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JET STREAMS IN RELATION TO FRONTS AND THE FLOW AT LOW LEVELS

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Summary.—Since surface observations are made more frequently and extensively than upper air observations, the accuracy of 300 mb charts, whether actual or forecast, is increased by making the fullest use of associations between jet streams and surface features. A brief examination of low-level winds beneath fairly strong jet streams is followed by a description of the jet-stream model at 300 mb in relation to fronts and surface circulations in different stages of development.

Introduction.—In 1947,[1] if not earlier, it was noted that a jet stream that could be associated with a frontal surface always lay on the warm side of it. Subsequently Palmén[2] stated that the jet stream was to be found nearly vertically above the intersection of the frontal surface and the 500 mb surface. This concentration of horizontal wind shear and correspondingly of horizontal temperature gradient, extending from the jet stream down to the surface front, suggested that the jet stream and the front were related dynamically, and the nature of the relationship has been studied by Sawyer.[3]

As was stated in the introductory paper,[4] we are concerned here with associations which are of practical forecasting use, regardless of whether the jet stream is the cause or the consequence of the feature with which it is associated. Forecasting by observed association is common practice since the forecaster's world is one in which observations are never as complete at any instant as he would wish. He is forced to infer from an observation in one place what is happening to another element elsewhere, the two places perhaps being separated vertically as well as horizontally. Before the last war his forecast of upper air flow was largely an inference from the surface pattern. Nowadays, with regular upper air observations and electronic computations, the primary forecast pattern is that of the middle troposphere and the surface pattern is made to conform to it. Nevertheless the jet stream is defined by lateral dimensions that are small in relation to the features of an upper air chart. It is smoothed in objective analysis—and often in subjective analysis—and still more so in a forecast chart, where it may even be impossible to locate the axis from the contours. It is therefore necessary for the forecaster to make what use he can of the surface analysis in locating the jet stream, and this paper deals with some empirical relationships between them.

The general association between jet streams and fronts.—Murray and Johnson[5] have given examples of the variability of jets in relation to fronts, but it is believed that more systematic relationships exist than seem to be implied by their examples.

A jet stream is intimately related to a strong baroclinic zone; a concentrated horizontal temperature gradient is the fundamental property of a front. Inevitably, therefore, a jet stream is associated with a front unless the front is thermally weak. An occlusion is an example of such a front, since by definition it lies outside a main thermal belt. Hence any relationship which appears to exist between a jet and an occlusion is almost certainly fortuitous. Such a jet is more likely to be associated with a secondary cold front behind the occlusion.

The wind at 300 mb is the resultant of the sea-level gradient wind and the intervening thermal wind. It is to be expected that relationships between the 300 mb wind and the surface fronts will show the greatest consistency in situations where the sea-level gradient wind is either relatively small or shows little variability. The investigation to be described was therefore restricted to occasions when the thermal wind component was most likely to dominate the 300 mb flow, so the selection was made using only the stronger jets. Occasions were first tabulated when any British radiosonde station reported a maximum wind of at least 130 knots (corresponding to a 300 mb wind of about 115 knots, the mid-point of the 'strong' category[4] used earlier). There were just over 400 such reports in the months October to March of 1960–61 and 1961–62.

The jets were classified according to the type of surface front with which they were associated. Of the 86 jets, 52 were ahead of warm fronts and 30 behind cold fronts; the remaining 4 could not be classified satisfactorily. None of these strong jets was associated with an occlusion. The distinction between warm- and cold-type jets was not always certain when the fronts and jets showed little lateral movement.

Warm-front jets in relation to the underlying 900-metre wind.—Comparisons were made between the 300 mb winds on or near the jets and the 900 m winds on the corresponding upper air ascents.

The 52 warm-front jets provided 273 pairs of observations. The directions of the jets ranged from 230° through north to 030°, 92 per cent of them lying between 260° and 360° and 64 per cent between 300° and 350°.

With jets in the sector from 300° to 350° the average backing of the 900m wind from the 300 mb wind was zero at 350°, 10° at 330° and 20° at 300°. Three-quarters of the 900m wind directions were within 20° of the direction given by this rule. The stronger the low-level wind the more commonly it conformed in direction, and differences exceeding 20° occurred mostly with 900m winds under 30 knots. Warm-front jets outside the sector 300° to 350° were associated with lighter and more variable 900m winds.

A result here which is of some forecasting importance is that when the direction of the warm-front jet is known to be at an angle of more than 20° to a surface geostrophic wind of 30 knots or more, the jet is unlikely to be a strong one. This is consistent with the well known weakening of a warm-front jet within the central area of a deepening surface depression.

Cold-front jets in relation to the underlying 900-metre wind.—In the same period there were 30 cold-front jets and a total of 124 pairs of observations on them. The directions of the jets lay entirely between 200° and 340°, 72 per cent of them being in the sector 240° to 300°.

There was greater uniformity than with warm-front jets in the directional relationship between 300 mb and 900m, the backing with height averaging less than 5° and with little systematic dependence on the direction of the jet. Ninety per cent of the 300 mb winds had a direction within 20° of that of the 900m wind.

Winds at 900m were markedly stronger than under warm-front jets, 90 per cent of the speeds being at least 30 knots. The lighter winds tended to veer more from the jets, being presumably at points towards the anticyclonic end of a cold front. Wind directions at 900m were between 230° and 330° in all but 2 of the 124 observations under cold-front jets.

The fact that a strong cold-front jet requires an accompanying surface geostrophic wind of at least 30 knots and little change of wind direction up to 300 mb is a useful safeguard against overestimation of the speed of the jet. Moreover, such conditions can rarely be satisfied except where the isobars are cyclonic.

The location of jet streams relative to warm fronts.—An attempt was next made to locate the jets relative to the pattern of fronts and isobars, using the same observations but without regard to whether the wind speed along the jet axis continued to exceed any particular figure. Starting from the British Isles a number of warm-front jets were tracked upwind on 300 mb charts until they passed over or near a surface front, however weak the flow may have become at some stage. The number of jets that could be followed satisfactorily was 44. It was noted that the position of many was related to the axis of the surface ridge ahead of the warm front, the mean position being 120 nautical miles (n.miles) beyond it (see Figure 1). The large majority of jets lay within little more than 100 n.miles of this mean position. On occasions when

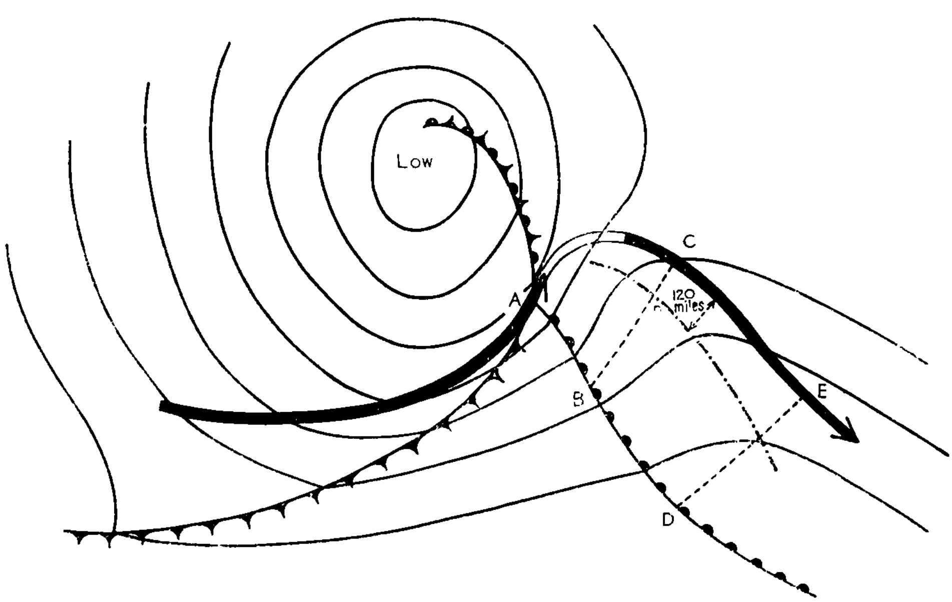


FIGURE 1—JET-STREAM MODEL IN RELATION TO SURFACE FRONTS

·——·——· Ridge line. The broad arrow represents the jet at 300 mb, the unshaded portion being a weak or broken jet.

the ridge axis became nearer the warm front at higher pressures it was found best to apply this 120-n.mile rule at the place where the axis was farthest from the front and draw the jet so that it approached no closer to the front at higher pressures (DE not less than BC in Figure 1). On occasions the rule failed through the jet being markedly backed from the ridge line, so every opportunity should be taken to obtain confirmation of direction from the thermal field. A few situations were also found when the ridge axis was not clearly defined on a single chart because the ridge travelling with the warm front had amalgamated with a pre-existing ridge: it is the former ridge which is associated with the jet. Finally the 120-n.mile rule is subject to modification towards the tip of the warm sector in a way that will next be described.

An essential characteristic of occlusion is that the major thermal belt, being the boundary to the warm sector, moves away from the primary surface depression. The jet moves laterally with it and hence the strong wind belt around a partly occluded warm sector is somewhat similar in shape to that around a warm sector in which occlusion has not begun. From a study of the 300 mb flow about 40 warm sectors, both with and without occlusion, it was found that the jet axis was on the average practically above the tip of the warm sector. This relationship was a fairly consistent one, though it should not be overlooked that the analyst takes into account a relationship of this kind when drawing the charts. It was further noted that the direction of the strongest wind at 300 mb was the same as that of the underlying sea-level isobars in the warm sector.

The majority of strong jets over the British Isles ahead of warm fronts were found to lie between 300 and 450 n. miles from the front, this distance being measured perpendicular to the jet (BC in Figure 1). The larger distances were found when the front was slow moving but there were a number of exceptions. The relationship between the distance from the front and the distance from the tip of the warm sector (BC to AB in Figure 1) was also a variable one but it appeared that the average distance was fairly constant until AB reduced to a distance equal to 7° latitude, from which stage the line of the jet turned in towards the tip of the warm sector.

From the relationship with the ridge, the direction and position of the jet over the tip of the warm sector and from the 7° relationship we have a first approximation to the position of the warm-front jet for use when upper air information is scanty.

The location of jet streams relative to cold fronts.—The strong cold-front jet is linked at each end to a warm-front jet or axis of strong wind, and in addition the direction of the jet near the tip of the warm sector is known. The tendency of the jet to cut surface isobars at a very small angle is a further aid in locating it. It was also found that the majority of strong cold-front jets were at a distance behind the front which was proportional to the distance from the tip of the warm sector, the separation being increased by 140 n.miles, on the average, for each 10° latitude distance. A minority of jets departed far from this relationship.

Jet speed in relation to the low-level pattern.—As yet no mention has been made of the variations of speed except to imply that the relationships between the jet and other features described above do not necessarily hold for weaker jets. Without adequate upper air information it does not seem possible to estimate the strength of a jet but the low-level pattern gives an indication of the relative speeds along a jet. The statistics given above as to the sectors in which strong jets are found and the relationships with low-level winds indicate at least the circumstances in which a strong jet is not to be expected. It is of interest to contrast the situation over a depression possessing a small circulation with that existing when a depression is in a later stage of development. The former is illustrated by the charts of 0000 GMT on 20 January 1962 (Figure 2) when a strong warm-front jet existed over Scotland and there was no opposing sea-level gradient wind. The cold-front jet, favoured by supporting low-level

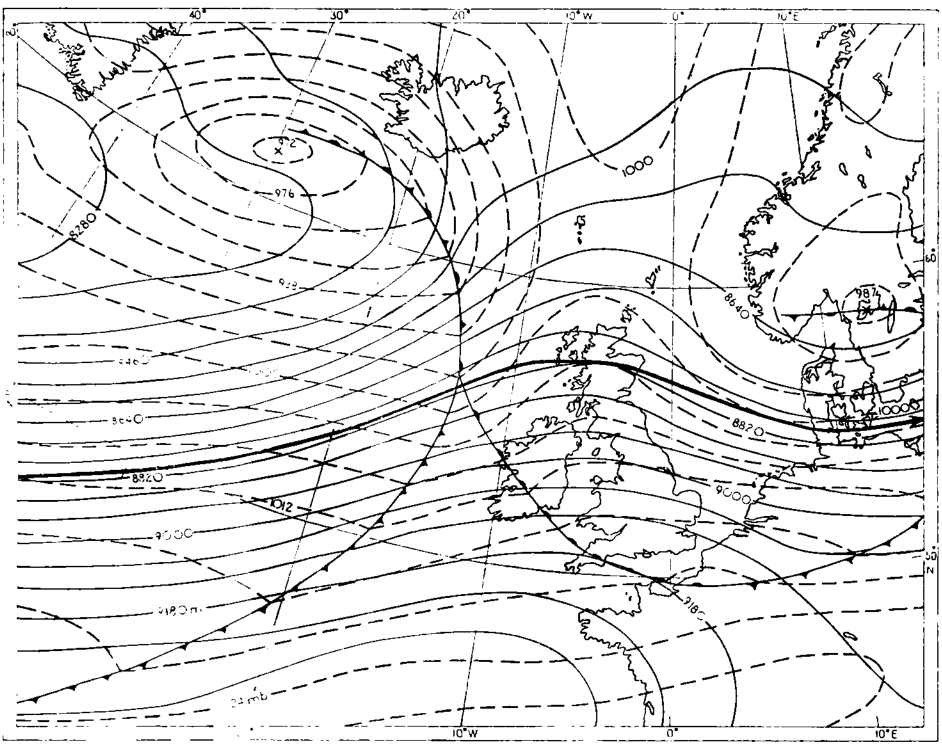


FIGURE 2—WARM-FRONT JET CONTINUOUS WITH THE UPSTREAM COLD-FRONT JET AT 0000 GMT, ON 20 JANUARY 1962

———— 300 mb contours, - - - - surface isobars. The broad arrow shows the position of the jet.

winds of over 40 knots, extended to join the warm-front jet in a continouus flow around the frontal system. Essentially the strong unbroken jet resulted from the absence of a surface pattern which would have given meridional advection of thickness lines. A different pattern is that of 1200 GMT on 31 January 1960 (Figure 3). Over this depression the surface flow around the warm sector was more meridional and there was consequently a greater amplitude in the 300 mb flow. The strong cold-front jet weakened or broke over the upper ridge and strengthened again to become a strong warm-front jet east of Denmark. In general the weakening between a cold-front jet and a warm-front jet is more pronounced the greater the direction change between them. Large curvature in the upper ridge imposes a limiting speed since the negative relative vorticity cannot exceed the Coriolis parameter for any length of time.

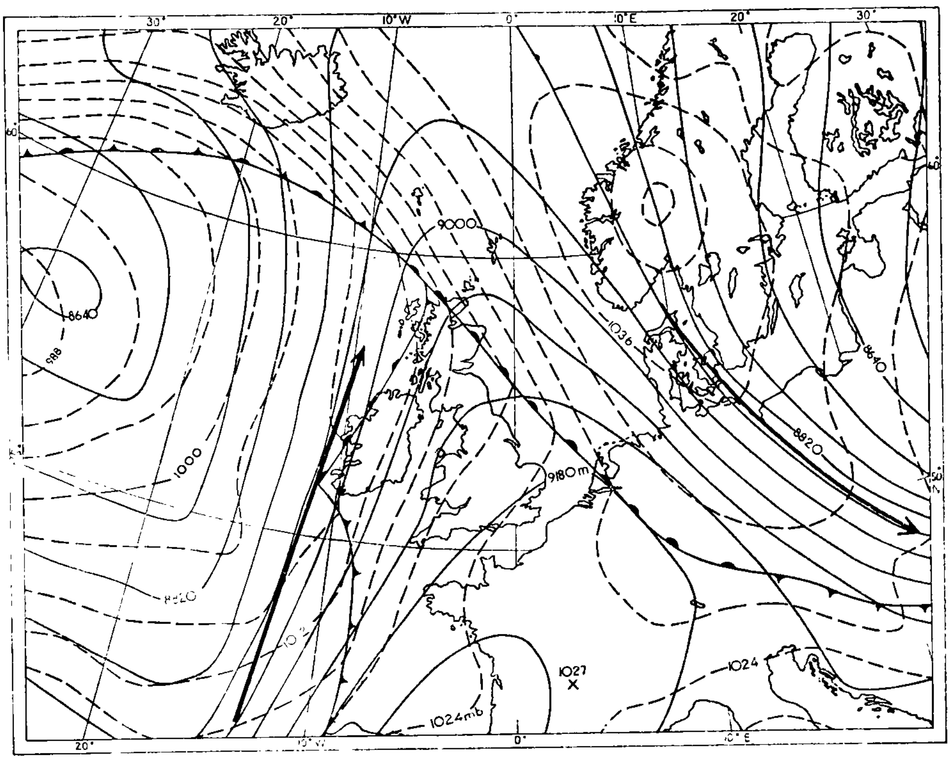


FIGURE 3—WARM-FRONT JET SEPARATED FROM THE UPSTREAM COLD-FRONT JET AT 1200 GMT, ON 31 JANUARY 1960

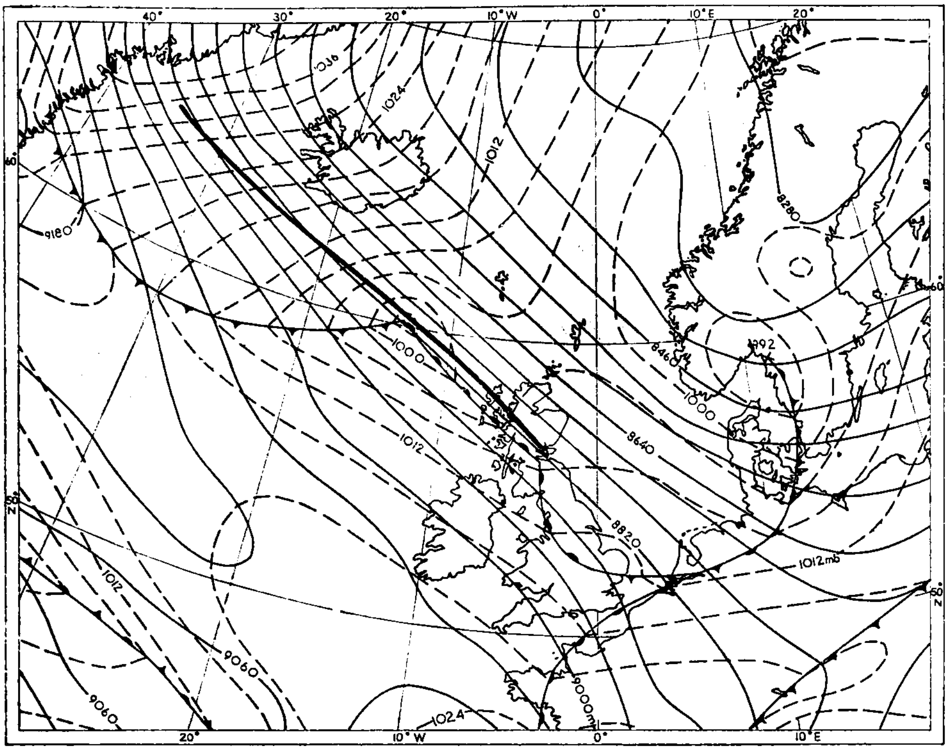
——— 300 mb contours, - - - - surface isobars. Broad arrows show the position of the jets.

Changes in the orientation of a jet.—Since the jet is a feature of a change to a more meridional flow the jets themselves must become more meridional, at least in the earlier stages of development. Thus a cold-front jet, formed by cold advection on the east side of an upper trough, should back with time, and a warm-front jet, on the east side of an upper ridge, should veer. More loosely it can be said that north-westerly jets tend to veer and south-westerly ones to back, but it must be remembered that, particularly when the wave-train itself is turned from the west–east direction, the character of a jet is not defined by its direction. Figures 4(*a*) and (*b*) depict a north-westerly jet which was mainly of cold-front type and therefore backed as cold air moved further south over the Atlantic than over Scotland.

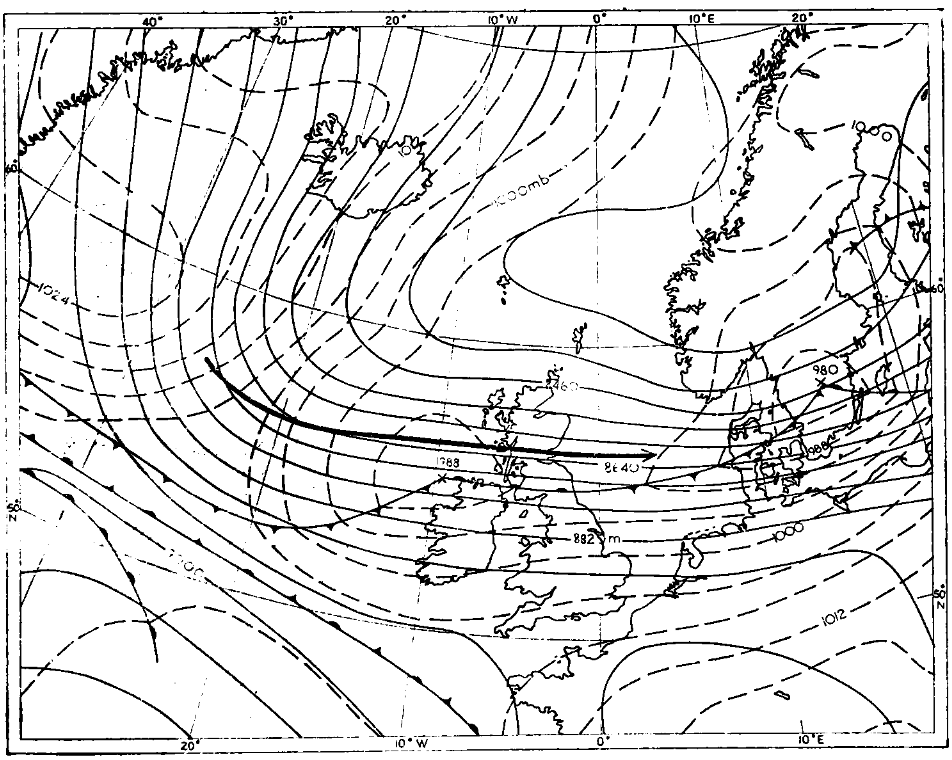
Warm-front jets.—The large majority of warm-front jets are from a north-westerly point and, like the associated front, either veer or maintain their direction in a manner which is not unduly difficult to forecast by the method of thickness advection. Following perhaps two or three days of veer at an average rate of 20° per 24 hours the ultimate development is likely to be one of the following, of which (ii) occurs most frequently:

(i) The jet shortens and weakens as the upwind ridge draws closer to the downwind trough. This is usually accompanied by a backing of the jet.

(ii) A cut-off low forms and the jet gradually propagates forward round the east side of the low.



(*a*) 0000 GMT, on 18 January 1960

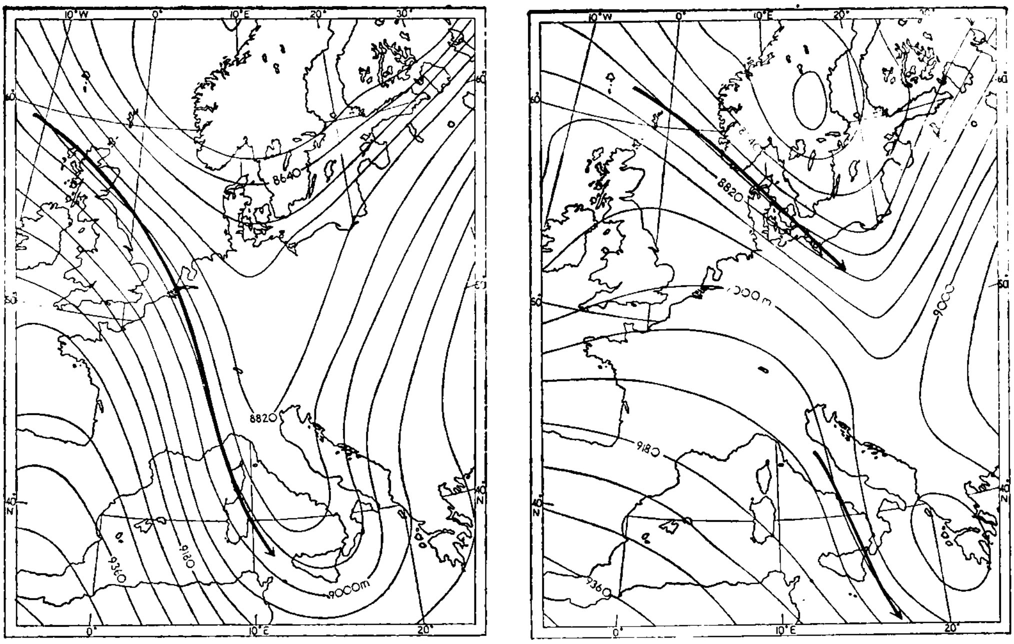


(*b*) 0000 GMT, on 19 January 1960

FIGURE 4—SEQUENCE SHOWING MARKED BACKING OF A NORTH-WESTERLY JET

——— 300 mb contours, – – – – surface isobars. Broad arrows show the position of the jets.

(iii) A cut-off low forms and the jet divides as shown in Figures 5(*a*) and (*b*), one part of the jet rounding the low, as in (ii) above, and the other part forming the western limb of the new trough, backing as it moves east.



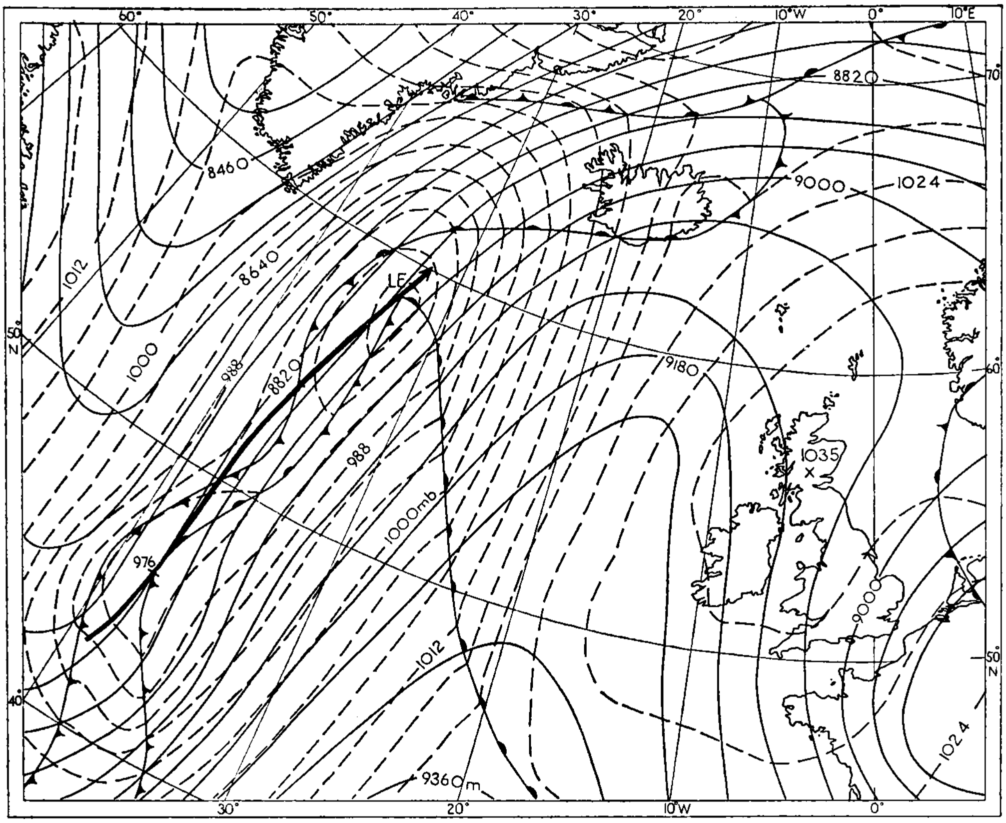
(*a*) 1200 GMT, on 7 December 1961 (*b*) 1200 GMT, on 8 December 1961

FIGURE 5—SEQUENCE SHOWING THE BREAKING OF A JET ON FORMATION OF A CUT-OFF LOW, WITH BACKING OF THE NORTHERN SECTION

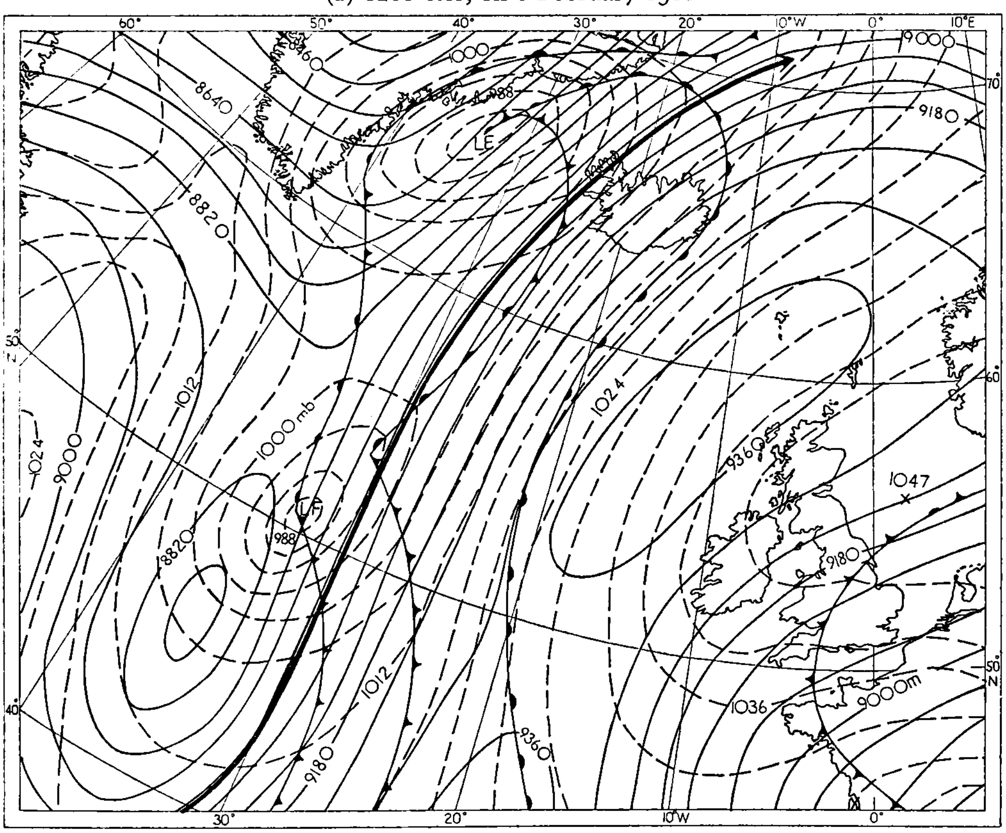
———— 300 mb contours. Broad arrows show the position of the jets.

It is not possible to be as specific in regard to the curved part of the warm-front jet which is linked to an upwind cold-front jet (see Figure 2). It is difficult to specify a direction for such a jet, so the terms 'veering' and 'backing' have little meaning. On most of these occasions there are no major systems below the jet and the upper ridge probably moves very slowly east with little change of shape, so over a fixed point the jet tends to back slowly. However, each situation is best considered individually in terms of thickness advection.

Cold-front jets.—A cold-front jet usually has cyclonic curvature over a considerable distance and often merges with an upwind warm-front jet. It is broadly true that the cold-front jet backs with time, the sharpening of the trough between the two jets eventually being relieved by the formation of a cut-off low. Nevertheless the backing of the cold jet is often intermittent and local because it lies over the region where cyclogenesis is most likely to occur. The formation of a surface depression under the eastern limb of an upper trough increases the eastward movement of the thickness lines to the south of it, and thus of the jet. The north-eastward movement of this low induces a travelling wave in the jet which normally increases the net eastward movement of the jet. Whether the jet is finally backed or veered from its earlier orientation depends on the rate of development of the depression relative to its speed along the jet. On many occasions, if not most, the jet extends north-east behind the depression but remains fairly straight. On the other hand Figure 6 shows how large deepening can cause a jet to veer and break. At 1200 GMT on 6 February 1960, low 'LE' was moving north-east (Figure 6(*a*)) and 24 hours later (Figure 6(*b*)) the jet (essentially of cold-front type) had extended beyond Iceland with



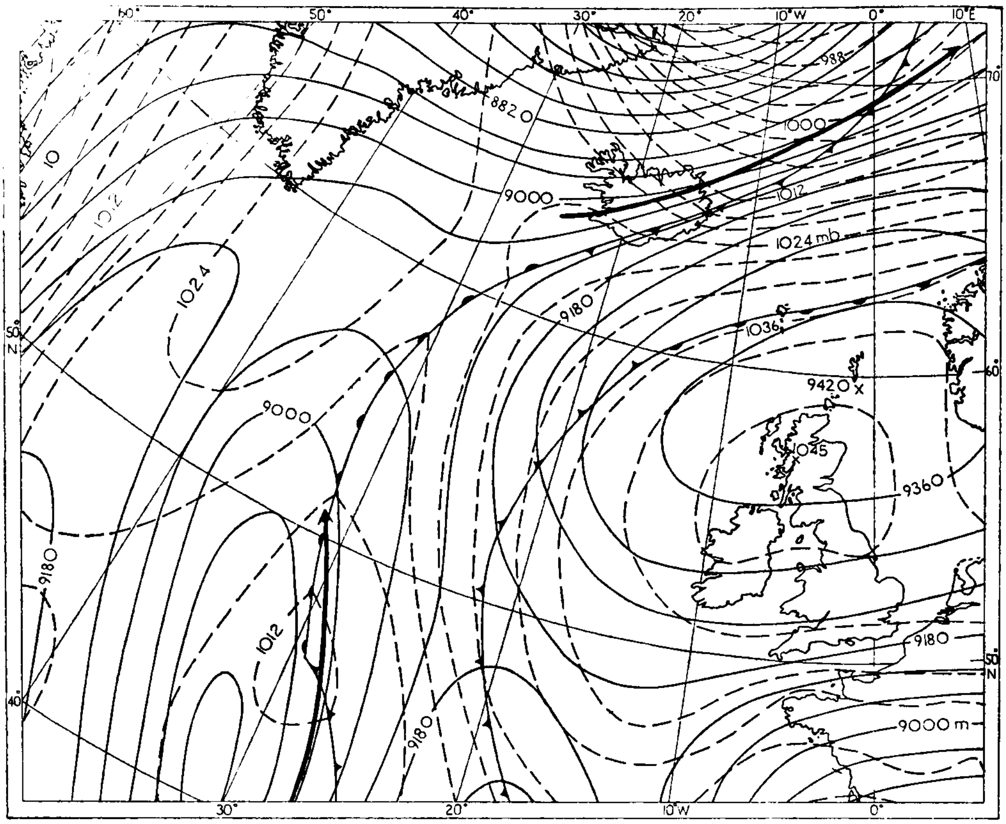
(*a*) 1200 GMT, on 6 February 1960



(*b*) 1200 GMT, on 7 February 1960

FIGURE 6—SEQUENCE SHOWING THE VEERING AND BACKING OF A COLD-FRONT TYPE JET

———— 300 mb contours, – – – – surface isobars. Broad arrows show the position of the jets.



(*c*) 1200 GMT, on 8 February 1960

FIGURE 6—SEQUENCE SHOWING THE VEERING AND BACKING OF A COLD-FRONT TYPE JET—*continued*

little change of direction. At its southern end, in latitude 45–50°N, there was some backing. By 1200 GMT on 8 February (Figure 6(*c*)) low 'LE' formed part of an intense low off the coast of north-east Greenland and the strong south-eastward advection of cold air behind it caused a substantial veering of the jet. It split away from the low latitude part and subsequently crossed Scandinavia as a north-west wind. Whereas backing rather than veering is characteristic of a cold-front jet, this example demonstrates the limitations of any empirical rule.

In conclusion it is appropriate to stress that the facts presented in this paper were mostly based on the stronger jet streams. Since the borderline between a jet stream and a belt of strong winds is arbitrarily chosen, one cannot expect a jet to show characteristics which can be narrowly defined. Jet streams, like fronts call for individual assessment in which experience and subjectivity play an essential part.

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THE COMPUTATION OF GEOSTROPHIC WINDS BY OBJECTIVE ANALYSIS

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

Introduction.—Measurements of geostrophic winds are often required in meteorological investigations. If a statistical treatment is to be used a large number of observations will probably be needed and the labour of making numerous geostrophic wind measurements from synoptic charts can be considerable. It was therefore decided to use the computer METEOR to analyse sets of pressure values objectively and evaluate the resulting geostrophic winds. For the period since January 1957 most of the data required have been punched on cards, and it is possible for the pressure values to be converted to punched tape by machine methods. The production of tapes for a network of stations covering the whole British Isles would entail a fairly considerable amount of work, but once the tapes were available, geostrophic (and gradient) winds for any location within the network could be run off on METEOR at a rate of about 30 per minute.

Description of the METEOR programme.—The computer has been programmed to 'read in' a series of surface pressure values from data tapes for up to 22 stations, and checks are included to ensure that each group of data has the correct number of observations. The grid co-ordinates for each station precede the relevant pressure data. The co-ordinates of the position for which winds are required (normally near the centre of the network of reporting stations) are then fed into the machine.

If x and y are the distances east and north of a given station from the selected central position (which becomes the origin), and p is the pressure then the machine derives a formula

$$p = ax^2 + bxy + cy^2 + dx + ey + f \qquad \ldots \quad (1)$$

where the coefficients a,b,c,d,e and f are chosen so as to produce a quadratic surface which is the best fit to the set of observed pressures. The usual criterion that the value of the sum of the squares of the errors shall be a minimum is used. If a particular value, say 1000 mb, is given to p then equation (1) is the equation of the 1000 mb isobar; if p is made equal to f then we have the equation of the isobar through the origin. The pressure gradient may be found by differentiating equation (1), and hence the geostrophic wind can be calculated. The wind speed depends on the latitude, pressure and temperature. The first two are known from the data on the tapes, but an assumed average value, 10°C, had to be used for the temperature. The results will be in error by $3\frac{1}{2}$ per cent for each 10°C by which the temperature differs from 10°C.

In order to provide some information on the accuracy with which the observations have been fitted, the root mean square error between the fitted and the observed pressures is calculated, and the largest individual error is examined. If a large error occurs it is quite likely that it is due to a mistake in the data, and whenever the error is greater than one millibar a statistical test is carried out to examine the likelihood of the observation being wrong. If the fit as a whole is not very good, as sometimes happens for example with strong winds and large tendencies, rejecting an apparent error as large as one millibar may not be justified. The largest error is compared with the standard error of the remaining pressure values using Student's t-test. (If n is the total number of pressure values, then both the standard error and the value of t are based on $n - 7$ degrees of freedom.) If the largest error fails this test, and the corresponding pressure value can then be considered to be wrong with at least a 95 per cent probability, the offending pressure is rejected and the formula is recomputed using one less station. The process of checking and rejecting is continued until all pressures are acceptable or only six are left, when the data will be fitted exactly. The errors in any rejected pressures are recomputed using the finally accepted formula. Lastly the winds and errors are printed and tapes of wind speed and direction are punched.

Comparison between computed and measured winds.—A set of 1012 geostrophic winds for London (Heathrow) Airport at 0600 GMT in November, December and January 1946–57 were available from another investigation. They had been measured by hand from hourly synoptic charts prepared in the Central Forecasting Office and were used for comparison with computed winds for the same period. METEOR was used to work out the vector difference between each pair of winds. There did not appear to be any systematic differences between the two sets of winds, but out of 1012 occasions there were 69 with vector differences of 15 knots or more. An independent remeasurement of the geostrophic wind was made for each day with a large discrepancy, the isobars being carefully redrawn when necessary. This check revealed a number of serious mistakes in the original measurements, even though a good deal of trouble had been taken to get a good set of data. After remeasurement 50 of the 69 discrepancies were reduced to less than 15 knots. Of the 19 large discrepancies which remained 9 occurred when there was a front with a sharp trough near London and the machine had fitted a smooth curve instead of the discontinuity normally drawn. The other 10 discrepancies were caused by the machine not rejecting observations which a skilled analyst, having a much wider network, would have discarded. Nevertheless, on the whole, agreement between computed and measured winds was very good; on 85 per cent of occasions the vector differences were less than 10 knots, 13 per cent of the time they were between 10 and 14 knots, and there were only 2 per cent of discrepancies of 15 to 25 knots. On balance the computed winds were slightly better than the measured winds since before correction the latter had 7 per cent of errors greater than 14 knots.

Choice of network.—Several experiments were made to determine the best network of pressure reporting stations. A network covering too small an area would produce a very local and possibly unrepresentative wind, whereas too large a network might introduce too much smoothing. A quadratic surface cannot fit an inflexion; over a small area this will not matter, but poor results could sometimes be expected over a large area.

The figures quoted in the previous section related to a network of 15 to 18 stations extending 80 to 100 miles to the north and west of London, but only 50 to 70 miles to the south and east. It was evident that sparsity of data to the south-east had contributed to some of the poorer results, but on the whole this network could be considered satisfactory for the computation of geostrophic winds. Trials were made with fewer stations, and results were very nearly as good when the network was reduced to one central station and 9 around the edges. However with as few as 10 stations one wrong report may be rather serious.

At this stage in the investigation an addition was made to the METEOR programme so that the radius of curvature of the isobar through the origin and the gradient wind were also printed out. Only a short series of hand measurements of gradient wind were available for comparison, but it appeared that the computed curvature was frequently too great. This is probably because the fit of the objective analysis will tend to be least good around the edges and if the edges of the network are too close to the central station then noticeable errors may occur in the curvature of the isobars. Trials were therefore made with a wider network consisting of one central station, 6 equally spaced at a radius of about 75 miles and 12 at a radius of about 150 miles. Several continental stations were used in this wider network. The computed geostrophic winds were almost as good as those derived from the smaller network, but the gradient winds showed a marked improvement. There was rarely more than a few knots difference between the cyclostrophic corrections computed on METEOR and those derived from the hand measurements. To investigate the differences, an independent set of hand measurements was made; the differences between the two sets of measurements were comparable in size with the differences between the computed and the measured cyclostrophic corrections. This emphasizes the subjective nature of measurements of curvature and the difficulty of obtaining reliable gradient winds. Boyden[1] concludes that except with marked cyclonic curvature it is better to use the geostrophic rather than the gradient wind, and a comparison with the Crawley 900-metre wind for the short run of data examined supported this opinion.

Occasions will arise when geostrophic winds will be required for a coastal station where it is impossible to provide a network surrounding the station. In order to assess the accuracy attainable in these circumstances, winds were computed for London based on a network of 22 stations to north of a line Portland Bill–London–Felixstowe. The accuracy of the geostrophic winds so obtained was about as good as that of the networks with London in a central position, but the gradient winds were not very good.

Probably the optimum network would consist of about 10 stations at a radius of 80 to 100 miles from the central point together with 5 or 6 stations equally spaced within the circle. If gradient winds are important and a slightly lower general standard can be accepted, then some of the closer stations should be replaced by 5 or 6 others at a radius of 120 to 150 miles.

Errors in pressure data.—A by-product of the computations is the information on suspected errors in the pressure data. On examination a fairly large proportion of the errors proved to have been made during the extraction and taping of the reports. These were corrected and there remained, out of nearly 9000 pressure values, 41 which were suspected of having errors; for these occasions the records were carefully examined, and 25 mistakes were found. On the other 16 occasions, when the suspected errors ranged from 1.3 to 3.2 mb, there was no other evidence to indicate that the records were incorrect. Thus, on this sample of data, the programme served the useful purpose of identifying pressures which had been wrongly entered in the records on about 0.2 per cent of occasions.

Conclusions.—The objective analysis of a set of pressure values by computer provides a satisfactory technique for the calculation of a series of geostrophic winds. The values obtained will be slightly more reliable than those resulting from hand measurements from synoptic charts unless particular care is taken in the analysis. The extraction and taping of the necessary pressure data is not however a trivial job.

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551.579.2

WATER YIELD FROM SNOW

By A. B. THOMSON, M.A.

Introduction.—Various authors in *British Rainfall*,[1] *Symons's Meteorological Magazine*[2] and the *Quarterly Journal of the Royal Meteorological Society*[3] give the amounts of water obtained by melting samples of freshly fallen snow. Colonel Ward of Calne, Wiltshire, and J. H. Dyson of The Old Vicarage, Preston, Canterbury, provided most of the data. Some of Colonel Ward's investigations were made in Switzerland, but his results and those of others show that, in general, the mean depth of snow required to produce an inch of water varies from about 9 inches to around 12 inches. The least is about 5 inches and the most about 35 inches in Britain, though two extreme cases from Switzerland are quoted by Colonel Ward, where 50 inches and 113 inches of snow produced only one inch of water.

This paper presents the relationship between snow depth and water yield which has been found from snow samples taken in Scotland.

Data used.—In December 1955, the City Engineer, Aberdeen, arranged for a number of his rain-gauge stations in the catchment area of the River Dee to measure each morning the depth of snow which had fallen in the preceding 24 hours on a flat board laid on the ground, or on top of previously fallen snow in the vicinity of the rain-gauge. Using the inverted funnel of the rain-gauge, a cylindrical snow sample was then cut from the full depth of measured snow on the board. The sample was melted and measured in the glass rain measure to obtain the water yield. The board was swept clean after each observation.

Equivalent snow depth.—A total of 381 observations of snow depth were made at the seven stations listed in Table I during the period December 1955 to December 1961. Each of these observations was used to calculate the 'equivalent snow depth', i.e. the depth of snow that would be required to yield one inch of water.

TABLE I—MEAN 'EQUIVALENT SNOW DEPTHS' CALCULATED FOR STATIONS IN THE DEE CATCHMENT AREA

Station	Elevation *feet*	National grid reference	Number of samples*	Mean 'equivalent snow depth' *inches*
Derry Lodge	1400	37/036932	127	11.9
Inchnabobart	1270	37/310876	116	10.7
Gairnshiel Lodge	1100	38/295008	24	12.7
Braemar Irrigation Farm	1060	37/148921	25	9.4
Ballater Irrigation Farm	633	37/381966	44	10.8
Tarland Irrigation Farm	467	38/488040	17	11.9
Aboyne Irrigation Farm	380	37/542982	28	11.9

*All available samples between December 1955 and December 1961.

The resulting combined data are shown in the form of histograms in Figure 1, each histogram indicating, in addition to the 'equivalent snow depth,' the various actual depths of the snowboard samples comprising the group. For example, the modal group contains 92 cases in which the 'equivalent snow depth' ranged from 12.0–12.9 inches, the 92 cases being made up of 51 snowboard samples of depth less than 3 inches, 25 of 3–5.9 inches, 10 of 6–8.9 inches and 6 of 9 inches or more.

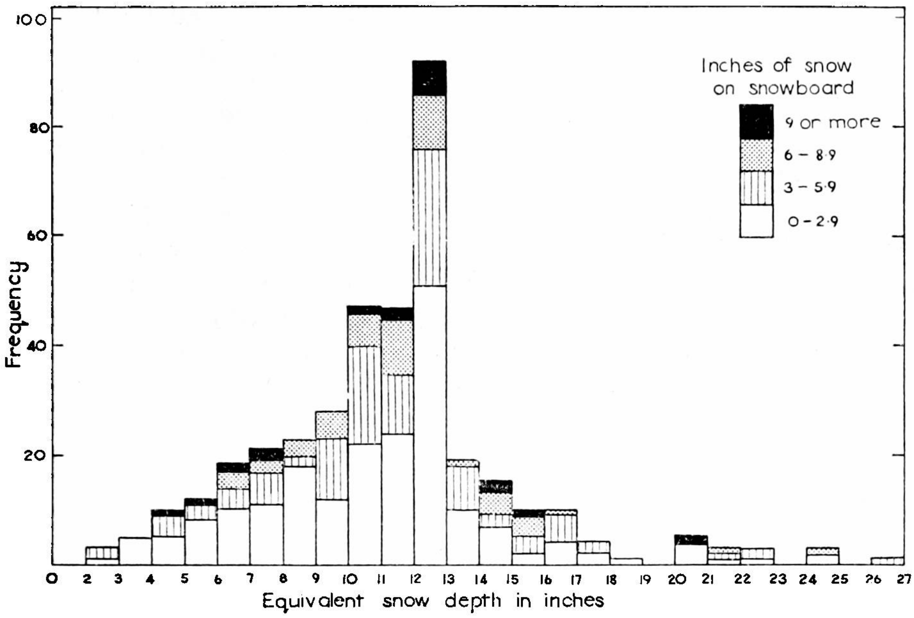


FIGURE 1—FREQUENCY OF 'EQUIVALENT SNOW DEPTHS' YIELDING ONE INCH OF WATER

Although Figure 1 shows the depths in one-inch classes for convenience, the observations were initially tabulated in ½-inch classes and the mean and standard deviation calculated from the latter distribution. The mean 'equivalent depth' found was 11.23 inches with a standard deviation of 3.75 inches while 94.8 per cent of the observations were no further from the mean than twice the standard deviation (i.e. equivalent depths 3.7–18.7 inches). The mode lies in the range 12.50–12.99 inches.

To determine whether there was any significant difference in the mean 'equivalent depths' found for light snowfall and for heavy snowfall, the means were also calculated separately for snowboard depths of less than 3 inches and for depths of 3 inches or more. In both cases the mean value was approximately 11 inches. The mean 'equivalent depths' were also determined for each station separately. These are shown in Table I together with the number of samples examined for each station.

Over the five winters from 1937 to 1942 J. H. Dyson[3] recorded the water equivalent of melted snowfall at The Old Vicarage, Preston, Canterbury. The annual means of 'equivalent depths' providing one inch of water were 10.8 4.7, 11.1, 9.0 and 10.9 inches, giving a mean over the five years of 9.3 inches.

Table II lists the frequencies, at the Deeside stations, of the various actual depths of the snow on the snowboards during the same period as for Table I. It will be seen that slightly more than half the samples were under 3 inches deep. There is no reason to doubt that the samples are reasonably representative of upland areas.

TABLE II—FREQUENCY OF VARIOUS ACTUAL DEPTHS OF SNOW OBSERVED AT STATIONS IN THE DEE CATCHMENT AREA

Depth of snow on snowboard (*inches*)	<1	1–1.9	2–2.9	3–3.9	4–4.9	5–5.9	6–6.9	7–7.9	8–8.9	9–9.9	>9.9
Number of samples	64	71	66	48	37	25	25	16	11	3	15

Temperature effect.—The 381 'equivalent snow depths' for the seven stations (Table I) were tabulated against the mean daily temperature ($\frac{1}{2}$ maximum + $\frac{1}{2}$ minimum) at Braemar for the 24 hours preceding the time of observation. The temperatures used were those recorded at the Braemar Climatological station, whose elevation is 1111 feet—comparable to the mean height of the 7 stations. Five of the samples were taken when the temperature was under 17°F and five when above 39°F, but for convenience these were included with the samples taken at 17° and 39° respectively. Figure 2 shows the relationship graphically for 3° and 6° intervals, the values being plotted at the mid-points of the intervals.

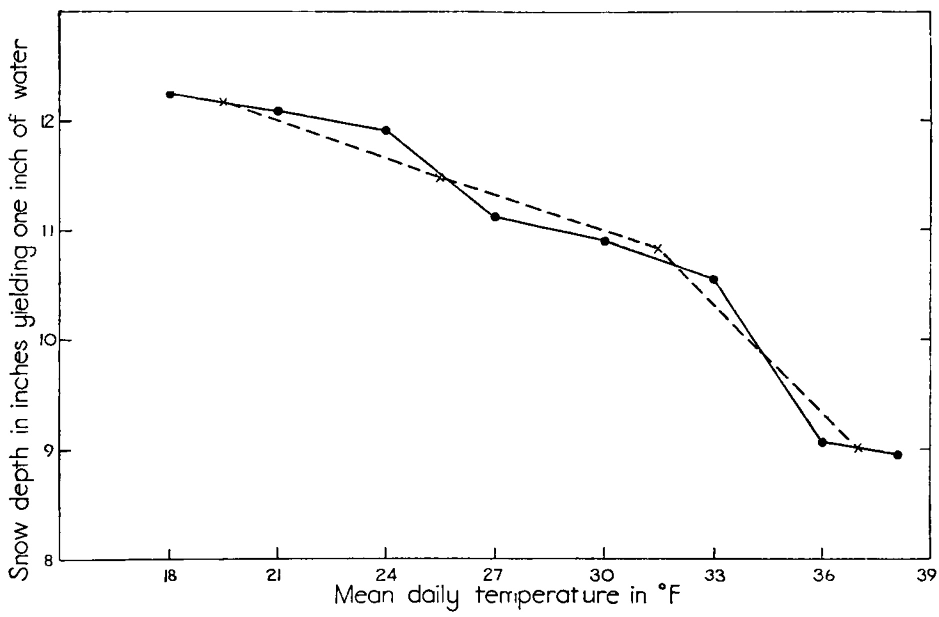


FIGURE 2—RELATION BETWEEN 'EQUIVALENT SNOW DEPTH' AND MEAN TEMPERATURE

•———• 3° intervals, x - - - x 6° intervals.

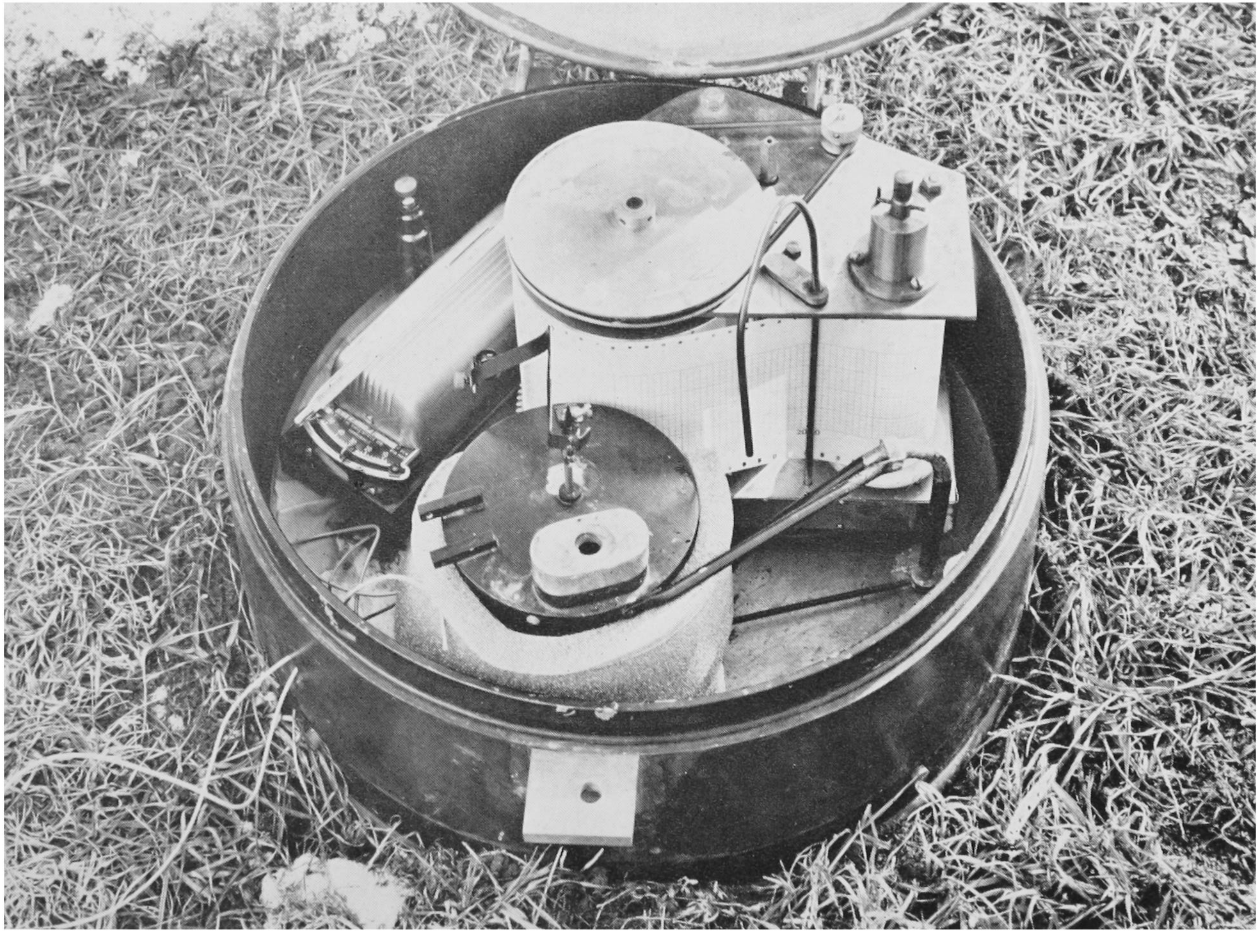
Values are taken at the mid-point of the interval.

As one would expect, there is a steady increase with temperature in the water yield per inch of snow from the samples, and a sharp increase around the freezing-point.

Photograph by R. K. Pilsbury

PLATE I—RIME ON CHAIN-LINK FENCING (2-INCH MESH)

This photograph was taken at Bracknell at 1800 GMT on 24 January 1963 after a day of fog and temperatures below freezing. A black cloth provided the background and flash was used to give sparkle.



By courtesy of the Hydraulics Research Station

PLATE II—MODIFIED RAIN-RECORDER WITH EIGHT-DAY STRIP CHART MECHANISM, EQUIPPED WITH LOW-VOLTAGE HEATING AND WALL THERMOSTAT

Note the lagging round the chamber. (See p. 337.)

By courtesy of the Hydraulics Research Station *Crown copyright*

PLATE III—STANDARD RAIN-RECORDER WITH LOW-VOLTAGE HEATING SYSTEM AND SMALL THERMOSTAT
(See p. 338.)

By courtesy of the Hydraulics Research Station

PLATE IV—TWO RAIN-RECORDERS SHOWING ACCUMULATORS FOR LOW-VOLTAGE HEATING SYSTEM

(See p. 338.)

Conclusions.—The large standard deviation of the 'equivalent snow depths' (nearly 4 inches) shows the imperative need to obtain the actual water equivalent by melting wherever possible. The use of a conversion factor 1/10 (or 1/12 as recommended in *Rules for rainfall observers*[4]) can be regarded as a poor substitute method to be used only as a last resort when melting cannot be carried out.

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551.508.77:551.524.37

A NOTE ON THE OPERATION OF RAIN-RECORDERS DURING COLD WEATHER

By J. C. RODDA, B.Sc., Ph.D.

(Hydrological Research Unit, Hydraulics Research Station, Wallingford, Berks.)

Introduction.—The continuous operation of any Meteorological Office standard rain-recorder in weather conditions like those experienced during the 1962–63 winter is an extremely difficult task. The float in the collecting chamber has to be protected against frost damage, and the capability of the gauge to record rain and other forms of precipitation has to be maintained during frosty weather. This paper briefly considers the problem, and describes field trials of an electrical method of heating a rain-recorder by means of an accumulator. The system which results is an approach to a recorder which would function at an isolated site for a week under frosty weather conditions without attention or refuelling, but it is not designed for snow measurement.

Frost protection.—

(i) *Anti-freeze.*—Apart from removing the float chamber unit, perhaps the simplest way of affording frost protection is to make periodic additions of a freezing-point depressor to the rain-water standing in the collecting chamber. The volume of liquid that needs to be added for a particular level of protection can be calculated, but dilution by rain falling between additions can make this method ineffective.

(ii) *Use of plastic material.*—Ice formed in the collecting chamber because of frost can distort or puncture metal floats, but some successful experiments[1] in the use of plastic floats have been carried out recently as part of the Meteorological Office rainfall investigation near Winchcombe, Gloucestershire. When these floats were examined after being employed in standard rain-recorders exposed to temperatures as low as −20°C, it was found that the plastic floats had suffered no damage.

(iii) *Heating.*—Frost damage can be prevented by arranging for the gauge to be heated by a small heat source. The heating required is discussed more fully in later paragraphs.

Recording during frosty weather.—While these measures prevent damage to the float, they are not effective ways of ensuring that the recorder will function in freezing conditions when further precipitation occurs, whether it falls as rain, snow or in some other state. So that the gauge will operate in these circumstances heat has to be injected into it, the amount depending upon the form of the precipitation. The largest amount of heat is required by the recorder when it is operating as a gauge to record the amount and rate of snowfall. Then enough heat has to be supplied to maintain the gauge's interior temperature above freezing-point and melt the snow as rapidly as it falls into the funnel. However, since the gauge is not designed for collecting snow, it is doubtful whether the complications involved in producing and controlling the necessary heat would be justified by the record which would be obtained. As a result it was decided to design a heating system using a lesser amount of heat which would protect the float mechanism and allow the gauge to record 'rainfall' in temperatures below freezing-point.

As there are obvious limitations to the use of mains electricity the installation of a 25-watt lamp inside the recorder, as advised by the Meteorological Office,[2] was not carried out. The alternative, two night-lights placed below the funnel, was also rejected, one reason being that unless ventilation is carefully adjusted excessive condensation can occur which will ruin any chart record. A reliable, self-contained heating system was sought, not employing a flame burning inside the recorder, but utilizing instead heat produced by a source outside the gauge.

Evaluating the heating requirement.—To determine what quantity of heat was required to prevent freezing in the collecting chamber, a cooling experiment was performed on a rain-recorder in the laboratory. The time taken for water in the collecting chamber, at a known temperature, to cool to room temperature was measured by stop-watch and thermistor thermometer, the thermistor being placed in the collecting chamber. The experiment was repeated for various volumes of water between 100 cm^3 and 200 cm^3 and over a range of temperatures from 5.4°C to 14.0°C above room temperature. From these measurements, and after determining the water equivalent of the collecting chamber, it was possible to deduce that the average rate of heat loss was approximately 0.4 cal/sec for these volumes of water and range of temperature. Assuming that the experiment simulated the effect of nocturnal cooling in the field, it followed that heat must be put into the chamber at a rate greater than 0.4 cal/sec to maintain the chamber temperature just above 0°C with an outside temperature of about −5°C. It was considered that with lagging and a heat source producing between 0.8 and 1.0 cal/sec, the collecting chamber might remain unfrozen and able to accept rain-water in temperatures as low as −10°C. Several attempts to confirm these figures have been made by carrying out cooling experiments in the field, but these have been difficult to conduct because of changes in air temperature and wind velocity during the experiment. However measurements have been made giving values between 0.5 cal/sec and 0.9 cal/sec for the average rate of cooling for 100 cm^3 and 200 cm^3 of water up to 10°C in excess of the ambient temperature.

Heating system.—

(i) *Hot air.*—Experimental work was commenced to find a suitable heating system first using several types of small paraffin heaters, the hot air generated being conducted through the rain-recorder within a narrow-bore copper tube. The tubing was coiled inside the walls of the lower part of the gauge and finally led out through the window in the side of the funnel housing. Although several modifications were made to the heater housing, which acted as a duct for the hot air from the heater, the temperature inside the gauge could not be raised more than 1°C above room temperature. It is probable that with a larger flame and a more efficient heat exchanger the temperature increase inside the gauge would have been greater.

(ii) *Water circulating system.*—The Department of Forestry at Oxford University has had considerable success in heating a rain-recorder using first butane gas then paraffin as fuels.[3] A water circulating system was employed with a flame heating a boiler sunk in a pit alongside the gauge, the whole gauge being heated from a coil of copper tubing under the funnel.

(iii) *Electrical.*—An electrical method of heating was eventually chosen for this project because of the difficulties of using a flame-heated circulating system, particularly at water-logged sites. The comparatively small amount of heat required to maintain the collecting chamber at a temperature above freezing can be produced efficiently by an accumulator. An experiment was conducted with a 12-volt accumulator and a length of heating tape as this seemed to be an efficient way of heating the chamber. There are several types of this plastic-covered heating tape available; some can be used over a range of voltages and in various lengths for different outputs; others are meant to be run at the mains voltage so producing a fixed amount of heat. A length of this second type of tape was employed but at 12 volts d.c. rather than that intended by the makers. At this voltage it was found that the resistance was 2.6 ohms/in., so that an output of approximately 1 cal/sec was achieved with 13 in. of tape and 0.8 cal/sec by a length of 16½ in.

Trials of equipment in cold weather.—Field tests of the heating system were commenced at the Hydraulics Research Station on 4 January 1963. A standard Meteorological Office rain-recorder had been modified to the specifications of the Road Research Laboratory (L. H. Watkins[4]) by substituting an 8-day strip chart mechanism for the standard clock, sealing all unnecessary holes in the gauge to make it damp-proof, and fixing the tilting chamber so that it emptied by siphoning alone. A 13-in. length of tape was wound around the collecting chamber of the gauge and connected to an accumulator by a circuit which included a wall thermostat set at a little above 0°C. Apart from reasons of economy of current the thermostat was used to prevent overheating of the collected rain-water. Ideally it should have been set in the collecting chamber but no model could be found which was sufficiently small for this.

This system operated for a week at temperatures shown in Table I before the quarter-full collecting chamber became frozen on 10 January 1963. As an additional measure, the sides of the chamber were lagged including the heating strip (see Plate II) and the gauge operated successfully in this state until 23 January when it froze for a second time. The addition of a small quantity of anti-freeze prevented the same thing happening on the following night when the air temperature fell to almost −16°C.

TABLE I—MINIMUM TEMPERATURES RECORDED AT THE HYDRAULICS RESEARCH STATION, WALLINGFORD, DURING JANUARY 1963

Date (January)	4	5	6	7	8	9	10	11	12	13	14
Air temperature in °C	−1.1	−1.4	−1.4	−2.1	−2.2	−7.9	−9.3	−11.8	−13.6	−6.7	−8.2
Grass temperature in °C	−0.7	−3.1	−1.4	−3.1	−3.4	−10.0	−10.9	−14.3	−14.5	−6.7	−10.4

Date (January)	15	16	17	18	19	20	21	22	23	24
Air temperature in °C	−7.3	−6.7	−9.5	−9.8	−6.8	−6.4	−4.2	−13.7	−16.0	−15.8
Grass temperature in °C	−9.4	−6.5	−11.0	−12.6	−8.9	−7.5	−6.8	−12.9	−15.9	−15.9

At a later date a standard rain-recorder was lagged and equipped with the same type of heating system (see Plate III). In this case a heating strip producing 0.8 cal/sec was used, and after lagging the top and sides of the collecting chamber, a test was made to ensure that tilting occurred at the same point as before modification. Because of the limited amount of space available in this gauge a thermostat of the type used in convector heaters was included in the circuit, rather than the more bulky but more sensitive variety used before. Although temperatures in February did not fall to January levels this gauge continued to function at temperatures well below freezing-point (e.g. on 25 February; –10.8°C air minimum, –13.2°C grass minimum).

Both rain-recorders were heated by current produced from standard 50 ampere-hour accumulators housed alongside the gauges in wooden boxes (see Plate IV). The life of these accumulators was more likely to be between 35 and 45 ampere-hours when fully charged, and so to avoid running them to exhaustion a change was made every 3 to 4 days during the coldest weather and then at intervals of 5 to 6 days when conditions were less severe. In the worst possible weather with current being consumed continuously, one 70 ampere-hour accumulator would provide ample power to protect a rain-recorder for one week, but if temperatures were not below freezing-point all the time one 50 ampere-hour accumulator might be sufficient. No doubt greater thermal efficiency could be achieved by lagging the outside of the gauge and around its base, but without making a complete change of design the other points in the recorder susceptible to freezing could not be heated by this method unless a wind generator or similar charging device could be incorporated in the system.

Acknowledgements.—This paper is published by permission of the Director of Hydraulics Research. The assistance of Mr. A. L. Maidens and several other staff of the Meteorological Office has been of considerable importance in the preparation of this paper, and their help together with that given by the author's colleagues is gratefully acknowledged.

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551.586:612

AN INDEX OF COMFORT FOR SINGAPORE

By P. M. STEPHENSON, M.Sc.

Introduction.—A superficial examination of the climatological data for Singapore, which is situated about 80 miles north of the equator, indicates an annual monthly-mean temperature range of only 3°F and humidity range of only 4 per cent (see Table I). This might lead one to believe that the climate was uniformly hot, humid and unpleasant throughout the year. This runs completely contrary to all experience which, even with Europeans who have been resident in Singapore for years, indicates that one feels distinctly more comfortable at some times of the year than at others irrespective of the time of day.

Consideration of this point leads to a search for an easily recognizable index of comfort and the simplest index which has been suggested is wet-bulb temperature. As a point of interest it has been suggested that the upper limit of wet-bulb temperature for *sustained* white labour is about 78°F. The annual range of average 24-hour wet-bulb temperature in Singapore is only 3°F with a minimum of 75°F in January and a maximum of 78°F in May so that clearly the wet-bulb temperature is not a particularly useful criterion in Singapore.

Other indices which have been suggested by different authorities are based on one or more of the elements: temperature, humidity and wind speed. A convenient and apparently very satisfactory scale taking into account temperature, humidity and wind speed, is the 'effective temperature' scale devised by the American Society of Heating and Ventilating Engineers (ASHVE).[1]

Effective temperature.—'Effective temperature' is defined as "that temperature of saturated motionless air which would produce the same sensation of warmth or coolness as that produced by the combination of temperature, humidity and air motion under observation," and it will be evident that the effective temperature is dependent upon the amount of clothing worn. ASHVE obtained two scales by calibrating the opinions of a group of trained observers, either stripped to the waist or lightly clad, who passed back and forth between two adjoining air-conditioned rooms in which the temperature was varied but the air was maintained fully saturated and with a constant air movement.

Nomograms relating effective temperature to dry-bulb and wet-bulb temperatures and wind speed for the two categories of clothing are published by the Air Ministry.[2] For the purposes of this note the scale appropriate to lightly clad persons only has been used.

The 'comfort zone' of effective temperature (i.e. the zone within which the majority of individuals will be content and able to work at maximum efficiency), for acclimatized persons in hot regions is 66° to 76°F with an optimum of 69°F. If maximum efficiency is to be obtained from sedentary workers, 76° to 78°F is considered the highest permissible effective temperature. The critical effective temperature, above which muscular effort would cause the body temperature to rise rapidly to danger level, is probably between 85° and 90°F. It is possible to do sedentary work at 90°F effective temperature, but owing to discomfort it may not be particularly productive.

Since the effective temperature in Singapore rarely, if ever, exceeds 85°F, outdoor sports can be safely indulged in at all times of the year provided the participant can, or does not mind that he does, perspire freely.

Summary of data used.—Climatological data for Singapore Airport (located at Kallang until July 1955 and at Paya Lebar subsequently) are published regularly, and 10-year means (1952 to 1961) of dry-bulb temperature and relative humidity were calculated for each month of the year (Table I) together with mean scalar wind speeds (Figure 1).

TABLE I—MEAN DRY-BULB TEMPERATURE AND RELATIVE HUMIDITY FOR SINGAPORE AIRPORT (1952–61)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
						degrees Fahrenheit						
Mean dry-bulb temperature	78	79	80	81	81	81	81	81	80	80	79	78
						per cent						
Mean relative humidity	85	83	84	85	85	83	84	84	84	84	86	87

Mean wet-bulb temperatures which were not readily available were deduced from the mean values of dry-bulb temperature and relative humidity using hygrometric tables. The values thus obtained would be slightly higher than true means calculated from hourly readings of the wet-bulb thermometer, but the error would rarely exceed 1°F.

The corresponding mean 24-hour effective temperature, as read from the appropriate nomogram, together with the dry- and wet-bulb values are plotted in Figure 2.

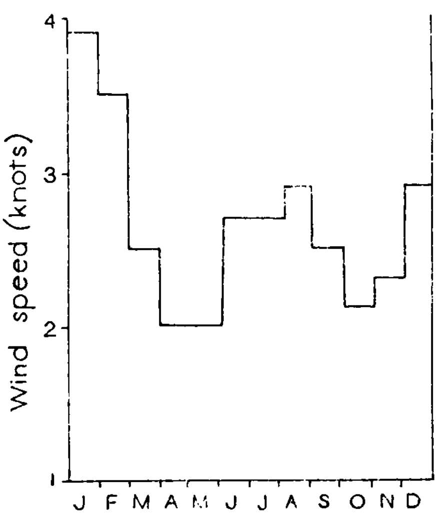


FIGURE 1—MEAN 24-HOUR SCALAR WIND AT SINGAPORE AIRPORT (1952–61)

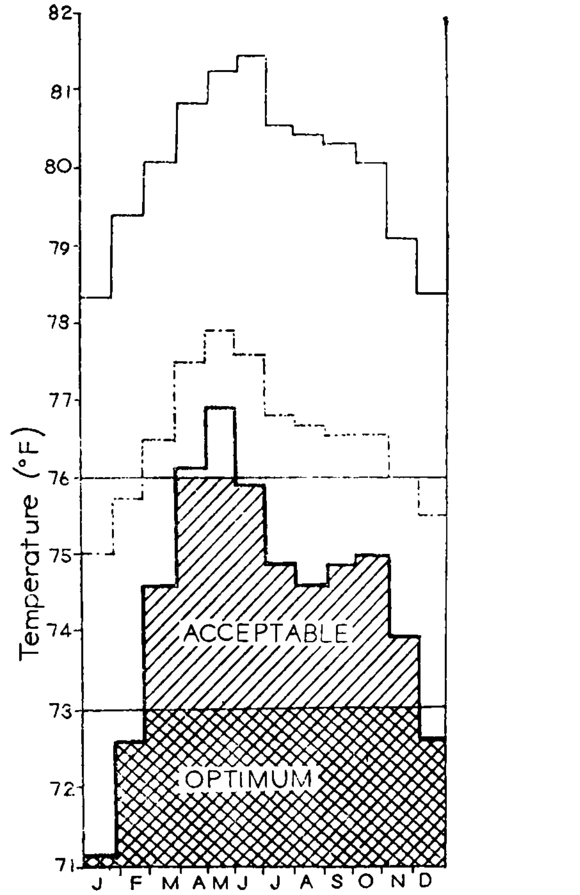


FIGURE 2—MEAN 24-HOUR TEMPERATURES AT SINGAPORE AIRPORT (1952–61)

—— dry-bulb temperature, -·- wet-bulb temperature
▬▬ effective temperature

Three-hourly values of dry-bulb and wet-bulb temperatures and wind speed for a 5-year period (1951 to 1955) which were readily available for Changi Airport were used instead of data from Singapore Airport to assess the diurnal variation of effective temperature. These observations also enabled a comparison to be made between Changi, which is located on the eastern end of Singapore Island, and the Paya Lebar–Kallang area which is on the eastern outskirts of Singapore City nearer the centre of the Island.

The variations of dry-bulb and wet-bulb temperatures, wind speed and effective temperature over 24 hours for each of the months January, April, July and October for Changi are shown in Figures 5 and 6, whilst in Table II a comparison is made between Singapore Airport and Changi Airport.

Figures 3 and 4 show the effective temperatures which would correspond to various wind speeds at 0430 and 1330 zone time in an average April at Changi, assuming that dry-bulb and wet-bulb temperatures at each of these hours were fixed at the appropriate average values.

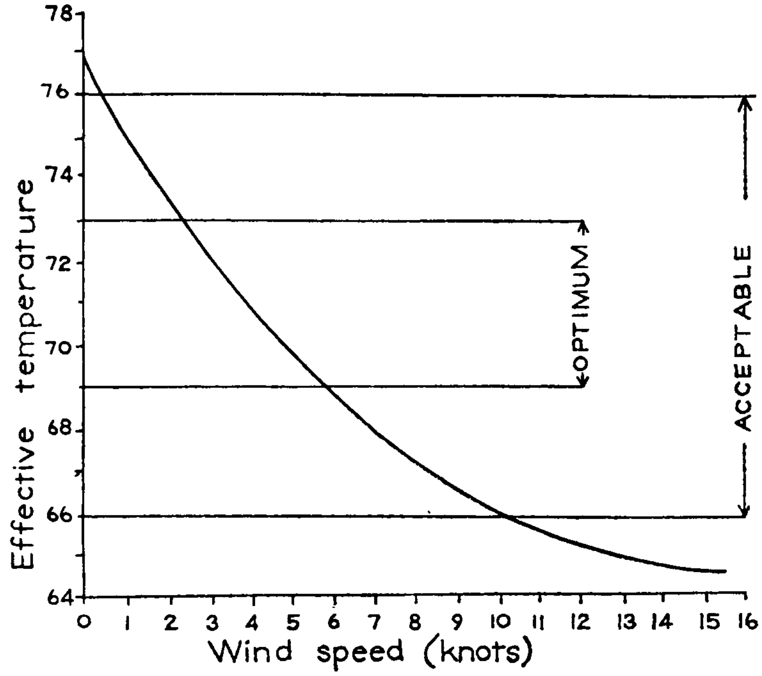


FIGURE 3—VARIATION OF EFFECTIVE TEMPERATURE WITH WIND SPEED AT CHANGI AT 0430 ZONE TIME FOR AN AVERAGE APRIL
(average dry-bulb temperature 77.7°F)
(average wet-bulb temperature 76.0°F)

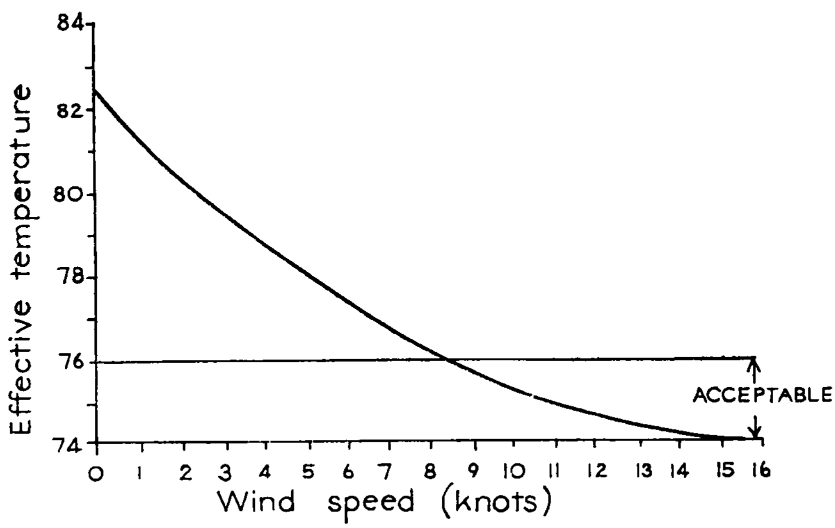


FIGURE 4—VARIATION OF EFFECTIVE TEMPERATURE WITH WIND SPEED AT CHANGI AT 1330 ZONE TIME FOR AN AVERAGE APRIL
(average dry-bulb temperature 87.6°F)
(average wet-bulb temperature 79.0°F)

Discussion of data.—

1. *Annual variation of effective temperature.*—Figure 2 shows that January is by far the most comfortable month in Singapore and that two periods, namely April to June and September to October, are the least comfortable. This accords with experience and also to a slight degree, with the dry-bulb and wet-bulb temperatures except in October. However these latter temperatures do not indicate the *extent* to which January differs from May, which is due largely to the combination of high wind speed and low temperature in the former contrasted with low wind speed and high temperature in the latter. The two minima of effective temperature in January and August occur one to two months after the solstices, when the sun is at its furthest from Singapore, and when the north-east and south-west monsoons respectively are producing a steady flow of wind over the Island. The two maxima in May and October occur similarly after the equinoxes when the sun is virtually overhead and when the winds are light and variable during the transition stages between the two monsoons.

It can readily be seen from Figure 2 that only in the months December, January and February do the effective temperatures fall within the *optimum range* for hot climates, whilst in April and May the effective temperatures are outside the *acceptable range* for efficient sedentary work. In theory, the effective temperatures indoors could be artifically reduced by means of fans, but Figure 4 demonstrates that on an April afternoon a wind speed of at least 8 knots would be required to bring the effective temperature below the acceptable level, whilst even 15 knots would not produce optimum comfort. The latter would moreover scatter any loose papers far and wide over the office and would not be practicable.

It can be seen from Table I that relative humidity which is considered by many to be a significant factor in comfort is most unreliable, and in fact the most comfortable months have the highest relative humidity.

Table II clearly illustrates the advantage of using effective temperature to assess climate. Inspection of either the dry-bulb or wet-bulb temperatures or both would give the impression that Singapore and Changi Airports had virtually identical climates, whereas the effective temperature, which makes allowance for wind speed, shows that Changi, in fact, enjoys a more comfortable climate than central Singapore. This is consistent with Changi being situated on the more exposed extreme eastern tip of Singapore Island.

TABLE II—COMPARISON OF TEMPERATURES AND WIND SPEEDS FOR SINGAPORE AND CHANGI AIRPORTS

	Mean 24-hour dry-bulb temperature				Mean 24-hour wet-bulb temperature			
	Jan.	Apr.	July	Oct.	Jan.	Apr.	July	Oct.
	degrees Fahrenheit							
Singapore Airport	78.3	80.9	80.6	80.1	75.0	77.5	76.8	76.6
Changi Airport	78.3	81.7	80.7	80.7	75.0	77.3	76.4	76.3

	Mean 24-hour wind speed				Mean 24-hour effective temperature			
	Jan.	Apr.	July	Oct.	Jan.	Apr.	July	Oct.
	knots				*degrees Fahrenheit*			
Singapore Airport	3.9	2.0	2.7	2.1	71.1	76.1	74.9	75.0
Changi Airport	6.5	3.7	4.4	4.1	68.8	74.8	73.1	73.5

2. *Diurnal variation of effective temperature.*—In addition to the annual variation, effective temperature also shows a marked diurnal variation, the nights being generally cooler than the days, as might be expected. What is perhaps somewhat unexpected is that each of the diurnal curves of effective temperature shows a secondary maximum occurring shortly after midnight coinciding with the wind speed minimum.

Other points of interest arising from the diagrams of diurnal variation (Figures 5 and 6) are:

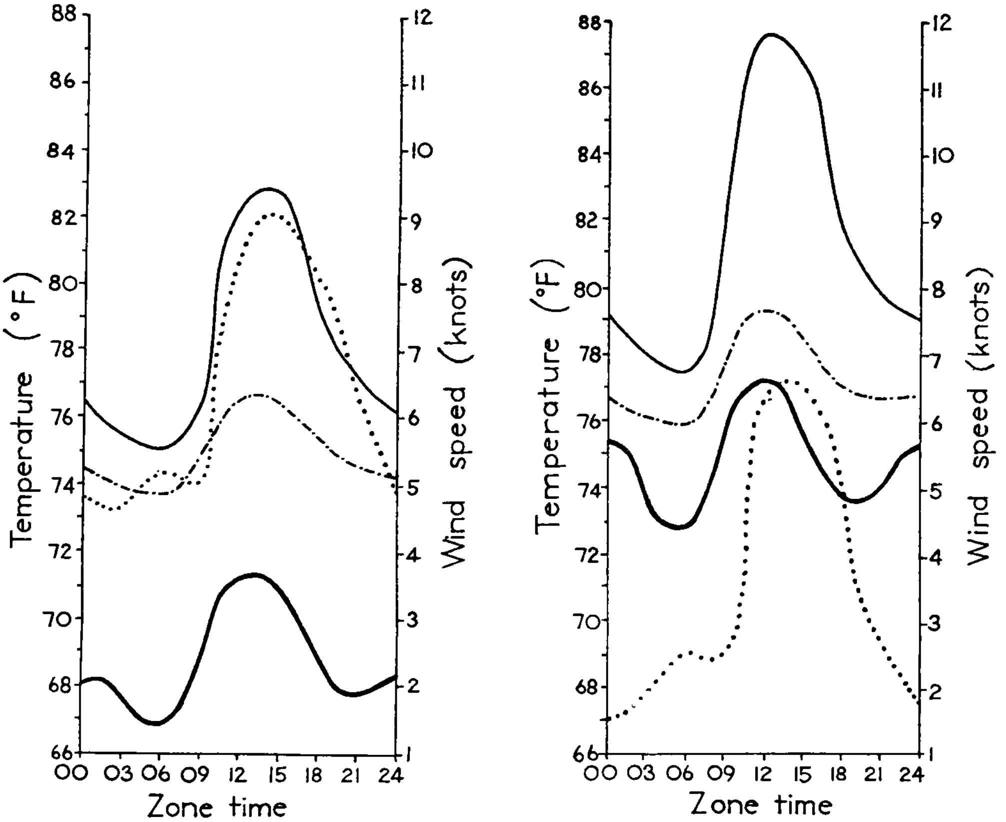
(i) The time of maximum discomfort is an hour or so earlier than the time of maximum temperature, the effect of the latter being offset by the corresponding wind speed maximum.

(ii) The most comfortable time of day at all seasons is generally about 0500–0600 zone time with a secondary comfortable period occurring at about 2000.

(iii) Taking 69° to 73°F effective temperature as the optimum comfort zone for the tropics, we can deduce the following:

(*a*) January is not at any time of the day too hot and in fact during the early hours of the morning the effective temperature is too cool for comfort.

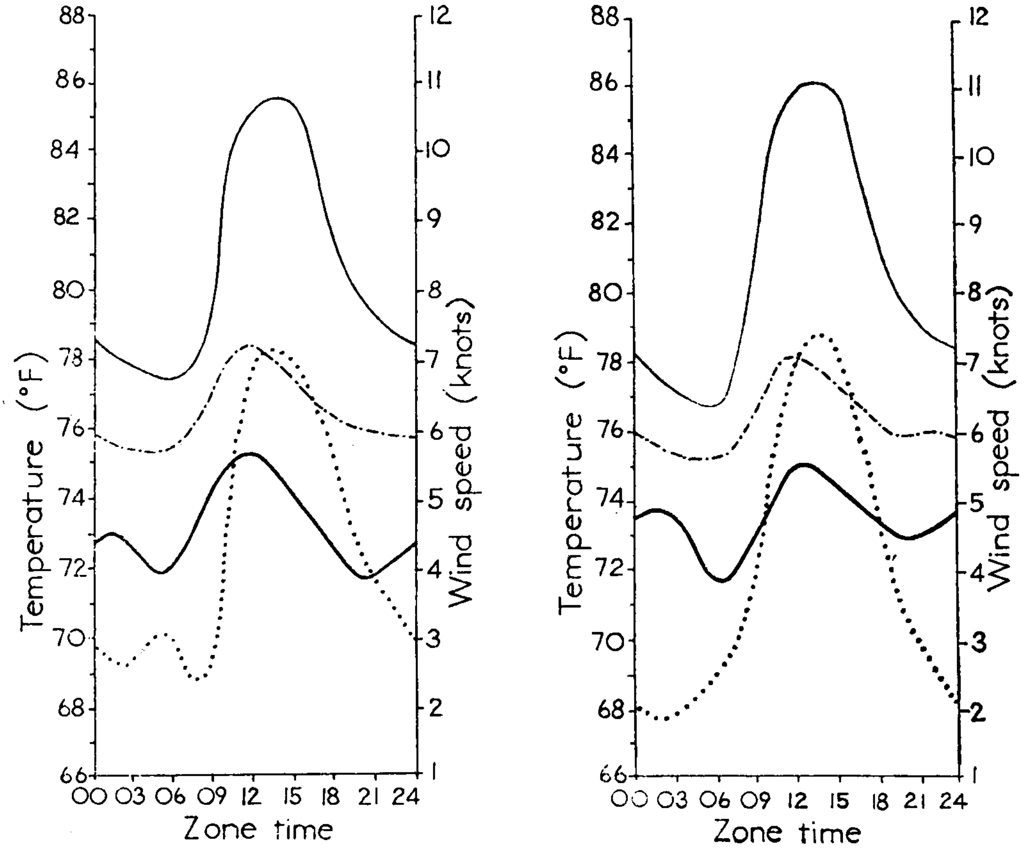
(*b*) April is uncomfortably hot virtually throughout the 24 hours.



(*a*) January (*b*) April

FIGURE 5—DIURNAL VARIATION OF WIND SPEED AND TEMPERATURES AT CHANGI

——— dry-bulb temperature
━━━ effective temperature
–·–·– wet-bulb temperature
.... wind speed



(a) July (b) October

FIGURE 6—DIURNAL VARIATION OF WIND SPEED AND TEMPERATURES AT CHANGI

——— dry-bulb temperature ▬▬▬ effective temperature

–·–·– wet-bulb temperature .... wind speed

(c) July is uncomfortably hot from about 0800 to 1700 (the normal working day in this part of the world is from 0800 to 1600).

(d) October is uncomfortable for all except 5 (0400 to 0900) of the 24 hours.

(iv) Rather surprisingly at first sight the diurnal variation of the effective temperatures is not as great as that of the corresponding dry-bulb temperatures, whilst the annual variation of the former is greater than that of the latter.

(v) The lowest night time effective temperatures during the warm months are higher than the highest daytime effective temperatures in January.

3. *Effect of rainfall and sunshine.*—The effective temperature index as designed is clearly only applicable to conditions under cover.

Rainfall and sunshine have a bearing on comfort, particularly when working out of doors. In Singapore the temperature during prolonged rainfall is generally in the low seventies so that, with the air almost saturated and in the absence of any wind, the effective temperature would be within the optimum comfort zone. Thus one would expect to feel pleasantly comfortable indoors during rainy spells. This is borne out by experience, it being often unnecessary to switch on any fans at such times. However, a combination of wind and rain, particularly outdoors, can be most unpleasant. Apart from the inconvenience of getting wet, the effective temperature falls below the optimum level, producing uncomfortably cool conditions. Such conditions are most likely to occur during the north-east monsoon when Singapore experiences its highest rainfall (See Table III).

Prolonged exposure to sunshine also produces discomfort, due largely to the actinic rays which are the primary cause of sunburn. The danger from these rays however is greater in dry tropical countries and in the highlands of Malaya than near sea level in Singapore where the water vapour in the air absorbs a large proportion of the ultra-violet. In fact many Europeans in the area do not tan readily. Table III also shows that prolonged bright sunshine is rare in Singapore with an average of less than half an hour's sunshine per daylight hour so that, despite its proximity to the equator, protection against sunshine is not as essential in Singapore as in some other parts of the tropics and subtropics.

TABLE III—MEAN RAINFALL AND SUNSHINE FOR SINGAPORE AIRPORT (1951–61)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
							inches						
Rainfall	9	6	7	6	5	7	6	8	5	7	10	12	88
							hours						
Sunshine	147	166	194	178	181	178	176	171	159	171	129	148	1998

Conclusions.—(i) Temperature and relative humidity alone are insufficient guides to climatic comfort in the tropics and relative humidity on its own is particularly unreliable.

(ii) An effective temperature which takes into account wind speed as well as temperature and humidity produces results which accord with local experience in Singapore.

(iii) Forced ventilation (e.g. using fans), while adequate for producing comfortable conditions at some times of the day and year, is incapable of dealing with the more extreme conditions, particularly during the months April to June whilst for optimum comfort at the height of the north-east monsoon, some form of protection against excessive wind speed or ventilation is desirable.

(iv) Staff being posted to Singapore from temperate climates would find it best to arrive in one of the 'winter' months, and in particular February, whilst Treasury inspections, to produce the optimum result, should be made in April or May!

REFERENCES

1. New York, American Society of Heating and Ventilating Engineers. Effective temperature chart showing normal scale of effective temperature. Applicable to inhabitants of the U.S. under certain conditions. *Guide, New York*, 1944, p. 61.
2. Air Ministry. Handbook of preventive medicine, A.P. 1269B. Air Ministry, London.

NOTES AND NEWS

Meteorological Magazine: increase in price

We regret that owing to further increases in the cost of printing and publication it has become necessary to raise the price of the *Meteorological Magazine*. The price will be 3*s*. 0*d*. an issue with effect from the January 1964 number. The net annual subscription will become 39*s*. including postage. Present subscribers will remain on the existing rate until renewal of their subscriptions is due.

Klimaschwankungen und Grossräumige Klimabeeinflussung, by H. Flohn. 6½ in. × 9½ in. pp. 61, Westdeutscher Verlag, 567 Opladen/Rhld, Oplovener Strasse 1–3, 1963. Price: 6 DM.

This booklet on variations of climate, both natural and artificially provoked, with English and French summaries each half a page in length, plus brief discussion, will provide a handy introduction for many to a subject of increasing and somewhat anxious importance. The work is a concise review of a field that is wider than meteorology itself, written with the authority of a leading meteorologist with an unusually wide knowledge. Its distinguishing characteristic is the attempt to provide quantitative estimates, wherever possible, of the influence of each of the many factors that affect world climate. Inevitably these are confined in some instances to mere illustration from special observations at some sample locality (usually in central Europe) and in other cases to admittedly very broad estimates. (English readers may not be familiar with two abbreviations used in Flohn's estimates: '/d' to mean 'per diem' and '/a' to mean 'per annum'). Some of the estimates may not stand the test of time. However all this is clearly stated, and the occasion used to point the need for specific further research to improve on existing knowledge.

The 75-entry bibliography, with items on radiation balance, moisture transport, general-circulation dynamics, effects of local geography, effects of volcanic eruptions and hydrogen bombs, proposals for artificially regulating the climates of the globe and resettling hundreds of millions of people, reveals the awe inspiring scope of the subject and the author's wide acquaintance with it. Only about half the papers cited are published in Germany, the remainder representing work in more than a dozen countries including the U.S.A., Russia, Britain, Israel, Japan, India, East and South Africa, Australia and South America—29 items in English, two in Russian and one in Spanish.

Flohn accords greater importance than most workers hitherto to annual bush fires in tropical lands (putting, he reckons, nearly as much carbon dioxide into the atmosphere as does industrial and domestic burning of coal and oil mainly in temperate countries) and to the change of albedo brought about when natural forest is cleared and converted to grass or crop land. The latter change has been progressing over the last 5000 years.

The author's thesis is that by now the existence of cumulative, unintended effects upon world climate resulting from the activities of man cannot be denied. Therefore the question of large-scale modification of climate must receive the attention of science. Treatment must be based upon the laws of physics and demands a quantitative theory of climate and the ('climatogenetic') processes that produce it. This goes beyond any knowledge or understanding scientists yet have, but attacks on the problem have begun from various sides, notably the mathematical concepts of the general circulation associated with Rossby, Neumann and their successors, the laboratory models of rotating fluids, due to Riehl and Fultz, and the more largely empirical work of Budyko, Wexler and others.

Several large-scale projects for the manipulation of climate have already secured serious attention. These are briefly described and reviewed by Flohn.

The "Stalin plan for the transformation of nature", and particularly the Russian engineer Davydov's scheme for diversion of Siberian rivers and formation of an inland sea have been the first of these to acquire the status more or less of government policy, though apparently things are not yet beyond the stage of instigating much research (resulting in some toning down of the expectations). Other grandiose proposals such as the artificial melting of the Arctic ice, the sealing off of the Mediterranean and the damming of the waters of the Nile at various latitudes, are briefly noticed and a suitable meteorological critique applied. In every case it is clear that scientists are not yet in a position to predict the outcome satisfactorily. At this stage therefore action is premature and likely to lead to disappointment (the Aswan dam is mentioned), if not to disastrous side effects.

H. H. LAMB

Atmospheric turbulence and its relation to aircraft, Proceedings of a Symposium held at the Royal Aircraft Establishment, Farnborough on 16 November 1961. London, Ministry of Aviation. 9½in. x 6½in., pp. iv + 287, HMSO, London, 1963. Price: 30*s*.

A considerable volume of data has accumulated in recent years regarding atmospheric turbulence. At the same time, the importance of turbulence to aircraft has increased with the advent of new types of aircraft having characteristics appreciably different from their predecessors. The reported symposium was therefore especially welcome as it brought meteorologists and aeronautical workers together and provided a valuable exchange of ideas.

The symposium was divided into two basic sections. After an introductory paper the meteorological background was first covered, then came papers which looked at aircraft response to turbulence and at the considerations which have to be paid to turbulence in regard to airworthiness of aircraft.

The introductory paper, by J. K. Zbrozek, looks at the problem as a whole. It outlines those aspects of aircraft engineering affected by turbulence and gives an engineer's view of the turbulence. The *discrete-gust* and *spectral density* methods of assessing aircraft response are discussed and examples of measured spectra are given. This paper is especially interesting to the meteorologist anxious to understand more fully the problems of the engineer.

The meteorological papers are introduced in a paper, by P. A. Sheppard, which presents a general picture of the incidence of atmospheric turbulence and gives a broad outline of the turbulence-generating processes which provides an important background for the later papers. The next paper, by T. H. Ellison, is a fundamental and provocative discussion of the mechanisms of turbulence in which some stimulating ideas are put forward regarding the effects of density gradients. In the fourth paper F. Pasquill gives a compact summary of the statistics of turbulence, in the lowest layers, considered from the spectral view-point. He presents the progress made toward a coherent description of three aspects; the shape of the high-frequency side of the spectrum, the scale and the intensity of turbulence. The effects of finite sampling are discussed.

The remaining meteorological papers consider special facets of atmospheric turbulence. Paper 5, by J. K. Bannon, summarizes existing knowledge on high-level turbulence. Paper 6, by F. H. Ludlam, presents new views on air movement inside cumulonimbus cloud and stresses the importance of wind shear. A storm is presented as a heat engine in which the efficiency is increased by organized up and down-draughts. The severity and dimensions of the draughts are discussed in relation to aircraft. Paper 7, by R. S. Scorer, considers possible mechanisms for inducing stirring motions in stably-stratified air-streams by flow over mountains. Findings of theory are supported by inference from observations and some excellent photographs of billow patterns in cloud are presented.

The aircraft side is introduced in Paper 8, by G. F. H. Hemsley. This paper looks at air turbulence in relation to aircraft design and reviews the critical effects of atmospheric conditions on structural design, fatigue life, aircraft control and performance and on aircraft equipment. Next N. I. Bullen, in a discussion of gust loads on aircraft, describes methods of measurement and of analysis. A review of available information is made and the main results summarized. In Paper 10 J. Burnham gives a study of aircraft response to turbulent air. On the limited information available he shows that load histories experienced by different aircraft are related in a way which is essentially the same for the 'discrete-gust' and 'spectral' methods of assessing response. However, before reliable estimates can be made for possible future aircraft, information is required about turbulence spectra for the long wavelengths to which these aircraft predominantly respond. Finally Paper 11, by W. Tye, reviews the applications of the knowledge of atmospheric turbulence and underlines the problems which appear to the airworthiness engineer to need the most urgent attention.

It is considered that this book is a valuable contribution to the co-ordination of understanding concerning the application of turbulence information to aircraft. Particularly useful to the reader are the reported discussions. Meteorologists should certainly get a clearer idea of the problems involved and of the ways in which workers in meteorology may be of more service to their opposite numbers in the aeronautical fields.

The book represents remarkable value for the modest price. The printing and diagrams are clear though the covers do not, unfortunately, maintain the same high standard.

J. BRIGGS

LETTER TO THE EDITOR

Complete and incomplete wind data collections

Mr. Dewar's interesting paper 'The computation of monthly summaries of winds from incomplete data', in the *Meteorological Magazine* for April 1963, compares 100-mb wind statistics from complete and incomplete data collections for three stations in England. Mr. Dewar properly hesitated to draw conclusions from his data concering comparisons at other altitudes.

In this connection, I invite attention to comparisons between five-year serially complete once-daily wind data sets, and incomplete data collections comprising all available observations for periods of at least five years, at several stations in the United States.[1] The comparisons were made between vertical profiles of the zonal mean components and their standard deviations, as derived from the incomplete and complete data sets, at a total of eighteen stations.

Differences during summer were not appreciable, but in the winter season, profiles at four stations showed biases in the 'incomplete' zonal means amounting to about 30 per cent, at and near jet stream altitudes. As a matter of possible interest, the four pairs of zonal mean wind profiles reproduced in reference 1 indicate a tendency towards minimum differences near the 100-mb level.

Winter differences in the standard deviations of the zonal components were of comparable size, but not biaises, inasmuch as the values from the incomplete data set were both larger and smaller than those from the complete wind series.

I would like to suggest that a 'missing link' of concern to analyses of this sort involves serial persistence inherent in the data. One would expect the larger magnitudes in an incomplete wind collection to be relatively statistically independent, compared to the numerous smaller values which however contain substantial statistical redundancy. This effect is not significant of course if one is describing a defined set of observations, but it might be important if one's purpose is to estimate future observations, by use of statistical inference.

Washington, U.S.A. B. N. CHARLES

REFERENCE

1. CHARLES, B. N.; On some limitations of upper wind records. *J. geophys. Res., Richmond, Va.*, **64**, 1959, p. 343.

METEOROLOGICAL OFFICE NEWS

Retirements.—The Director-General records his appreciation of the services of:

Miss A. E. Murray, Experimental Officer, who retired on 11 July 1963:

Miss Murray retired after a long career in the Office, spent entirely on Climatological work. She joined the staff of the Scottish Meteorological Society in Edinburgh in 1919 and came into the Meteorological Office in April 1920, when the Office took over the work of the Society. She was transferred to M.O.3 at Harrow in October 1947. Miss Murray was most adept at dealing with masses of data involved in climatology. She once contributed regular articles to the *Glasgow Herald*; but undoubtedly her greatest contribution to the work of the Office was through her pleasant assiduity in dealing with inquirers of all types, and there is no doubt that many inquirers will miss her cheery voice, as will her colleagues in the Office.

R.H.C.

Mr. J. F. Oliver, Experimental Officer, who retired on 31 July 1963 after 44 years' service:

'Olly,' as he has been affectionately known throughout the Office, began his career as a Boy Assistant in British Rainfall Organization. Although he has served at a number of outstations, most of his time has been spent at Headquarters where he has been engaged on duties involving the staffing of outstations serving both military and civil aviation. Olly has always had the general welfare of the staff uppermost in mind and has, like others before him, spent a great deal of time and energy smoothing out the many difficulties that arise in any big organization. He will continue to help and serve others as a lay preacher in the Methodist Church. D.J.W.

Wt. 22, K16, 11/65, Gp. 1535