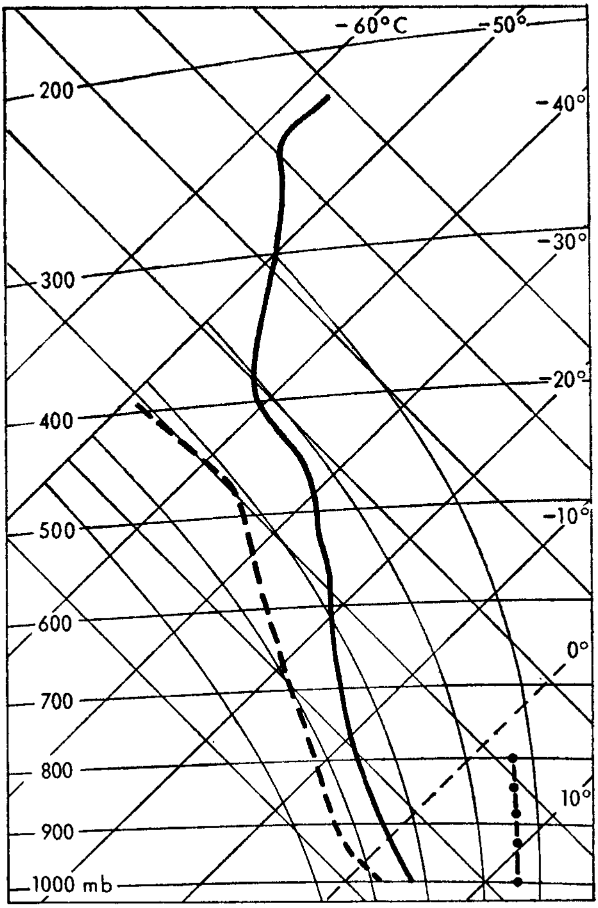
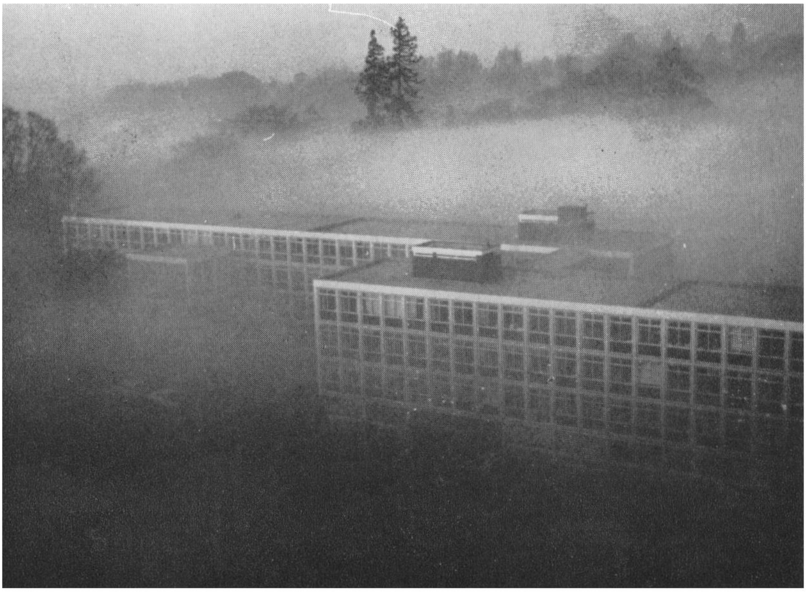


FIGURE 5—UPPER AIR SOUNDING FOR OCEAN WEATHER STATION 'J' AT 12 GMT, 11 FEBRUARY 1970

The corresponding profile of temperature above the frontal wave tip is indicated at the right-hand side of the tephigram.

——— Dry-bulb temperature − − − Dew-point temperature



Photograph by Mrs Mary Holmes

PLATE III—FOG FORMATION AT BRACKNELL ON THE AFTERNOON OF 10 DECEMBER 1969

(Photographs taken from the roof of the Meteorological Office)

To face page 27

PLATE IV—AWARDS TO CIVIL AIRLINE PILOTS

From left to right : Captain and Mrs R. D. Hall, Director-General of the Meteorological Office, Mrs Caesar-Gordon, Captain E. Caesar-Gordon (see p. 32).

a temperature of 13°C at 1000 mb, it will be clear that considerable instability was present just north of the wave tip. Even allowing for the uncertainties in the upper air structure above the surface centre, the evidence strongly suggests that copious supplies of latent and sensible heat were being released at 12 GMT and contributed largely to the rapid development of the surface centre during the next 12 hours.

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MINIMUM TEMPERATURES AT THE SURFACES OF CONCRETE ROADS AND CONCRETE SLABS

By G. E. PARREY, W. G. RITCHIE and S. E. VIRGO, O.B.E.

Summary. This paper discusses the results of forecasting night minimum temperatures by applying the methods which were devised for concrete roads at Watnall and Wyton to four other sites at which the only available minimum temperatures have been measured on Meteorological Office standard concrete slabs.

The authors have reported[1] the results of three methods of forecasting night minimum temperatures at the surfaces of roads built of concrete some 8 inches deep at Watnall and Wyton. One method involves direct regression from the temperature and dew-point the previous day. The other two methods, devised by Parrey[2] and Ritchie,[3] depend upon a forecast of air minimum temperature, M_A, by one of the recognized methods, and then a forecast value of $M_A - M_R$ has to be subtracted to obtain M_R, the forecast minimum temperature at the road surface. For the observations on which the tests were based ordinary minimum thermometers were used with their bulbs resting on the road surface.

Most forecasters, however, are dependent on observations made with minimum thermometers exposed as in the road experiments but on the concrete slabs 3 feet × 2 feet × 2 inches thick (1 foot ≈30 cm) which have now become standard equipment in some Meteorological Office instrument enclosures. This paper reports the results of applying the methods which were developed for the two roads to data obtained from the concrete slab at Watnall and also to data from four other places in the Midlands and East Anglia where the only data available were obtained at the surfaces of standard concrete slabs.

As Parrey's method and Ritchie's method both depend on forecast values of the air minimum temperature, it was necessary to choose places for which the errors in forecasting this quantity had already been assessed. Steele, Stroud and Virgo[4] have done this for a number of places and from their list Waddington, Marham, Wittering and Finningley were chosen for the present investigation.

Comparison of minimum temperatures over concrete roads with those over concrete slabs. The first step is to compare minimum temperatures over the roads at Wyton and Watnall with those over neighbouring concrete slabs. Table I shows that the difference is less than ¾ degC throughout the winter months of October to March inclusive, and between 1 and 2 degC during the months of April to September inclusive. This suggests that the year falls naturally into two seasons and that the six months from October to March could be considered as the winter season; but the main practical application is to frost prediction, predicting when temperatures of 0°C or less will occur, and as forecasters have to assess the probability of frost in April, this month has been included in the period of the year for which the various forecasting methods have been tested. The distribution for the whole year is shown in Figure 1. Like the other two distributions illustrated in Ritchie's paper[3] it has a sharper peak than the normal distribution.

TABLE I—MONTHLY MEANS AND STANDARD DEVIATIONS OF ROAD MINIMUM TEMPERATURE MINUS CONCRETE-SLAB MINIMUM TEMPERATURE

Site and period		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year	Oct.–Apr.
								degrees Celsius							
Wyton	Mean	0·0	0·5	0·6	1·3	1·1	1·9	1·6	1·1	1·2	0·7	0·2	0·3	0·9	0·5
Jan. 1969–Dec. 1969	S.D.	0·6	0·7	0·8	1·2	0·7	1·0	0·8	0·6	0·8	0·9	1·0	0·7	1·0	0·9
Watnall	Mean	0·3	−0·1	0·2	1·3								0·1	—	0·4
Dec. 1968–Apr. 1969	S.D.	0·7	0·9	0·8	1·1								0·5	—	0·8

The tests described below relate to data obtained over concrete slabs. Some forecasters however may still have to do forecasts for places from which observations are available of grass minimum temperature only, or perhaps these may be the only data available for assessing the accuracy of their forecasts; Table II has been compiled for their benefit.

TABLE II—MONTHLY MEANS AND STANDARD DEVIATIONS OF ROAD MINIMUM TEMPERATURE MINUS GRASS MINIMUM TEMPERATURE

Site and period		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year	Oct.–Apr.
								degrees Celsius							
Wyton	Mean	1·3	1·2	1·2	2·6	2·5	3·3	3·3	2·0	2·6	1·7	0·2	0·4	1·8	1·2
Jan. 1969–Dec. 1969	S.D.	0·6	1·0	1·2	1·4	1·1	2·0	1·8	1·0	1·8	1·5	1·4	0·9	1·6	1·2
Watnall	Mean	0·8	1·1	1·9	3·4						1·7	1·2	0·8	—	1·5
Oct. 1967–Apr. 1968	S.D.	1·4	1·2	1·4	2·2						1·3	1·4	1·5	—	1·8

The data for road minimum temperatures minus grass minimum temperatures in Table II for the two sites for the months October–April taken as a single period are not samples of the same population, but a *t*-test performed on the figures for the same months taken together in Table I gives strong grounds for asserting that these are indeed samples of the same population; if we reject this assertion, we shall be wrong on 85 per cent of occasions. The best estimates of the mean and standard deviation of this population are

$$\text{mean} \quad (\delta) = +0{\cdot}45 \text{ degC},$$

$$\text{standard deviation} \quad (\sigma_0) = 0{\cdot}85 \text{ degC}.$$

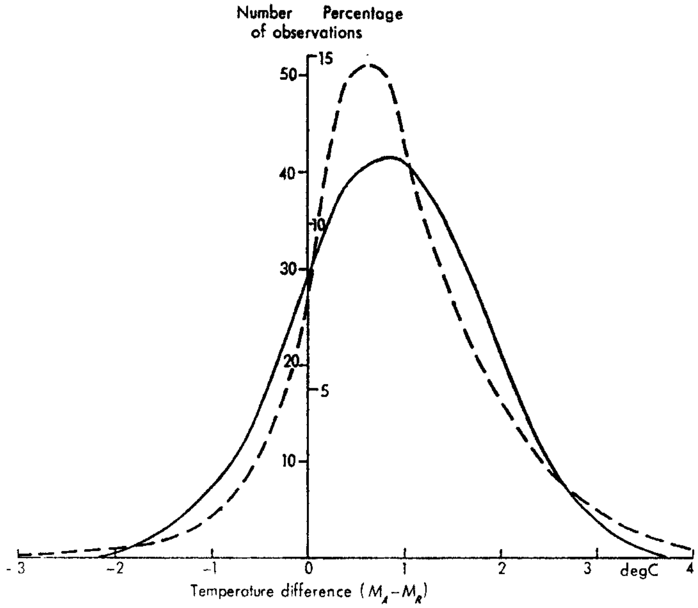

FIGURE I—ROAD MINIMUM TEMPERATURE MINUS CONCRETE-SLAB MINIMUM TEMPERATURE

– – – Actual distribution of temperature differences
——— Normal distribution with the same mean and standard deviation for 345 observations made at Wyton during the year 1969

Forecasting errors involved in the direct regression method. As in previous papers an error is reckoned as the forecast minimum temperature minus the observed minimum temperature. By applying the direct regression method, forecast errors were obtained on the assumption that the road minimum temperature was always the same as the slab minimum temperature. This is not so, and the real mean must therefore be obtained by subtracting $\delta = 0{\cdot}45$ degC from the estimated mean. To obtain the corresponding standard deviation, let σ_1 be the standard deviation calculated on the assumption that the road minimum temperature and the slab minimum temperature are the same. Then the total standard deviation σ is derived from the relation

$$\sigma^2 = \sigma_0{}^2 + \sigma_1{}^2 = (0{\cdot}85)^2 + \sigma_1{}^2.$$

Table III gives the means and standard deviations obtained by the direct regression method after these adjustments have been made and shows the

TABLE III—MEANS AND STANDARD DEVIATIONS OF ERRORS ARISING FROM THE DIRECT REGRESSION METHOD AFTER ADJUSTMENTS HAVE BEEN MADE FOR THE DIFFERENCES IN MINIMUM TEMPERATURES OVER ROADS AND OVER SLABS

Place	Number of occasions	Without cloud correction		With cloud correction	
		Mean	σ	Mean	σ
		degrees Celsius		*degrees Celsius*	
Waddington	253	−1·03	2·97	−0·53	2·77
Marham	129	−0·33	2·86	+0·06	2·63
Wittering	246	−0·27	3·19	−0·40	2·88
Finningley	248	−0·71	2·92	−0·04	2·70
Watnall and Wyton	554	−0·14	2·56	+0·38	2·42

approximate accuracy which could be expected if the direct regression equation derived from observations on a road at Watnall were used to forecast minimum temperatures on roads at the other four sites. Figures for Watnall and Wyton have been included for comparison. For Waddington, Wittering and Finningley the data comprised observations for the 12 months, December 1968–April 1969 and October 1969–April 1970, but observations on the slab at Marham did not start till October 1969. Occasions when a front passed the site between 12 GMT and 06 GMT next morning have been excluded from the analysis. Likewise all occasions when the dew-point at 12 GMT the previous day exceeded 10°C have been excluded. Since the cloud amount was estimated in retrospect from the *Daily register*, there are no forecasting inaccuracies and the improvement obtained by applying the cloud correction is therefore the maximum possible.

Forecasting errors involved in Parrey's and Ritchie's methods. Because these two methods forecast the quantity $M_A - M_R$ and depend on a forecast of M_A by some other means, the calculations of mean and standard deviation each involve three components instead of two.

Let m_1 be the mean error in the forecasts of $M_A - M_R$ on the assumption that the road minimum temperature and the slab minimum temperature are the same,

and m_2 be the mean error in the forecasts of M_A.

Then the mean for the whole operation is given by

$$m = m_1 + m_2 - \delta = m_1 + m_2 - 0{\cdot}45.$$

Similarly, if σ_0 has the same connotation as before (p. 29),

σ_1 is the standard deviation of the errors in forecasts of $M_A - M_R$ on the assumption that temperatures on road and slab are the same,

and σ_2 is the standard deviation of the errors in the forecasts of M_A,

$$\text{then } \sigma^2 = \sigma_0{}^2 + \sigma_1{}^2 + \sigma_2{}^2$$
$$= (0{\cdot}85)^2 + \sigma_1{}^2 + \sigma_2{}^2.$$

In these formulae the terms have not been weighted in proportion to the numbers of occasions from which they were derived; it has been assumed that the values in each case are the best possible values for the quantities concerned.

Estimates of m_2 and σ_2 were obtained by compounding the figures given by Steele, Stroud and Virgo[4] for clear and cloudy nights for the period October 1967–March 1968 and making the assumption that what is valid for one year is equally valid for another. The results are given in Table IV, together with the figures for Ritchie's method for Wyton taken from the previous paper.[1] The test at Watnall was done for the period October 1969–April 1970 with forecast values of M_A and the values of m and σ (although therefore not strictly comparable) have been included in the table.

Discussion of Table III and Table IV. Table IV shows that there is little to choose between Parrey's method[2] and Ritchie's method[3] but a comparison with Table III shows that both are superior to the direct regression

TABLE IV—MEANS AND STANDARD DEVIATIONS OF ERRORS ARISING FROM PARREY'S AND RITCHIE'S METHODS

Place	m_2	σ_2	Parrey's method m_1	σ_1	m	σ	Ritchie's method m_1	σ_1	m	σ
	degC			*degC*				*degC*		
Waddington	−0·23	1·74	+0·01	1·01	−0·67	2·18	−0·19	1·02	−0·81	2·19
Marham	+0·01	2·47	−0·24	1·11	−0·66	2·84	−0·43	1·05	−0·87	2·82
Wittering	+0·61	1·73	+0·33	1·29	+0·49	2·29	+0·07	1·23	+0·23	2·26
Finningley	−0·04	1·51	+0·24	1·27	−0·25	2·15	−0·03	1·19	−0·52	2·10
Wyton	−1·10	2·79					0·00	1·09	−1·14	2·97
Watnall					−0·45	2·20				

The number of occasions are the same as in Table III (96 for Watnall and 468 for Wyton). The symbol at the head of each column has the connotation given in the text.

method. The main error in Parrey's and Ritchie's methods is in the forecast of air minimum temperature and, as Steele, Stroud and Virgo[4] have shown, this varies widely from place to place. Doing the forecast in two stages allows the forecaster to take this variation into account.

Analysis of variance shows that the distributions of errors either in Parrey's method or in Ritchie's method at the various places are not samples of a single population; it would have been most surprising if they had been. Nevertheless they are all of the same magnitude, and therefore Parrey's method and Ritchie's method are offered as aids to forecasting frost on roads in the Midlands and East Anglia — at least until a better method becomes available.

Two of the component populations which have gone into computing the final means and standard deviations in Table IV are normally distributed, but, as Figure 1 shows, the third and smallest component is not normally distributed. If however it is accepted as a reasonable approximation to a normal distribution, the final means and standard deviations obtained by both Parrey's method and Ritchie's method may be regarded as referring to populations which themselves approximate to normal distributions. On that basis tables similar to Table V of the paper by Steele, Stroud and Virgo[4] can be constructed from the data of Table IV of the present paper. They lead to the working rule that with a forecast road minimum temperature of + 2°C the probability of a temperature of 0°C or less on roads is about 20 per cent and with a forecast of − 2°C the probability is about 80 per cent. In other words, with a forecast of + 2°C the odds are 4 to 1 against a temperature of 0°C or less on roads and with a forecast of − 2°C the odds are 4 to 1 on.

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NOTES AND NEWS

Meteorological Office awards to captains, first officers and navigators of civil aircraft

A system of awards was introduced in 1954 to encourage the making of air reports by civil airline pilots and navigators.

The awards are in two categories. Books, suitably inscribed, are awarded to the captains and navigators who have provided the best series of reports during the year under review, while aircraft captains who have given long and meritorious service in the provision of air reports receive brief-cases.

This year brief-cases were awarded to Captain R. D. Hall of BOAC and Captain E. Caesar-Gordon of BEA by the Director-General at a ceremony held in the Headquarters of the Meteorological Office at Bracknell on Thursday, 24 September 1970. Plate IV shows the Director-General with the recipients and their wives.

Book awards for the year 1969 have been sent to :

Captains D. H. Banton, J. H. Wickson, C. H. Earthrowl, G. R. Sharp, J. S. Cooksey and W. F. Strange, and 1st Officers P. C. E. Cox, Peter D. Adams, P. H. Jefferies, R. A. Lake, D. G. Wyard and A. N. Moffat of BOAC, Captains W. J. Ferries, J. Cunningham, K. Mountney, H. Tarran-Jones, H. J. King, K. D. G. Mitchell, G. G. Bell, G. A. Stone, J. McCarthy and C. Cooper of BEA, and Navigating Officers H. L. Chandor, R. H. Williamson, R. Webb, H. F. Musker, K. R. Charles, J. I. Jones, A. L. Brzezina and J. F. Archer of BUA.

OBITUARY

It is with regret that we have to announce the death of Mr C. W. Cozens (Scientific Assistant) on 15 September 1970.

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NOTICES

It is requested that all books for review and communications for the Editor be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire, RG12 2SZ, and marked 'for Meteorological Magazine.'

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