

METEOROLOGICAL OFFICE

THE METEOROLOGICAL MAGAZINE

VOL. 81, No. 956, FEBRUARY 1952

SOUTH POLAR ATMOSPHERIC CIRCULATION AND THE NOURISHMENT OF THE ANTARCTIC ICE-CAP

By H. H. LAMB, M.A.

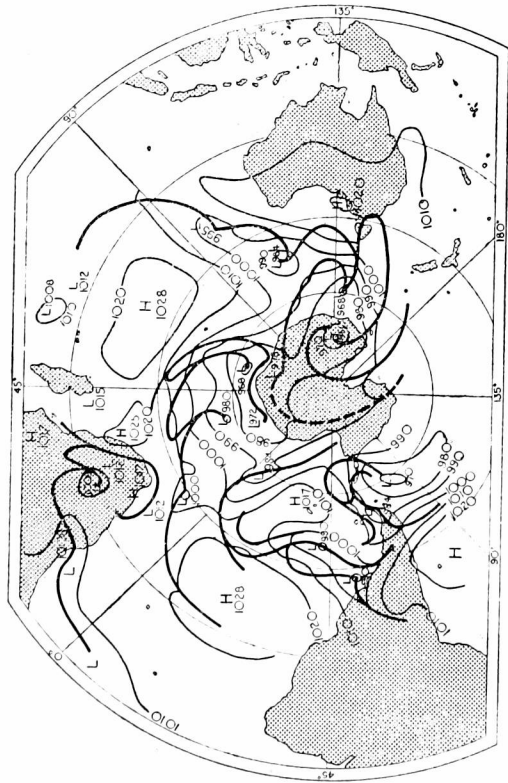
Introductory.—This article overlaps, and to a considerable extent summarizes, a paper, read before the Hydrology Association (Commission for Snow and Ice) of the International Union of Geodesy and Geophysics at Brussels in August 1951, on meteorological situations in the South Polar regions and the nourishment of the Antarctic ice-cap. This summary, however, covers also certain more general aspects of the atmospheric circulation over the southern hemisphere which are of interest to synoptic meteorologists.

The material used came out of the work of the *Balaena* expedition 1946–47, which has already been briefly described in this magazine¹ with some reference to the manner in which it was found possible to draw the daily surface weather maps covering much of the southern hemisphere. Later study of the original maps for November 1946–March 1947, using data for a region in 60–65°S. from which no information was available when they were first plotted, showed probable errors amounting to ± 6.8 mb. in pressure and 150–190 miles in the positions of the major frontal systems. The 8-day series of re-analysed maps, March 18–25, 1947, presented in Fig. 1 was chosen as one of the best sequences in the original maps; the analysis shown here incorporates a good deal of additional observational material from ships' logs which came in later, including radio-sonde observations made by the Dutch whaling factory *Willem Barendsz*, south of 60°S. in the Atlantic sector.

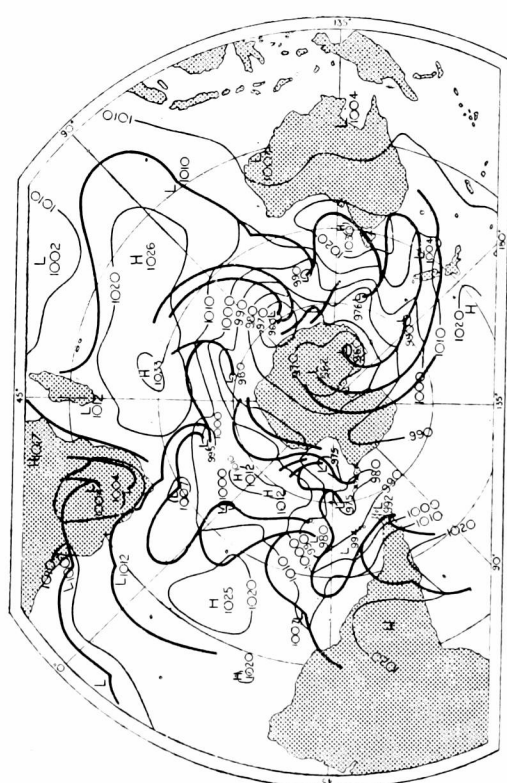
These maps should therefore be closer to fact than the original series, and the major features can hardly be in doubt. Isobars are shown at 10-mb. intervals. Fictitious isobars over the antarctic continental massif have been drawn in relation to the surface winds and pressure values observed when the pressure systems concerned passed over the coastal regions.

This re-analysis was the product of collaboration between Mr. B. L. Cardozo, the meteorologist who accompanied the Dutch whaling factory, and the author who was kindly invited to de Bilt for the purpose in 1948 by Dr. Bleeker of the Koninklijk Nederlandsch Meteorologisch Instituut.

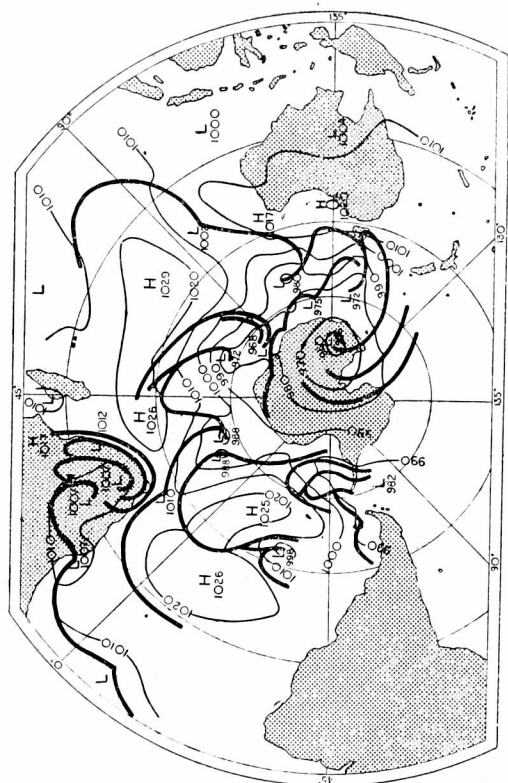
Occurrence of antarctic anticyclones as a variable and impermanent feature of the general circulation.—The most striking feature of the maps is that there is not always an anticyclone present over Antarctica. Indeed, however tentatively these maps were completed, there was clearly no room for any anticyclone between the known depressions in several sectors south of 60°S. either on March 18–20, 1947, or for some days before that.



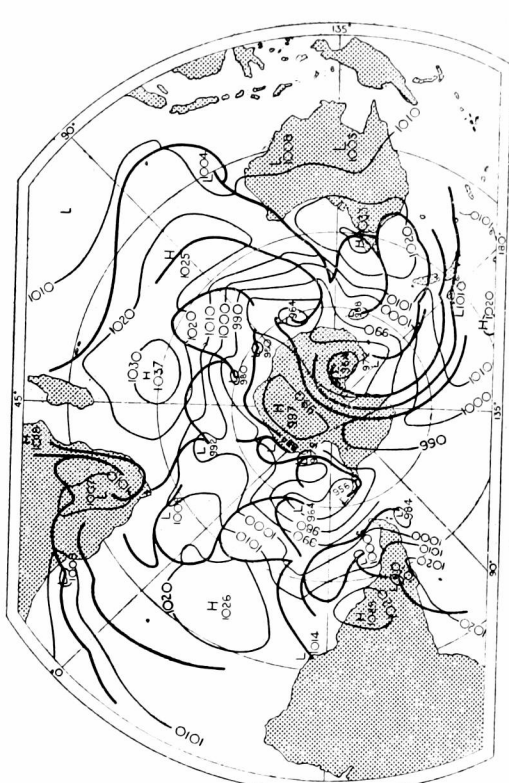
0600 G.M.T., March 18, 1947



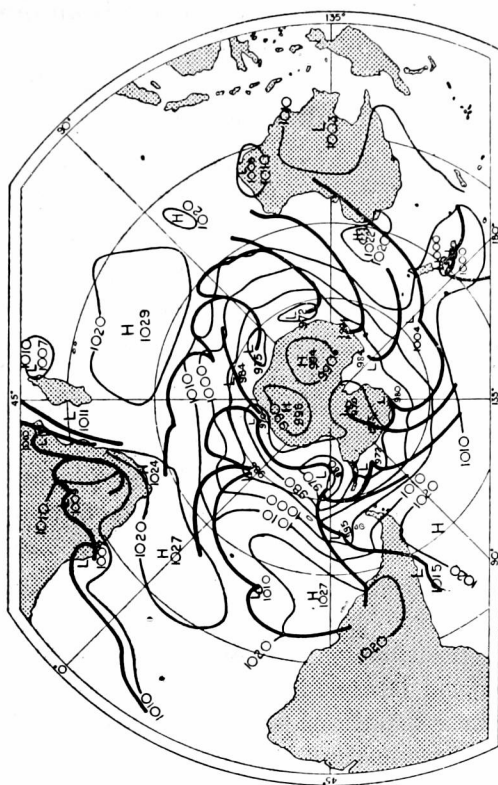
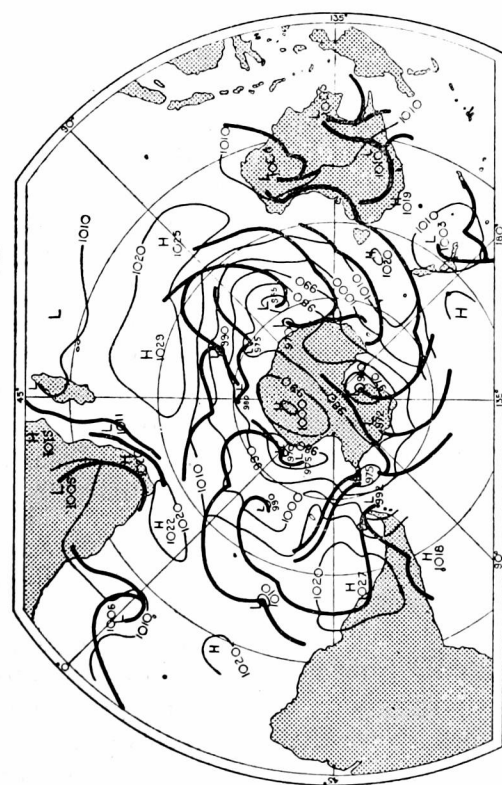
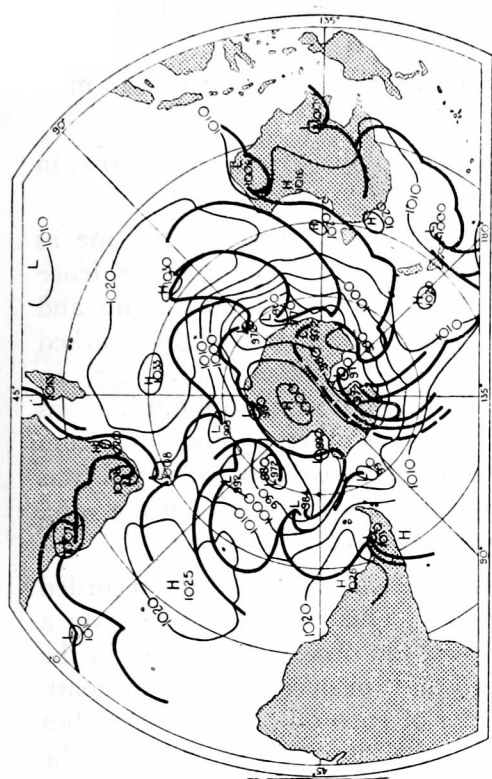
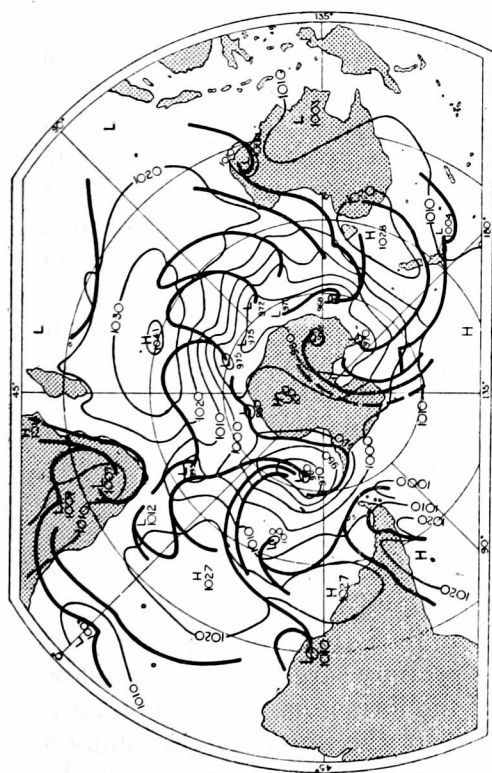
0600 G.M.T., March 20, 1947



0600 G.M.T., March 19, 1947



0600 G.M.T., March 21, 1947



0600 G.M.T., March 24, 1947

That cyclonic situations occur from time to time over the South Polar regions might be deduced from

(i) occurrences of westerly winds around the coast, sometimes in most sectors simultaneously;

(ii) occurrences of very low pressures (commonly 970 mb. or below) in very high latitudes, particularly in the Ross and Weddell Seas;

(iii) the fact that cloud types over Antarctica are by no means confined to stratus and stratocumulus sheets with indications of subsidence above, but include typical extensive frontal upgliding cloud systems and instability types. The latter were sometimes characterized by marked vertical growth over the coastal mountains. On March 17, 1947, an occlusion, preceded by altostratus in which a wall of cumulonimbus was embedded near the line of the surface front, was observed emerging from the continental interior; its passage over the *Balaena* in 64°S., 105°E. was marked by precipitation of moderate intensity (snow and soft hail), a wind shift, barometer kick and slight rise of temperature.

When anticyclones do occur over Antarctica, the sea-level pressures recorded are low by comparison with northern standards. This is obvious whenever a high-pressure system comes from Antarctica over the observing stations in the Falkland Islands Dependencies (e.g. Graham Land) or over ships off the coast. In these situations pressure maxima of the order of 1010 mb. are common, but values somewhat below 1000 mb. also occur. Kidson^{2,3} remarks that the extreme pressure of 1030·5 mb. recorded by Mawson's expedition at Commonwealth Bay, Adélie Land in 1912 was probably quite unusual, and it has never been equalled since in any records of which the author is aware.

The anticyclone which appeared over Antarctica on March 21, 1947, (Fig. 1) was probably associated with dynamic (warm) anticyclogenesis near the tip of the great warm ridge which must have been thrusting south-east aloft ahead of the depressions in the Ross Sea–Australian antarctic sector. Its appearance was forecast on this basis at the time and resulted in a gradual change-over to easterly winds, which became strong in some sectors, around the coast. The origin of this anticyclone may thus be interrelated with the great ridge of high pressure in the South Pacific and with the subtropical anticyclone just east of New Zealand. The connecting ridge between the ice-cap anticyclone and these systems in other latitudes was soon severed by the cool polar-maritime air masses advancing from the west between 50° and 70°S. on March 21–22, 1947, evidently before much meridional transport of air could take place. If this sequence is typical, it may go some way towards explaining the prevailing low level of pressure in the South Polar regions and the possibility of development of certain chemical peculiarities⁴ in air which may be isolated there for some time.

The deduced pressure surge accompanying the formation of the anticyclone over the inland ice on March 20–21, 1947, followed the route described by Simpson⁵ save that instead of radiating from 80°S., 120°W. it passed into Antarctica from near this point. If Simpson's pressure surges do indeed follow a preferred route, this case may be typical of the formation of antarctic anticyclones. Nevertheless it seems clear that some of the minor surges Simpson described are merely associated with dumb-bell rotations of depressions in the Ross Sea⁶.

On March 20, 1947, another great warm ridge aloft was present in the South Atlantic sector, raising the freezing level to the exceptional height of 2.2 Km. (7,000 ft.) over the *Willem Barendsz* near 64°S., 23°W. This was doubtless associated with the anticyclone shown a little further east in that sector, in an unusual position near 60°S.; but it is not clear that this warm ridge had anything to do with the formation of the ice-cap anticyclone.

The evidence suggests that both these anticyclones in high southern latitudes were warm anticyclones, formed in connexion with other events in the general circulation over the southern hemisphere.

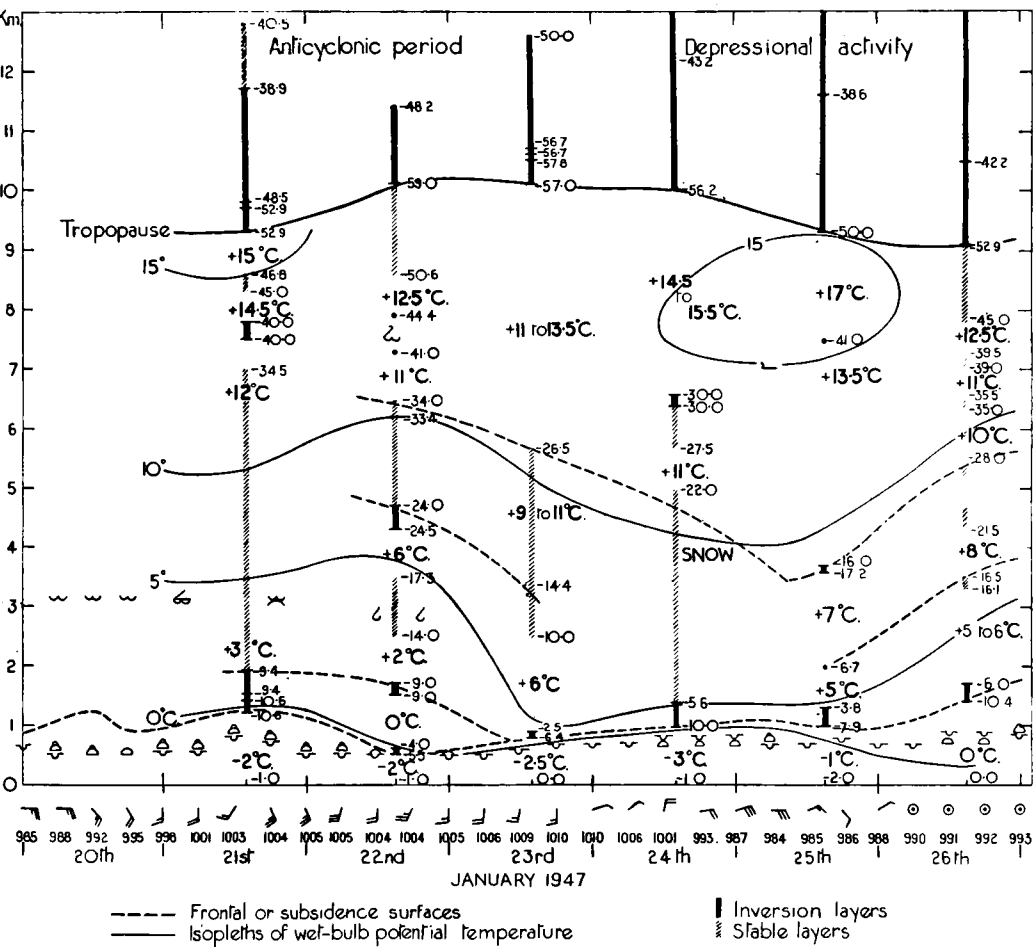


FIG. 2—CROSS-SECTION THROUGH AN ANTICYCLONE OVER THE WEDDELL SEA

Radio-sonde ascents from the *Willem Barendsz* in 62° to 63°S. and 10° to 12° W. The large figures refer to mean wet-bulb potential temperature in various layers. Surface pressure (in millibars) and surface wind are also shown below the diagram for four observations a day.

Indeed the evidence of another occasion, in January 1947 when the *Willem Barendsz* lay near the centre of an anticyclone which had moved out from Antarctica over the Weddell Sea, suggests that polar-plateau anticyclones may even show the relatively high tropopause characteristic of warm anticyclones, exceeding 10 Km. in these regions (see Fig. 2). In the warm ridge on March 20, 1947, the tropopause rose to 11 Km. in 64°S., 23°W.

By March 25, 1947, (Fig. 1) the ice-cap anticyclone was five days old, by which time most warm anticyclones in other parts of the world would have been either dislodged by a deep cold air mass advancing behind the cold front of a depression or rejuvenated by an incursion of shallow cold air behind a weak cold front pushing into the surface layers beneath the subsidence inversion⁷. Neither of these things seems to have happened to this South Polar high. Importance may come to be attached to the lesser probability of break-down of a stable anticyclone here (also in the Arctic basin in summer or in Siberia in early winter) than in most other parts of the world, on account of the unlikelihood of any deep, colder air mass existing outside the anticyclonic area. This may result in long persistence of these highs until progressive shifts of the centre allow room for a cyclonic situation over some part of the cold region, where radiational cooling from the top of the cloud-filled air may produce a really deep cold air mass.

Cyclonic situations and nourishment of the inland ice.—Situations of generally cyclonic character over the continent (e.g. March 18–20, 1947) with westerly winds around the coast in many sectors but with some cols and weak ridges of higher pressure, especially in the higher parts of the interior, are believed to have been rather common during the second half of February and March 1947. At other times, too, large depressions centred off the coast left room for no more than a region of slack circulation and relatively higher pressure near the pole, though anticyclonic situations seem to have predominated over the polar plateau from December till mid February.

Once or twice in various eastern longitudes depressions appeared to emerge from Antarctica and pass on northward tracks rather near the *Balaena*, preceded by westerly and followed by easterly winds. Mostly their circulations were weak, but the medium and upper cloud sequences were always present. Lower cloud masses were often present too, in instances noticed east of 100°E., and appeared to have considerable thickness (or vertical depth); the lows presenting these cloud systems had supposedly passed on recurving tracks mainly close to the coast. On the other hand depressions emerging between 75° and 95°E. on January 19 and April 4–5, 1947, appeared to have come from far in the interior. In the latter case the *Balaena* was lying about 200 miles off the coast, and large cumulus and cumulonimbus and squally showers were soon observed over the open water in the air stream around the depression centre; this was the most vigorous of the depressions which appeared to have come from the interior (winds up to Beaufort force 6 were observed at the ship), and is believed to have been identical with a deep system travelling south-east in the Weddell Sea on April 1, after which it presumably crossed the high ice plateau somewhere south of the mountains of Queen Maud Land. An earlier depression, probably of the same series, had crossed from the Bellingshausen Sea into the southernmost part of the Weddell Sea on March 29–31, passing south of the Falkland Islands Dependencies' observing stations in Graham Land, where westerly winds were observed at 68°S. This followed closely the break-down of the ice-cap anticyclone of March 21–29, 1947.

It seems therefore that the early attempts to solve the problem of moisture supply to the inland ice, in terms of a search for some level aloft at which the mean anticyclonic circulation of the bottom 3 Km. or more is replaced by a mean cyclonic circulation higher up, will be resolved by study of the alternating sequence in time of anticyclonic and cyclonic situations.

The remaining difficulties are that,

(i) the cyclonic situations may be too few, or give too little snowfall, at the present epoch for full maintenance of the ice-cap;

(ii) whatever the frequency of the cyclonic situations at any period the maximum snowfall would probably always be somewhere near the coast, i.e. below the summit of the ice-cap.

The alternations between cyclonic and anticyclonic situations probably occur at all times of the year. Both the highest and lowest pressures so far recorded in Antarctica (respectively 1030·5 mb. at Commonwealth Bay, Adélie Land in 1912 and 932·5 mb. at Little America in 1940) occurred in the late-winter month of September.

Snowfall should be greatest when the uplifted air mass has had a short track from open water. One would thus expect cyclonic situations occurring between late summer and early winter, at the season when sea ice is least extensive, to make the biggest contributions in snowfall to feeding the inland ice. Court's evidence from Little America (78°30'S., 163°50'W.) suggests that this is so⁸. Times of little sea ice, when the main thermal contrast between ice and open water lies close to the coast, might also be expected to give the greatest frequency of "wave" depressions with appreciable snowfall over Antarctica and least opportunity for large anticyclones to form and dominate the region. Such epochs should therefore be most favourable for building up the ice-cap.

Minor wave activity is common even in summer (when the ice-cap is at its warmest and thermal gradients are fairly weak) on the antarctic front; bigger systems form on it in winter⁹, though these probably give little snowfall over the continent.

Annual precipitation totals near the coast of Antarctica are believed today to range from about 100 to 430 mm. a year and are surely insufficient for full maintenance of the inland ice. Nevertheless we need not assume the occurrence of abnormal processes such as ice spicules drawn down from cirrus clouds in the heart of a permanent glacial anticyclone¹⁰. It is now known that the Greenland ice-cap receives normal precipitation at all points, and this seems likely also in the cyclonic situations established as occurring over Antarctica. These cyclonic situations have probably varied in frequency and richness in precipitation at different periods of history. The snowfall would be heaviest at times when air temperatures close to, or slightly above, the freezing point penetrated far into the interior of the continent.

Precipitation may occur orographically, by air-mass instability, from frontal cloud masses, and in cyclonic situations. All these types were observed from the *Balaena* close to the coast of Antarctica and over the coastal mountains. Contributions from the first three causes must be increased in cyclonic situations (defined by cyclonic curvature of the isobars and air trajectories).

Fig. 3 shows the frequency (per mille) of occurrence of fronts per 10,000 square nautical miles taken from the original *Balaena* daily weather maps during March 1947. Fig. 4 shows all the depression tracks noted in the seven weeks between February 23 and April 5, 1947. Both maps are incomplete in much of the Pacific sector. The main features of interest are:—

(i) No region appears to be entirely immune from frontal or cyclonic activity, though the broadest part of the inland ice where the anticyclone

was centred from March 21, 1947, onwards (Fig. 1) is most nearly immune. This is also reported to be the highest part of the ice-cap¹¹. Undernourishment of this main part of the ice-cap seems to be implied, if this 31-42 day period is typical and if the ice-cap anticyclones habitually or commonly settle down here.

(ii) Certain preferred paths for depressions and frontal systems (where the daily frequencies are boosted by slow-moving systems, trailing fronts and wave disturbances) are evident around the coast of Antarctica and on tracks south-eastward from the principal locations of wave-genesis in temperate latitudes in the South Atlantic, South Indian and South Pacific Oceans.

(iii) Both depressions and fronts appear to have been frequent, at least during March 1947, over the Australian sector of the antarctic continent. These lows were considered (in common with many others during the season) to have crossed the coast and passed inland between 115° and

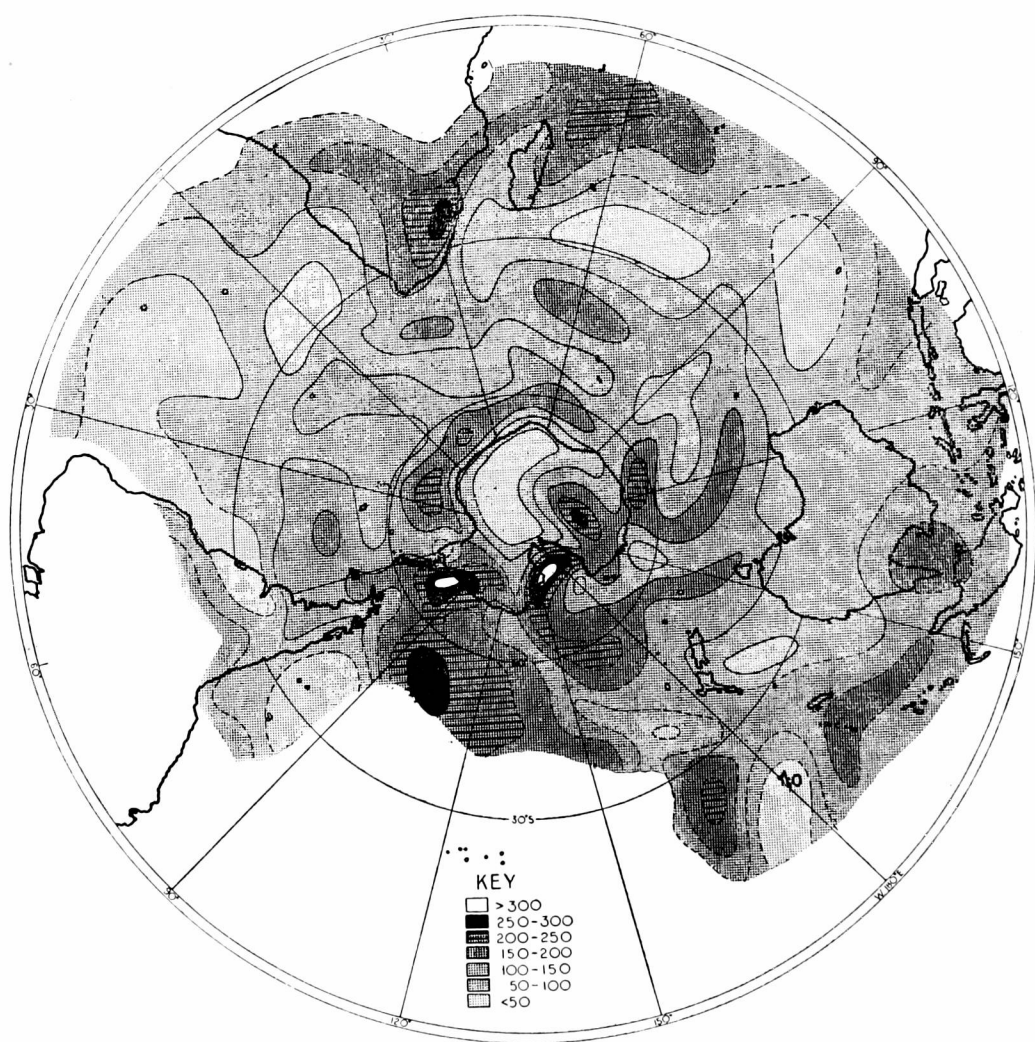


FIG. 3—FRONTAL FREQUENCIES IN THE SOUTHERN HEMISPHERE, MARCH 1947
Mean number of fronts occurring per day within an area 100 × 100 nautical miles (numbers shown in the key should be divided by 1,000).



Reproduced by courtesy of Cdr. E. R. Trendall

ALTOCUMULUS LENTICULARIS

This photograph was taken at 1030 on October 24, 1938, at Moray Firth, with the camera pointing south-eastwards.



CIRRUS IN TUFTS

This photograph was taken on October 5, 1938, at Tarbat Ness (Moray Firth), with the camera pointing eastwards at an elevation of 60° .

Reproduced by courtesy of Cdr. E. R. Trendall

140°E.—not far east of the *Balaena*. It did not seem necessary to assume any such common tendency for lows to pass inland elsewhere, except perhaps eastwards near the south-eastern extremities of the Ross and Weddell Seas. We have since learnt from Admiral Byrd's account of his aircraft explorations in 1946-47 in Operation Highjump¹² that the coast between about 115° and 140°E. is low-lying with the ice sloping up imperceptibly inland. This stretch of coast is probably therefore uniquely favourable for depressions to move inland, and the geographical discovery appears to support this feature of our weather-map analysis.

The distribution of precipitation in Antarctica must be related to the longer-period frequency distributions of frontal and cyclonic activity, to the moisture content of the air masses carried inland, and to the unknown orography of the interior. Further exploration and attempts at weather mapping over the hemisphere as a whole should throw light on all these factors.

In the discussion of the paper at Brussels, Prof. T. Bergeron thought that depressions passing over the inland ice might be weakened more than shown on the maps, though this would not affect their indicated position. Amundsen experienced snow from altostratus near the pole, followed by a clearance. Snow should fall mainly with on-shore winds; and, as it drifts most easily when newly fallen, Prof. Bergeron thought this might imply a net drift up-slope towards the

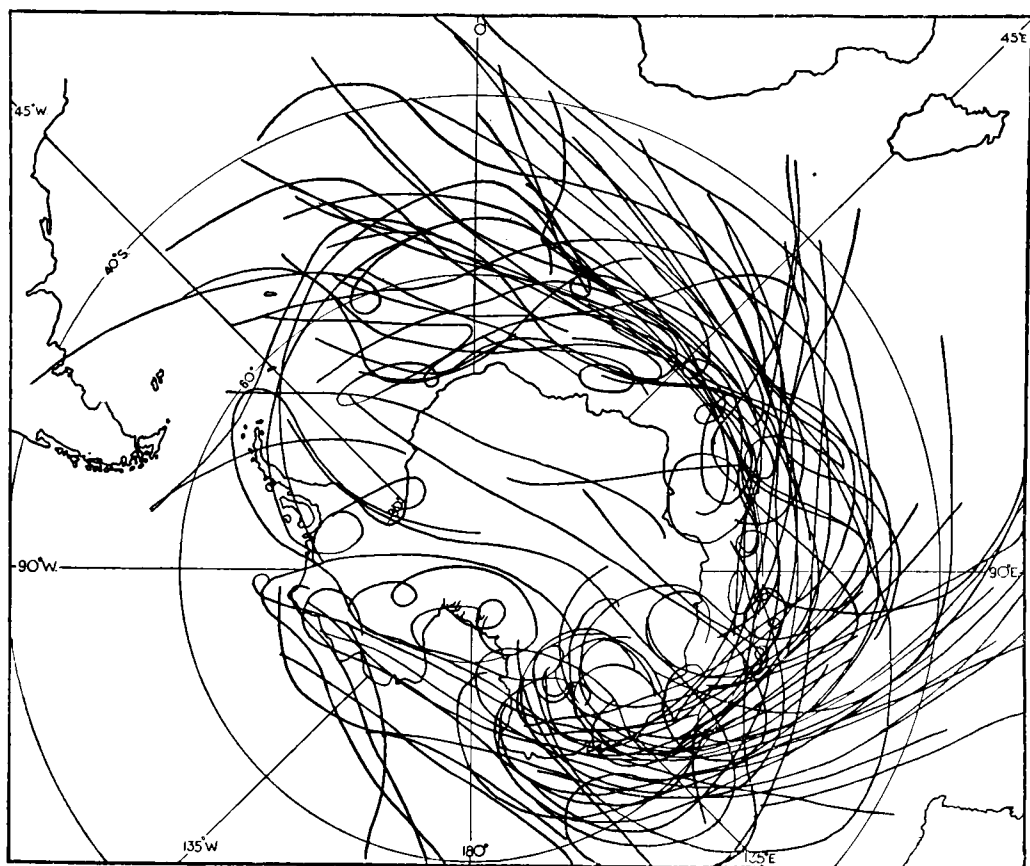


FIG. 4—DEPRESSION TRACKS—FEBRUARY 23—APRIL 5, 1947

The chart is incomplete in the Pacific sector between approximately 180° and 50°W. and everywhere north of 40°S.

interior in spite of the fact that down-slope winds prevail. Prof. Manley also referred to snowfall near the pole, where he estimated the present annual precipitation as being of the order of 40 mm. (equivalent rainfall) a year; presumably its occurrence is to be related to ascending air drawn from the Weddell Sea rather than over the known high mountain barrier between the pole and the Ross Sea.

REFERENCES

1. LAMB, H. H.; Scientific results of the *Balaena* expedition 1946-47. *Meteorology. Met. Mag., London*, **78**, 1949, p. 104.
2. KIDSON, E.; Meteorology: Discussions of observations at Adélie Land, Queen Mary Land and Macquarie Island. Australasian Antarctic Expedition 1911-14. Scientific Reports, Series B, Vol. VI. Sydney, 1946.
3. KIDSON, E.; Meteorology: Daily weather charts extending from Australia and New Zealand to the Antarctic continent. Australasian Antarctic Expedition 1911-14. Scientific Reports, Series B, Vol. VII. Sydney, 1947.
4. COURT, A.; Tropopause disappearance in the Antarctic winter. *Bull. Amer. met. Soc., Milton Mass.*, **23**, 1942, p. 220.
5. SIMPSON, G. C.; British Antarctic Expedition 1910-13. Meteorology, Vols. I-III. Calcutta, 1919-23.
6. RAMAGE, C. E.; The atmospheric circulation of the Ross Sea area. *Prof. Notes N.Z. met. Off., Wellington*, No. 2, 1944.
7. LAMB, H. H.; Essay on frontogenesis and frontolysis. *Met. Mag., London*, **80**, 1951, pp. 35, 65 and 97.
8. COURT, A.; Meteorological data for Little America III. *Mon. Weath. Rev., Washington D.C.*, Supplement No. 48, 1949.
9. ROBIN, G. DE Q.; Notes on synoptic weather analysis on the fringe of Antarctica. *Met. Mag., London*, **78**, 1949, p. 216.
10. HOBBS, W. H.; The glacial anticyclones. The poles of the atmospheric circulation. London and New York, 1926.
11. RITSCHER, A.; Deutsche antarktische Expedition 1938-39. Leipzig, 1942.
12. BYRD, R. E.; Our navy explores Antarctica. *Nat. Geogr. Mag., Washington D.C.*, **92**, 1947, p. 429.

PHYSICAL SIGNIFICANCE OF MEAN FLOW CHARTS

By R. W. JAMES, M.Sc.

Summary.—The magnitude of the ageostrophic components of the wind speed meaned over a period is assessed. It is concluded that these components may contain a vector error of the order of 1 kt. if the mean wind is equated to the mean geostrophic wind.

The most important ageostrophic component is found to be the cumulated cyclostrophic wind. A brief period of strongly curved flow may make an appreciable contribution to the mean cyclostrophic component for a period of the order of one month.

Despite this it is found that the mean isobaric or contour chart gives a close approximation to the mean flow, a consideration of the ageostrophic components only being necessary under special circumstances.

Introduction.—An isobaric map gives a geostrophic approximation to the instantaneous horizontal flow pattern in the atmosphere. Under favourable circumstances the ageostrophic components may be assessed, so that a closer approximation to the actual flow may be achieved. In general the geostrophic flow is found to be a close enough approximation for practical use, but this does not mean that closer approximations may not be desirable.

A similar problem arises in the study of mean pressure charts. Does the mean geostrophic wind give a satisfactory approximation to the actual mean wind

over a period? Is it possible to arrive at a closer approximation to the mean flow, assuming that only mean isobaric charts are available for analysis?

It is generally assumed that the mean isobaric chart gives a satisfactory approximation to the mean wind field. Indeed, it may be argued that the geostrophic approximation is closer on mean charts, for there is no preferred direction for the ageostrophic components which may therefore be expected to cancel each other out provided a sufficiently long meaning period is taken.

However, although such considerations of plausibility might enhance confidence in the use of mean charts, it is still important to attempt some estimate of the magnitude of the mean ageostrophic terms in order to assess the probable error in equating the mean geostrophic wind to the mean actual wind. This constitutes the purpose of the present paper.

Equation of mean accelerations.—The equations of horizontal motion in vector form are

$$\rho \frac{\partial \mathbf{V}}{\partial t} + \rho (\mathbf{V} \cdot \nabla) \mathbf{V} + l \mathbf{k} \times \rho \mathbf{V} + \nabla p - \frac{\partial}{\partial z} \left(\mu \frac{\partial \mathbf{V}}{\partial z} \right) = 0 \quad \dots (1)$$

where ρ is the density, \mathbf{V} is the horizontal velocity, l the Coriolis parameter, \mathbf{k} a vertical unit vector, p the pressure, μ the coefficient of turbulent diffusion, \times the symbol of vector multiplication, and ∇ the vector operator ($\partial/\partial x$, $\partial/\partial y$, $\partial/\partial z$). Taking mean values of this equation over a given time-interval T (the meaning process being indicated by a suffix m or by a bar over a combination of variables taken together, and dividing by the mean density for the period, ρ_m , we have the equation of accelerations,

$$\frac{1}{\rho_m} \left(\rho \frac{\partial \mathbf{V}}{\partial t} \right) + \frac{\rho (\mathbf{V} \cdot \nabla) \mathbf{V}}{\rho_m} + \frac{l \mathbf{k} \times \rho \mathbf{V}}{\rho_m} + \frac{\nabla p_m}{\rho_m} - \frac{1}{\rho_m} \frac{\partial}{\partial z} \left(\mu \frac{\partial \mathbf{V}}{\partial z} \right) = 0. \quad \dots (2)$$

The first term will be referred to as the isallobaric acceleration of the mean map, the second the space-acceleration, the third the Coriolis acceleration, the fourth the pressure-gradient (geostrophic) acceleration, and the last the frictional acceleration.

Let $\rho = \rho_m + \rho'$, $\mathbf{V} = \mathbf{V}_m + \mathbf{V}'$, $\mu = \mu_m + \mu'$, then equation (2) can be expressed as

$$\begin{aligned} \frac{\partial \mathbf{V}_m}{\partial t} + \frac{1}{\rho_m} \left(\rho' \frac{\partial \mathbf{V}}{\partial t} \right) + \frac{1}{\rho_m} \left[(\overline{\mathbf{V}_m + \mathbf{V}'} \cdot \nabla) (\overline{\mathbf{V}_m + \mathbf{V}'} \right) + \frac{1}{\rho_m} [\rho' (\mathbf{V}_m + \mathbf{V}') \cdot \nabla] (\mathbf{V}_m + \mathbf{V}') \\ + l \mathbf{k} \times \mathbf{V}_m + \frac{l}{\rho_m} \mathbf{k} \times \rho' \mathbf{V}_m + \frac{\nabla p_m}{\rho_m} - \frac{1}{\rho_m} \frac{\partial}{\partial z} \left(\mu \frac{\partial \mathbf{V}}{\partial z} \right) = 0. \dots (3) \end{aligned}$$

The second, fourth and sixth terms arise from a possible correlation between the departure from mean density and the wind, or its derivatives. The remaining terms are independent of density variation during the period.

If the mean equations of motion were exactly analogous to the instantaneous equations, they could be written in the form

$$\frac{\partial \mathbf{V}_m}{\partial \tau} + (\mathbf{V}_m \cdot \nabla) \mathbf{V}_m + l \mathbf{k} \times \mathbf{V}_m + \frac{\nabla p_m}{\rho_m} - \frac{1}{\rho_m} \frac{\partial}{\partial z} \left(\mu_m \frac{\partial \mathbf{V}_m}{\partial z} \right) = 0 \quad \dots (4)$$

where the time variable τ refers to some agreed epoch (taken for convenience to be the commencement) in the interval over which the mean is taken.

It is obvious that in general equation (4) will not be identical, term by term, with equation (2), and hence from serial mean charts alone it will not be possible to evaluate the individual accelerations arising in the mean equations of motion. It may be, however, that the mean accelerations entering into equation (4) are sufficiently close approximations to the corresponding mean actual accelerations for the mean chart to be used in a way exactly analogous to the use of instantaneous charts.

It may further become apparent that the two most important terms in the mean chart may be the Coriolis acceleration and the pressure-gradient term. If this should prove to be so, the mean flow over a period can be determined as a geostrophic approximation.

Before evaluating the individual accelerations in the mean equations of motion it is appropriate to make a few general remarks about their probable magnitude. The terms containing departure from mean density (ρ') may be expected to be relatively unimportant, as density never departs from its mean by more than a few per cent. Some correlation between ρ' and \mathbf{V}' may be anticipated, the density in southward moving air in general differing from that in northward moving air, so that the term $\mathbf{k} \times \overline{\rho' \mathbf{V}'} / \rho_m$ might be expected to be significant. On the other hand, no immediate connexion between ρ' and $\partial \mathbf{V} / \partial t$ is apparent, so that it would be expected that such terms as $(\overline{\rho' \partial \mathbf{V} / \partial t}) / \rho_m$ would be small.

If the wind follows an Ekman spiral, $\mu \partial \mathbf{V} / \partial z$ is a function of the angle between the surface wind and the isobars. Jeffreys's results* seem to show that the angle of surface inflow over the North Sea is different in southerly and northerly air streams, so that the correlation between μ' and wind direction may be appreciable, although there is no information regarding the correlation between μ and the vertical wind shear. It is not certain, therefore, whether the mean frictional acceleration $(1/\rho_m) \partial (\mu \partial \mathbf{V} / \partial z) / \partial z$ may be represented accurately by $(1/\rho_m) \partial (\mu_m \partial \mathbf{V}_m / \partial z) / \partial z$. If the wind field above the level of frictional influence is being considered, this term may, of course, be neglected.

The term $(\overline{\rho \mathbf{V} \cdot \nabla}) \mathbf{V} / \rho_m$ in equation (2) comprises the vertical velocity (w) term

$$\frac{1}{\rho_m} \left(\overline{\rho w \frac{\partial \mathbf{V}}{\partial z}} \right)$$

as well as terms relating to the horizontal variation of \mathbf{V} . Unless something is known of the vertical-velocity field, it will not be possible to assess this term.

It is apparent that with our present knowledge only some of the acceleration terms may be assessed. But while a complete estimate is not possible it is of interest to assess some of the terms in the equation of mean accelerations.

Isallobaric term.—The first acceleration term is the isallobaric term $(\overline{\rho \partial \mathbf{V} / \partial t}) / \rho_m$, which may be written

$$\frac{\partial \mathbf{V}}{\partial t} + \frac{1}{\rho_m} \left(\overline{\rho' \frac{\partial \mathbf{V}}{\partial t}} \right).$$

*JEFFREYS, H.; On the relation between wind and distribution of pressure. *Proc. roy. Soc., London*, A, **96**, 1919, p. 233.

Now

$$\overline{\frac{\partial \mathbf{V}}{\partial t}} = \frac{1}{T} \int_{\tau}^{\tau+T} \frac{\partial \mathbf{V}}{\partial t} dt = \frac{1}{T} [\mathbf{V}(\tau + T) - \mathbf{V}(\tau)] \quad \dots (5)$$

provided that there is no real discontinuity of \mathbf{V} in the interval τ to $\tau + T$ of t .

Equation (5) simply states that the mean acceleration over a period is equal to the vector difference of wind at the end and beginning of the period divided by the length of the period.

The mean isallobaric acceleration is likely to be the smaller, the longer the period over which the mean is taken. As an extreme case, for a 30-day mean chart, there might be a vector wind change of 100 kt., giving a mean isallobaric acceleration of 3.3 kt./day, a large value. Since

$$\begin{aligned} \frac{\partial \mathbf{V}_m}{\partial \tau} &= \frac{\partial}{\partial \tau} \left(\frac{1}{T} \int_{\tau}^{\tau+T} \mathbf{V} dt \right) = \frac{\mathbf{V}(\tau + T) - \mathbf{V}(\tau)}{T} \\ \frac{\partial \mathbf{V}_m}{\partial \tau} &= \overline{\frac{\partial \mathbf{V}}{\partial t}}. \end{aligned} \quad \dots (6)$$

The change in mean wind between serial mean charts gives the mean isallobaric acceleration, just as the wind change between instantaneous charts gives the isallobaric acceleration of the instantaneous wind.

The above results are only valid if there are no true discontinuities of wind. If there is a true frontal discontinuity of wind at time t_1 we have

$$\int_{\tau}^{\tau+T} \frac{\partial \mathbf{V}}{\partial t} dt = \mathbf{V}(\tau + T) - \mathbf{V}(t_1 + 0) + \mathbf{V}(t_1 - 0) - \mathbf{V}(\tau).$$

It is a debatable point whether an ideally sharp front is ever encountered. Even the very narrowest transition zone would suffice to validate expression (5). It will be assumed that perfectly sharp fronts do not exist, and that in consequence

$$\rho \overline{\frac{\partial \mathbf{V}}{\partial t}} = \frac{\partial \mathbf{V}_m}{\partial \tau} + \frac{1}{\rho_m} \left(\overline{\rho' \frac{\partial \mathbf{V}}{\partial t}} \right).$$

The value of the second term in the mean isallobaric acceleration has been determined for Aldergrove, Northern Ireland at the 800-mb. level for May 1948. Its numerical value was 0.02 kt./day, density above normal being correlated with W. and N. winds increasing with time.

This acceleration can be neglected in comparison with $\partial \mathbf{V}_m / \partial \tau$, which, in the present instance, was found to be 0.5 kt./day.

For illustrative purposes mean monthly charts have been considered. If the period is shorter than a month the magnitude of the isallobaric acceleration is greater. Thus for the same vector wind change between the beginning and end of a period, $\partial \mathbf{V}_m / \partial \tau$ will be six times as great in a 5-day mean as it is with a 30-day mean, say 3 kt./day as against 0.5 kt./day above. With a wind change of 100 kt. the isallobaric acceleration in a 5-day mean will be 20 kt./day, corresponding to an ageostrophic wind component of 2 kt.

Mean Coriolis acceleration.—The value of the mean Coriolis acceleration is

$$\frac{l}{\rho_m} \mathbf{k} \times \overline{\rho \mathbf{V}} = l \mathbf{k} \times \mathbf{V}_m + \frac{l}{\rho_m} \mathbf{k} \times \overline{\rho' \mathbf{V}_m}.$$

The mean wind at 800 mb. for Aldergrove in May 1947 was $246^{\circ} 30$ kt., so that $\mathbf{l}\mathbf{k} \times \mathbf{V} = 28.5$ kt./day. The value found for $\mathbf{l}\mathbf{k} \times \overline{\rho' \mathbf{V}} / \rho_m$ was 0.073 kt./day, or about $\frac{1}{4}$ per cent. of the magnitude of $\mathbf{l}\mathbf{k} \times \mathbf{V}_m$.

It is therefore obvious that the mean Coriolis acceleration can be evaluated with the required accuracy on the assumption of a constant density throughout the month.

On comparing the relative magnitudes of the isallobaric acceleration, 0.5 kt./day, and the Coriolis acceleration, 28.5 kt./day, the isallobaric wind is seen to be normally small enough to be neglected in comparison with the geostrophic wind.

Evaluation of the space acceleration.—The “spatial” mean acceleration is

$$\frac{1}{\rho_m} \overline{\rho (\mathbf{V} \cdot \nabla) \mathbf{V}} = \overline{(\mathbf{V} \cdot \nabla) \mathbf{V}} + \frac{1}{\rho_m} \overline{\rho' (\mathbf{V} \cdot \nabla) \mathbf{V}}.$$

In the case of the isallobaric acceleration and the Coriolis acceleration, it has been shown that density variation accounts for only about 1 per cent. or less of the total, and hence can be effectively neglected. Without actual proof there is a very strong presupposition that a similar result will be valid for the spatial mean acceleration, and hence the ρ' -term in the above expression will be neglected.

The evaluation of $\overline{(\mathbf{V} \cdot \nabla) \mathbf{V}}$ requires a knowledge of the space rates of change of wind velocity. For this purpose a network of three wind-observing stations, Aldergrove, Lerwick and Downham Market, were taken. The value of $(\mathbf{V} \cdot \nabla) \mathbf{V}$ at Aldergrove was taken as

$$(\mathbf{V}_A \cdot \nabla) \left(\mathbf{V}_A - \frac{\mathbf{V}_L + \mathbf{V}_D}{2} \right)$$

where the suffixes A, L and D refer to Aldergrove, Lerwick and Downham Market respectively. The values so computed were 8.5 kt./day towards the west, and 7.7 kt./day towards the north.

The magnitudes of the terms are very much affected by the observations for one day, May 5, 1948, when an intense low was centred north-east of Aldergrove. If this day is omitted from the computations we get revised accelerations of 7.1 and 1.1 kt./day towards the west and north respectively.

It is not difficult to see how the omission of one day's observations can make this considerable difference amounting to a vector acceleration of 4 kt./day. This corresponds to a mean cyclostrophic wind component of 0.43 kt. or a component of 13 kt. on one day. This is by no means an unusual value for the cyclostrophic wind component on a day of strongly curved motion.

It will be noticed that the mean “spatial” or cyclostrophic acceleration is of the order of a third of the mean Coriolis acceleration in the above example. Hence a considerable departure from its geostrophic value may be expected in the mean wind.

This, however, does not imply that the geostrophic approximation is less useful when applied to mean charts than when applied to instantaneous charts, for in regions of synoptic charts where the pressure-gradient is so slack as to correspond to a geostrophic wind speed of 3 kt. considerable percentage departures of wind from its geostrophic value are likely.

A further point of interest is to find out whether the mean cyclostrophic acceleration can be inferred from the mean chart itself, that is, whether

$$\overline{(\mathbf{V} \cdot \nabla) \mathbf{V}} \simeq (\mathbf{V}_m \cdot \nabla) \mathbf{V}_m$$

In the above example, $|(\mathbf{V}_m \cdot \nabla) \mathbf{V}_m| = 0.5$ kt./day or only a twentieth of the magnitude of $\overline{(\mathbf{V} \cdot \nabla) \mathbf{V}}$.

Hence the analogy between mean and instantaneous charts is not perfect, in the same sense that, ignoring friction, it is not possible to write

$$\frac{\partial \mathbf{V}_m}{\partial t} + (\mathbf{V}_m \cdot \nabla) \mathbf{V}_m + l\mathbf{k} \times \mathbf{V}_m + \frac{\nabla p_m}{\rho_m} = 0.$$

The proper equation governing mean motion is

$$\overline{(\mathbf{V} \cdot \nabla) \mathbf{V}} + l\mathbf{k} \times \mathbf{V}_m + \frac{\nabla p_m}{\rho_m} \simeq 0,$$

for experience with the May 1948 chart suggests that $\partial \mathbf{V}_m / \partial t$ can safely be ignored compared with the remaining accelerations.

The mean geostrophic wind is given by

$$l\mathbf{k} \times \mathbf{V}_{gm} = -\frac{\nabla p_m}{\rho_m}$$

so that the equation of mean motion may be written

$$\overline{(\mathbf{V} \cdot \nabla) \mathbf{V}} + l\mathbf{k} \times (\mathbf{V}_m - \mathbf{V}_{gm}) = 0$$

The term $\overline{(\mathbf{V} \cdot \nabla) \mathbf{V}}$ is almost entirely due to the cumulative effect of passing perturbations, that part of it due to the curvature of mean flow $(\mathbf{V}_m \cdot \nabla) \mathbf{V}_m$ being small. In the example chosen $\overline{(\mathbf{V} \cdot \nabla) \mathbf{V}}$ corresponds to an ageostrophic departure in the mean wind of 1 kt. The ageostrophic departures of mean wind are not likely to exceed this figure greatly, so that if the mean geostrophic speed is of the order of 10 kt. the geostrophic approximation may be expected to represent the mean flow to within 10 per cent. If mean winds are light, however, the geostrophic approximation will not be so close proportionately although the absolute departures are likely to be no greater.

It is therefore apparent that the geostrophic approximation is a close indication of mean flow where that flow is strong, as for example at the 300-mb. level, but is not to be relied upon when that flow is weak, as in surface charts.

Contour charts.—In terms of contour height ζ for a fixed pressure level the equations of horizontal motion may be written (ignoring friction and writing $\nabla_h = (\partial/\partial x, \partial/\partial y)$)

$$\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V} \cdot \nabla) \mathbf{V} + l\mathbf{k} \times \mathbf{V} + g\nabla_h \zeta = 0$$

The mean equations can be written

$$\frac{\partial \mathbf{V}_m}{\partial \tau} + \overline{(\mathbf{V} \cdot \nabla) \mathbf{V}} + l\mathbf{k} \times \mathbf{V} + g\nabla_h \zeta = 0.$$

In this particular case the density does not enter into the equations, and hence there are no terms including the density variation. The mean contour chart has, therefore, the advantage of theoretical simplicity over the isobaric chart, but the practical advantage is negligible, since, as seen above, the terms including density departure may safely be neglected.

Except for this slight difference the mean contour chart is in every way equivalent to the mean isobaric chart.

Conclusion.—It is concluded on the basis of one set of monthly data that the mean geostrophic wind represents the mean actual wind with a possible vector error of a knot or so.

A mean ageostrophic departure may arise from the isallobaric term, or from the cumulation of ageostrophic flows due to cyclostrophic components, the vertical velocity term and the frictional departures.

The isallobaric term increases in importance as the period of meaning is reduced; it can safely be neglected for monthly charts, but appreciable ageostrophic mean components may be introduced into 5-day means in special circumstances. If desired, the magnitude of this term may be assessed by "gridding" synoptic charts representing the beginning and end of the meaning interval.

Under some circumstances the cumulation of cyclostrophic components may give an appreciable ageostrophic mean wind component. It is not safe to assume that the cyclostrophic terms will be random as regards magnitude and sign; a low with an accompanying short period of intense curved motion may contribute appreciably to the mean cyclostrophic term. This has particular point with low-level charts where the mean flow is normally weak, and the ageostrophic term may be a substantial fraction of the mean geostrophic speed. At, say, 300 mb. the mean flow is normally strong compared with the perturbed flow, and disturbances are usually characterized by a succession of trough and wedge perturbations. Under such circumstances $\overline{(\mathbf{V} \cdot \nabla) \mathbf{V}}$ may normally be ignored, partly because the signs and amplitudes of the ageostrophic components are more random, and partly because the mean flow itself is stronger. Hence at high levels the mean geostrophic wind is expected to give a close approximation to mean flow.

It is not possible to assess the magnitude of the term $\overline{w \partial \mathbf{V} / \partial z}$ but on general grounds it is expected to be of the same order of magnitude as $\overline{(\mathbf{V} \cdot \nabla) \mathbf{V}}$.

Finally, the ageostrophic component of mean flow due to friction is difficult to assess. This problem arises most acutely with surface charts; it can be ignored in high-level flow.

The mean flow is very closely approximated by the mean geostrophic wind in the free atmosphere, but where the period of meaning is short and the pressure gradient slack, the contribution from ageostrophic components may be significant.

METEOROLOGICAL OFFICE DISCUSSION

Blocking action as a factor in the general circulation

The third Discussion of the 1951-52 series on December 10, 1951, dealt with blocking action as a factor in the general circulation, and was opened by Mr. F. E. Lumb who based his statement on the following papers.

REX, D. F.; Blocking action in the middle troposphere and its effect upon regional climate. I—An aerological study of blocking action, and II—The climatology of blocking action. *Tellus, Stockholm*, **2**, 1950, p. 196 and p. 275.

The normal circulation pattern at 500 mb. in the northern hemisphere is a relatively broad westerly current bounded to the north by the upper low of the polar region and to the south by the subtropical high-pressure belt. Occasionally the development of a pronounced quasi-stationary ridge or anticyclone at the 500-mb. level causes the westerly current to split into two branches. The ridge or anticyclone blocks the westerly current. This is blocking action in terms of the 500-mb. flow pattern.

The surface anticyclone associated with the upper anticyclone or ridge is called the surface blocking anticyclone.

For statistical purposes, an occurrence of blocking action has to satisfy five conditions:—

- (i) the basic westerly current must be split into two branches,
- (ii) each branch must be clearly defined by the 500-mb. contours,
- (iii) the two branches must extend over at least 45° of longitude,
- (iv) a sharp transition from zonal type flow upstream to meridional type flow downstream must be observed at the branch point of the two currents,
- (v) the pattern must persist with recognizable continuity for at least 10 days.

By way of illustration, the 500-mb. flow pattern on October 9, 1951, was examined.

Blocking action is said to be initiated when the basic westerly current splits into two branches, and to cease when any one of the five conditions is no longer satisfied.

During the periods 1932–40 and 1945–50 covering $13\frac{1}{2}$ years in all, 112 cases of blocking action were found. A statistical analysis shows two characteristics of blocking action of special interest:—

(i) The split of the basic westerly current into two branches, associated with the development of blocking action, occurs in two distinct longitudinal bands, one in the north-east Atlantic (82 cases) centred around 10°W. and one in the north-east Pacific (30 cases) centred around 150°W. In the large majority of cases in the north-east Atlantic the westerly current splits into two branches between 35°W. and 5°E.

(ii) Both for the Atlantic and Pacific cases, blocking action has a maximum frequency in winter and spring, and a minimum frequency in late summer. The percentage number of days characterized by blocking action in the north-east Atlantic averages 36 per cent. for the six months from December to May inclusive as compared with an average of only 16 per cent. for the three months, July, August and September.

Blocking action in winter is usually associated with a quasi-stationary anticyclone whose mean position is over southern Norway giving a spell of cold easterly or south-easterly winds over the British Isles. In summer blocking action is usually associated with a ridge or anticyclone centred over or very near to the British Isles, giving a spell of fine warm weather.

For a simple two-dimensional current of width $2a$ and constant speed u eastward, Rossby¹ has shown that the critical ratio $3u/\beta a^2$, where β is the rate of

change of the Coriolis parameter with latitude, is a measure of the susceptibility of the stream to blocking development. However, computed daily values of the critical ratio at the 500-mb. level prior to and during three periods of blocking action show erratic changes from day to day. There is no clear relationship between the critical ratio and blocking development.

An alternative explanation of the development of blocking action was then put forward by the opener, based on the inter-relation between the thickness pattern and the underlying surface-pressure pattern. Sutcliffe and Forsdyke² have shown that the development of a baroclinic anticyclone is associated with the growth of anticyclonic distortion of the thickness lines, and that this thermal synoptic system is a self-developing one. The baroclinic anticyclone will normally be subject to thermal steering south-eastward. If this self-developing system finds itself in an environment which is particularly favourable for the growth of anticyclonic distortion, the south-eastward movement of the anticyclone will be retarded; at the same time it will extend north-east. The anticyclone tends to become quasi-stationary and to build up into higher latitudes, in other words to become a blocking anticyclone.

Anticyclonic distortion of the thickness lines is typically associated with a warm ridge extending north-eastwards into relatively high latitudes, and an adjacent cold trough extending south-westwards into relatively low latitudes. If two adjacent regions can be found, one particularly favourable to the north-eastward advection of warm air and the other situated to the south-east particularly favourable to the south-westward advection of cold air, the blocking anticyclone will tend to develop in the strongly baroclinic zone between.

Sutcliffe and Forsdyke² have given charts showing the extreme displacements of certain thickness lines for each month of the year. The chart for January suggests that in winter warm air can readily penetrate into high latitudes on a north-north-east track over the north-east Atlantic into the Barents Sea. This would be expected on physical grounds: vigorous cyclonic activity over the western North Atlantic in winter and small gradient of sea temperature from south-south-west to north-north-east over the north-east Atlantic. Also the chart of extreme displacements of thickness lines in January shows that cold air can readily penetrate southwards over European Russia then westwards across the plains of Poland, Germany and France. Scandinavia would be in the strongly baroclinic region between the warm air being advected north-north-east over the north-east Atlantic and the cold air being advected southwards and westwards across Europe. It is therefore over or near Scandinavia that blocking anticyclones would be expected to develop in winter. This is in agreement with the results of Rex's investigation into the mean position of the surface blocking anticyclone in winter.

The chart showing the extreme displacements of certain thickness lines in July suggests that in summer warm air can more readily penetrate into high latitudes over Europe than over the north-east Atlantic, although decreased cyclonic activity in summer will make deep penetrations less likely than in winter. But for the marked growth of anticyclonic distortion of the thickness lines the south-westward advection of deep cold air should give a thickness trough to the south-east of the thickness ridge. Such a trough can at best be only a very temporary feature over a strongly heated continental land mass in summer. Hence blocking action cannot readily develop in summer. This is in agreement

with the figures given by Rex for the seasonal variation in blocking action, which was at a minimum in late summer.

As an example, the development of blocking action over north-west Europe between January 17 and 20, 1950, was examined. The development of an anticyclone over the North Sea and southern Norway was shown to be associated with the growth of anticyclonic distortion of the thickness lines, due primarily to the north-eastward penetration of a broad tongue of warm air into the Norwegian Sea.

The Director opened the discussion by suggesting it might be possible to forecast blocking action by forecasting changes in the thickness pattern.

Mr. Peters said that *Mr. Clements* had looked up the charts prepared in the Forecasting Division at Dunstable for the occasion in January 1950 described by *Mr. Lumb*. He had found that a remarkably accurate forecast was produced, on the morning of January 16, of the complete and rapid change of type which occurred between January 16 and 17—the crucial point in the weather of the month. Relevant forecast and actual charts for the 17th were shown, and the meeting acclaimed the prebaratic for the morning of the 17th as constructed 24 hours earlier. The further outlook issued on the morning of the 16th foreshadowed the marked change to colder weather which occurred a day or so later.

Mr. Davis showed maps of the mean vector wind $\bar{\mathbf{V}}$ and vector standard deviation σ at the 500-mb. level for the North Atlantic region taken from *Geophysical Memoirs* No. 85³. Consideration of the ratio $\sigma/|\bar{\mathbf{V}}|$ showed that the chance of obtaining blocking action was greatest over north-west Europe and greater in winter than in summer. The probable longitudinal distribution of blocking action agreed very well with that given by Rex. Assuming that blocking action leads to the development of winds at 500 mb. at 90° or more to the mean and *vice versa*, the frequency of occurrence can be calculated and is in good agreement with the 112 cases in $13\frac{1}{2}$ years given by Rex. Further consideration of the ratio $\sigma/|\bar{\mathbf{V}}|$ at other levels showed that blocking action was less frequent at 200 mb. with the centre of maximum occurrence further west, indicating that intense blocking action, which reached up to 200 mb., tended to drift westwards as it developed. Blocking action was more frequent at 700 mb., and it was tempting to assume that it was initiated in the lower layers and built upwards through the troposphere. Consideration, however, of the ratio at the 300-mb. level showed that, while this assumption was probably true in regions where blocking action was infrequent, over north-west Europe it was as frequent as at 700 mb. with the centre of maximum probability located in the same place. The conclusion is that blocking action is caused by air descending from 300 mb. through the non-divergent levels at 500 and 600 mb. to the lowest layers and thus causing the formation of a blocking anticyclone. The probable cause of air descending over north-west Europe from the 300-mb. level is to be found in the low tropopause over Russia—especially in winter—which would tend to drive the eastward moving tropospheric air at 300 mb. downward.

Mr. Veryard stressed that the development of blocking action was closely associated with the thermal contrast between ocean and land mass.

Mr. Sawyer stated that Rex's condition that the characteristic 500-mb. flow pattern should last for at least 10 days would greatly restrict the number of

cases of blocking action. Many cases have a shorter life, and can develop elsewhere than in the two longitudinal bands found by Rex. Rossby's theoretical explanation of blocking action involved several doubtful assumptions, and its failure to apply in practice should not be attributed solely to his basic assumption of a barotropic atmosphere. Blocking is not necessarily associated with the formation of an anticyclone, it may be due to intensive cyclonic development downstream.

Dr. Sutcliffe did not see the connexion between Mr. Davis's statistics and blocking action. Winds at right angles to the mean flow could be equally well associated with depressions over Scandinavia as with anticyclones. Blocking action is a new term for something known before. In the southern hemisphere zonal flow is much more constant than in the northern hemisphere where every ridge in the surface pressure pattern contains the threat of blocking development. Ridges may start anywhere but have favoured regions for settling down. The cause of ridge development is not local, but the cause of ridge persistence is local. A study is being made in the Forecasting Research Division at Dunstable of flow patterns which have long persistence.

Mr. Jacobs considered that Rex's investigation would have been of more value if he had chosen a shorter period than 10 days as criterion of blocking action. Rex gave a minimum frequency of blocking action in September, but Belasco⁴ had found a maximum frequency of anticyclones over the British Isles in September.

Mr. Gold said that for blocking action to develop cold air must come round to the south of the warm air mass. Blocking action is a new name for the "break-through" of cold air which concludes the life history of a family of depressions.

Dr. Sutcliffe added that the term blocking action was introduced in order to distinguish clearly between the long-lived blocking anticyclone and the relatively short-lived break-through ridges. It was important that such terms as "jet stream" and "blocking action" should not be allowed to depreciate in value.

The Director in closing the discussion emphasized the value of seeking for features of persistence in the general kaleidoscopic pattern of atmospheric circulation.

REFERENCES

1. ROSSBY, C. G.; On the dynamics of certain types of blocking waves. *J. Chin. Geophys. Soc., Nanking*, **2**, 1950, p. 2.
2. SUTCLIFFE, R. C. and FORSDYKE, A. G.; The theory and use of upper air thickness patterns in forecasting. *Quart. J. R. met. Soc., London*, **76**, 1950, p. 189.
3. BROOKS, C. E. P., DURST, C. S., CARRUTHERS, N., DEWAR, D. and SAWYER, J. S.; Upper winds over the world. *Geophys. Mem., London*, **10**, No. 85, 1950.
4. BELASCO, J. E.; The incidence of anticyclonic days and spells over the British Isles. *Weather, London*, **3**, 1948, p. 233.

OFFICIAL PUBLICATION

The following publication has recently been issued:—

PROFESSIONAL NOTES

No. 105—Diurnal variation of pressure in the Mediterranean area. By H. Jameson, D.Sc.

This note is a discussion of the harmonic dials representing monthly changes in the 24-hr. and 12-hr. pressure oscillations in various areas of the Mediterranean Sea and in neighbouring land areas. While the dials for the 24-hr.

oscillation differ considerably from one another, even in neighbouring areas, those for the 12-hr. oscillation show in most cases a fairly constant pattern, with changes in amplitude but constant phase, from May to October, and changes in both amplitude and phase during the remainder of the year, causing a counter-clockwise rotation of the dial point.

The mean annual phases of the 12-hr. oscillation in marine areas back appreciably from the values at land stations. A similar phenomenon had previously been noted in the tropics.

Harmonic dials of the 12-hr. oscillation in tropical marine regions are compared with those for the Mediterranean Sea. The marked difference between summer and winter in the Mediterranean dials appears also, in a somewhat modified form, in the northern and even in the southern tropics.

ROYAL METEOROLOGICAL SOCIETY

At the meeting of the Society held on December 19, 1951, the President, Sir Charles Normand presiding, papers were read on the heating of cold air masses over a warmer sea and on observations with a directional rain-gauge.

*Burbidge, F. E.—The modification of continental polar air over Hudson Bay**

The major topic of this paper by Mr. Burbidge of the Canadian Meteorological Service (read for him by Mr. Craddock) is the change in December in the modification of air passing over Hudson Bay. This change is ascribed to the formation of ice cover over almost the whole of the Bay. Mr. Burbidge points out that until 1948 little was known by direct observation about the central parts of Hudson Bay in winter, but reports by residents and explorers expressed the opinion that open water remained in the central parts throughout the year. This opinion was expressed also in the "Ice atlas of the northern hemisphere" produced by the United States Hydrographic Office in 1946. Mr. Burbidge examined the meteorological data and found a remarkable change in December which could only be ascribed to complete freezing of the Bay.

The data used were mainly comparisons between values of meteorological elements at Churchill on the west shore and Port Harrison on the east shore in about the same latitude. The results are briefly:—

(i) Mean temperature at Port Harrison is over 10°F. higher than at Churchill in November, but from January to June is practically identical at both places though the mean wind remains westerly.

(ii) The mean temperature at Port Harrison with easterly winds is 10°F. lower than with westerly winds in November, but from December to May there is little difference.

(iii) The greatest mean monthly snowfall at Port Harrison occurs in November.

(iv) A double cloud maximum, one in November and one in May, occurs in the Hudson Bay region. The November one is ascribed to heating of very cold air by a water surface and the May one to stratus produced over the ice and cold water of the Bay.

(v) Surface air trajectories from west to east over the Bay were examined for four years, and it was found that in November there was marked

* *Quart. J. R. met. Soc., London*, **77**, 1951, p. 365.

warming of air masses initially at a lower temperature than 30°F. but in December warming was much less. The values for the period January–May indicated negligible modification of air at so low a temperature that it could not have passed over any appreciable area of surface of the Bay at the temperature of about 30°F. appropriate to open water.

(vi) The lapse rates shown by radio-sonde ascents in air which had come over Hudson Bay showed in November a great change from extreme stability on the leeward side to extreme instability on the windward side. In December the change was very variable and from January to May there was little modification.

The conclusion that the whole Bay in midwinter freezes over was confirmed by flights made over the Bay in 1948 and 1949. The general result is that in the autumn Hudson Bay is open and strongly warms air masses originating over the neighbouring continent; in winter it is frozen and effectively a part of the continent; in spring and early summer it is partly frozen and is a source of cold air; in summer it is an area of cold water causing subnormal temperatures with much fog and low stratus in surrounding areas.

*Craddock, J. M.—The warming of arctic air masses over the eastern North Atlantic **

Mr. Craddock's own paper dealt with the warming of air masses moving from Iceland to the British Isles. Twenty-eight trajectories in which air moved from Reykjavik over the upper air sounding network in the British Isles were used. He pointed out that a difficulty in the work was that the heating produced a temperature gradient along the direction of motion which lead to shearing so that higher layers moved relatively towards the east. However, if there were a layer of the air mass within which (i) the wind shear at each level was in the direction of the isotherms, (ii) the isotherms and wind shear had the same direction at all levels in the layer, and (iii) the air at some one level in the layer could be directly tracked from the initial to the final sounding then a fair comparison could be made. The trajectories used were carefully selected to satisfy these conditions, and any which showed evidence of a thermal wind changing direction with height were rejected. The gain of heat and water vapour by the air in the selected trajectories was computed. The mean total rate of gain of heat of an Arctic air mass over the sea between Iceland and Britain was found to be 47 cal./cm.²/hr. which is about half the solar constant and exceeds the hourly rate of heating of air over land in the British Isles at noon on a clear summer day. The heating over the sea goes on throughout the 24 hr. so that it is a far more powerful method of heating the air than summer insolation. Part of the heat is derived from the condensation of water vapour evaporated from the sea. An upper limit to the amount of water evaporated can be obtained by supposing that all the heat is obtained in this way and a lower limit is found from the gain in water vapour content. The difference between the two rates of evaporation gives in a typical case an upper limit 0.5 mm./hr. to the precipitation. Mr. Craddock next considered the relation connecting the difference, mean sea temperature over track minus mean surface air temperature over track, with the rate of warming and rate of gain of water vapour for each of the trajectories and found a close connexion which could be expressed in the words "if the difference sea minus air temperature is $n^{\circ}\text{F}$. and the upper limit of convection is not above 700 mb. then the thickness of the layer from 1000 to 700 mb. will

* *Quart. J. R. met. Soc., London*, 77, 1951, p. 355.

increase by n ft./hr.''. Mr. Craddock's paper must be consulted for the application of his results to occasions when the convective limit differs from 700 mb. Finally Mr. Craddock considered all the possibilities of heating an air mass over the sea, namely advection, subsidence, lateral diffusion, radiation, evaporation of water vapour from rain falling from an upper warm front, and direct evaporation from the sea surface. He concluded that in the air masses he had considered evaporation from the sea surface provided the main source of heat with radiative effects producing a small loss.

In the discussion on Mr. Burbidge's and Mr. Craddock's papers, Dr. Robinson pointed out that Craddock's results applied to his and Rider's formula for heat loss corresponded to the reasonable mean wind velocity of 10 m./sec. Dr. Scorer agreed that in Craddock's situations there was little subsidence north-west of the British Isles but considered there was appreciably more in the same air stream south of the British Isles. Cdr. Frankcom was glad to see the Canadian work on the Hudson Bay area which was important for the shipping of grain. Dr. Sutcliffe was concerned as to whether the rising top of the convective layer in air heated by the sea could be confused with a front; Mr. Craddock said it was difficult to distinguish between them over Iceland but easy over Britain. Mr. Sumner asked if convection and subsidence are incompatible, and did not consider the question of the method of heating was settled; Mr. Craddock replied that in all his cases there was vigorous convection in progress on the north-west coasts of Britain, and that he was sure the amount of heating was related to the surface temperature difference which would not be so for subsidence heating.

*Lacy, R. E.—Observations with a directional rain-gauge **

Mr. Lacy opened his statement on the observations made with a directional rain-gauge at the Building Research Station, near Watford, Herts., by briefly recounting the importance of meteorological information in connexion with the weathering of building materials, the effect of soil humidity on foundations and the heat loss from buildings. The variation of rainfall with direction was important in studies of the wetting of walls, as wet bricks have twice the heat conductivity of dry bricks. The gauge used had eight apertures, directed to the eight main points of the compass, in its vertical sides and a normal horizontal aperture above them, and was exposed on the flat roof of a building. The results showed that the apertures facing south, south-west and west received more rain than the others with a maximum for the south-west one and a minimum for the north one. The mean ratio between maximum and minimum was about 4:1, with a larger value in winter and smaller in spring. The ratio between the catches in the vertical apertures and in the horizontal gauge varied with season because of the variations in the angle of incidence of the rain, but approximately over a year the rainfall on the wettest wall of a building is about $\frac{1}{4}$ of the rainfall on the ground, and the rainfall on the driest wall of a building is about $\frac{1}{4}$ of the fall on the wettest wall. Calculations of the angle of inclination of rainfall to the vertical showed a mean angle of nearly 30° for winter with its strong winds and 15° in summer. Mr. Lacy described how he had measured the electrical conductivity of walls facing in different directions during recent rain driving from north, and found the north-facing wall had an increase in

* *Quart. J. R. met. Soc., London*, 77, 1951, p. 283.

conductivity about half that expected from the rain catch. During the discussion Mr. Bonacina pointed out that the amount of rain reaching the ground is the same whether the angle of incidence is zero or nearly 90°. Mr. Craddock questioned whether owing to eddies the conventional gauge caught as much rain as the same area of ground, and Prof. Sheppard said the “collecting efficiency” of a house for raindrops should be about equal to that of the apparatus used for measuring the size of cloud particles.

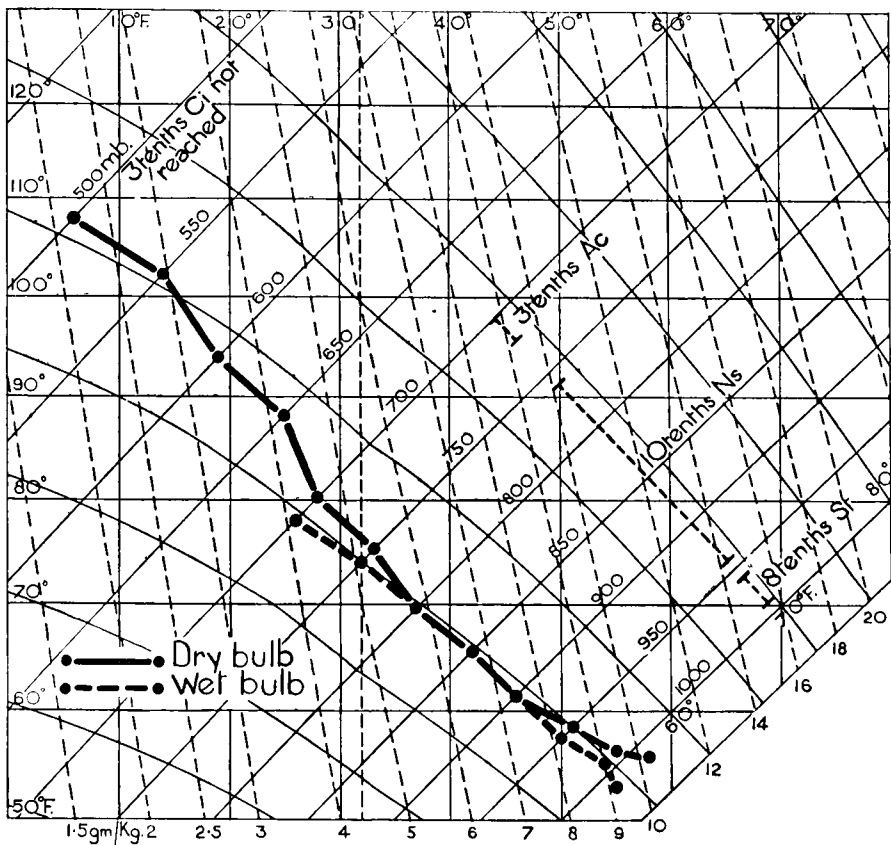
LETTERS TO THE EDITOR

Rain from non-freezing cloud

I well remember whilst flying on the war-time “Epicure” meteorological reconnaissance flight a particular occasion of rain from cloud whose top did not extend above the freezing level. Recently some photographs have come to light with a note of the date. These are reproduced facing this page. The following details have been taken from the log of the flight.

It was on May 22, 1945, at 1425 G.M.T. in 43°1'N., 14°3'W. (the ascent sounding position). There was moderate continuous rain below cloud, which was 10 tenths, apparently thick nimbostratus. The freezing level, at 740 mb., was higher than the tops of the nimbostratus. The mean-sea-level pressure was estimated at 1017 mb.

Photographs of the nimbostratus top were obtained; it was level but gently rippled, and, to all appearances, might have been that of an innocuous layer of stratocumulus. (I think, the amount of the altocumulus layer at 720–700 mb.



ASCENT IN 43°1'N., 14°3'W. AT 1425 G.M.T., MAY 22, 1945



Taken at 1445 from 15,000 ft.

Photograph by R.A.F.



Taken from 10,000 ft.

Photograph by R.A.F.

TOP OF 10 TENTHS NIMBOSTRATUS CLOUD (940-760 MB.) FROM WHICH MODERATE
CONTINUOUS RAIN WAS FALLING



Reproduced by courtesy of METPHOTO and Whites Aviation Ltd., New Zealand

LENTICULAR LEE-WAVE CLOUD OVER SOUTH ISLAND, NEW ZEALAND

This photograph was taken by Leo L. White, at a height of approximately 4,000 ft. over Sutton looking north-eastwards at 1330 on May 18, 1951. The aircraft was flying towards Middlemarch on course 20° true.

Recorded in the log as 8 tenths was a slip of the pencil for 3 tenths, as the nimbostratus top was photographed without difficulty.)

There is no record of the levels between which rain occurred, but almost certainly the nimbostratus was "wet", i.e. water droplets were impinging on the perspex of the aircraft, from base to top.

Abingdon, November 19, 1951

R. WARD

Lag of wet-bulb thermometer during rising temperature after frost

On the morning of December 12, 1951, after a night with hoar frost (but not rime) the thermometers in my screen read dry bulb $32\frac{1}{2}^{\circ}\text{F.}$, wet bulb $31\frac{1}{2}^{\circ}\text{F.}$ at 0925. The wet bulb was not wetted by direct application of water. The moisture in the muslin had reached it via the wick.

I had occasion to read the thermometers again at 1100, and was surprised by the large difference between them, dry bulb 37° , wet bulb 33° . Suspecting that this might be due to delay in thawing of the wet bulb I read the thermometers again at intervals. At 1110, the readings were 37° , 34° ; at 1130, $37\frac{1}{2}^{\circ}$, $35\frac{1}{2}^{\circ}$; and at 1140, 38° , 36° . These readings, I think, confirm my suspicion.

As I can find no reference to this possible source of error in wet-bulb temperature I feel justified in communicating the observations to you so that others may be made aware of it, and take precautions against it when the temperature is rising and the wet bulb goes above 32° , after frost.

E. GOLD

8 Hurst Close, N.W.11, December 12, 1951

[The effect reported by Mr. Gold produces a marked false drop in the dew point. The dew points corresponding to Mr. Gold's readings are: 0925, $29\frac{1}{2}^{\circ}$; 1100, 25° ; 1110, 29° ; 1120, $32\frac{1}{2}^{\circ}$; 1140, 33°F. —Ed. *M.M.*]

NOTES AND NEWS

Lenticular lee-wave cloud over New Zealand

The cloud illustrated in the photograph facing this page can best be described as a lenticular lee-wave cloud. It is, however, such an unusual formation that no similar illustration appears in any of the recognized cloud atlases. The physical processes underlying its formation are nevertheless the same as are commonly described in the formation of lenticular cloud.

Lenticular cloud forms are common over Canterbury and Otago provinces where the lower atmosphere is comparatively dry on the east coast of South Island and very moist on the west coast. They most commonly occur with föhn winds which in South Island are associated with the passage of a deep depression across the south Tasman Sea, preceded by very strong north-westerly winds. A well known example is the "Canterbury northwester", a hot dry gusty wind from which most of the moisture has been extracted during its passage across the Southern Alps.

The meteorological situation which produced the cloud form illustrated differed from that normally producing the föhn wind, although the results were rather similar. A deep depression lay far south of New Zealand with a cold front extending northwards from its centre orientated north-west to south-east across South Island moving to the north-east towards Dunedin at midday. An intense anticyclone was centred over the Tasman Sea, and extended to New Zealand, the isobars indicating a strong pressure gradient for SW.-WSW. winds over South Island ahead of the cold front. The air mass was comparatively stable.

At the time the photograph was taken, 1330 on May 18, 1951, the aircraft was approximately 60 miles north of the cold front at a height of 4,000 ft. over Sutton, and it is probable that the northwards movement of this front increased the pressure gradient ahead of it, and at the same time caused the westerlies aloft to veer towards NW. This effect was enhanced by the formation of an orographical low-pressure area on the leeward side of the Southern Alps.

The consequence of these conditions was that an exceptionally strong north-westerly wind blew across the mountain ranges of South Island parallel to the cold front from a direction of 310° true. Correspondingly severe up and down-draughts were produced over the many ranges and individual high mountains. The cloud in question was orientated north-west to south-east parallel to the wind, the front edge of the cloud shown on the left of the photograph lying farthest to the north-west and immediately in the lee of a 4,755-ft. peak of the Rock and Pillar Range. This peak, together with several others approaching the same height, lies off to the left of the photograph.

This particular cloud was caused by the strong north-westerly wind, impinging on the westerly side of the Rock and Pillar Range, being deflected upwards and over the high peaks. At the same time the wind would be increased in velocity over the top of the peaks and would descend on the leeward side, before again carrying out a reflected upward movement. It is apparent from the photograph that a wave motion was commenced in the air by the obstructions, resulting in several billows of increasing wave-length. These show up clearly in the cloud formation. The cloud, in spite of the remarkable impression it gives of ranging across the countryside (from right to left of the illustration), is stationary. This is apparent from the typical lens-shaped structures occurring throughout the cloud, and the generally striated form indicates that the wind is actually blowing at high velocity through it.

The cloud has appeared to the lee of the mountain rather than immediately over it, because the first deflection of air over the summit did not raise the billow of air to a sufficient height to produce the adiabatic cooling necessary for condensation to occur, although the temperature of the air above the summit was brought much closer to its dew point. The downward motion in the wave over the lee side of the mountain would dynamically warm the air slightly, thus removing any chance of condensation above the lee slopes, but the upward deflection has continued and been carried eastwards at higher levels. The next billow or wave crest occurred above the foothills shown in the left of the photograph, and the lifting with adiabatic cooling, has this time been sufficient to reduce a large body of air to its dew point. The front edge of the cloud thus marks part of the crest of the air billow, the coldest temperature in the billow occurring at the crest of the cloud. The crest of a second billow appears at the top right of the photograph where the cloud has the appearance of a false cirrus, and is at a very considerable height. The cloud is most dense in the middle of successive billows because of an increase in condensation there, and it thins out to the rear because of progressive evaporation. Individual droplets are quickly evaporated, and the cloud form is only preserved through continuous condensation from the renewed air deflected over the mountain. The evaporation taking place in the cloud is well shown in the clear space (upper right) where the wave motion is curved downward causing dynamical heating.

WHITES AVIATION LTD., NEW ZEALAND

Angle of deviation between the winds at 50 ft. and 2,000 ft. over the North Atlantic Ocean

In an earlier note* an analysis was made of the distribution of the ratio between observed velocities of the wind at 50 ft. and 2,000 ft. as a function of the lapse rate within this layer. The analysis was based on ocean weather ship observations at stations JIG (53°50'N., 18°40'W.) and ITEM (60°00'N., 20°00'W.). This analysis has now been extended to include the deviation in direction between the observed winds at the same two levels.

Table I shows the mean veer in direction of the wind between the surface and 2,000 ft. as a function of the lapse rate.

TABLE I—MEAN ANGLE OF DEVIATION BETWEEN THE WIND AT 50 FT. AND WIND AT 2,000 FT. AS A FUNCTION OF LAPSE RATE

| Lapse rate | Mean angle of deviation | No. of obs. | Notes |
|---------------|-------------------------|-------------|-------------------------------------|
| °F./2,000 ft. | ° | | |
| —9 to 0 | 17·4 | 64 | Isothermal or inversion |
| 1 to 3 | 15·9 | 99 | — |
| 4 to 6 | 11·8 | 178 | Saturated adiabatic, 6°F./2,000 ft. |
| 7 to 9 | 7·2 | 237 | — |
| ≥10 | 7·0 | 121 | Dry adiabatic, 11°F./2,000 ft. |
| | Mean: 10·5 | Total: 699 | |

The observations have been grouped into five classes of lapse rate ranging from inversion and isothermal to superadiabatic conditions. The number of observations upon which the mean values are based is shown for each class interval together with the mean veer in direction for the whole range of observations. Starting with the negative and isothermal lapse rate class the angle of deviation between the wind at 50 ft. and 2,000 ft. shows a steady decrease up to a lapse rate of 7–9°F./2,000 ft. The decrease appears to level off for lapse rates greater than the dry adiabatic. The general decrease with increasing lapse rate is the result of turbulent transfer of momentum downwards from the upper part of the 2,000-ft. layer where geostrophic flow is approached.

The scatter of the individual observations was large but the figures for standard deviations or extremes are not available for these particular observations.

A. H. GORDON

A proposed regional climatic survey

Dr. K. Knoch†, in an interesting article, sets out the need for a detailed climatic survey of Germany, analogous to the geological survey, primarily for the benefit of agriculture but also to aid in planning new settlements, siting buildings connected with the health service, and similar purposes. Such an idea is not new; Dr. Knoch himself in 1930 proposed a local evaluation of the climates of health resorts, and Dr. Weger has applied it to the Rhine wine-growing region. A parallel survey of the productivity of the soil in Germany has been partly completed on a scale of 1:25,000.

*GORDON, A. H.; The ratio between observed velocities of the wind at 50 feet and 2,000 feet over the North Atlantic Ocean. *Quart. J. R. met. Soc., London*, **76**, 1950, p. 344.

†KNOCH, K.; Über das Wesen einer Landesklimaaufnahme. *Z. Met., Potsdam*, **5**, 1951, p. 173.

Detailed mapping of such a complex entity as climate would present many difficulties. The network of official climatological and rainfall stations must form the basis, but apart from rainfall this is quite insufficient for maps on a larger scale than one in a million. Dr. Knoch proposes that the standard for any locality should be the "normal" climate of the region, derived from the climatological atlas of the country, and that local variations from this standard should be classed as: especially favourable, favourable, unfavourable, especially unfavourable. The charting would be done by specially trained field climatologists surveying the country, and using their own interpretations of the topography and visible signs and the local experience of the inhabitants obtained by questioning. The surveying would not involve actual micro-climatic measurements though such measurements would form part of the training of the surveyors.

Put like this the project does not seem to present any insuperable difficulties, but at once the question arises: favourable for what? Dr. Knoch recognizes that different scales would be desirable for different purposes—agriculture, forestry, settlement, building, etc. However, he thinks one general scale would serve for a first approximation, with special mapping of areas of climatic extremes such as frost pockets, very dry or moist sites, windy places and those subject to flooding or erosion. Some preliminary experiments would be necessary, but of the economic value of such maps there could be no question. It would, however, be much better if the scales could be made absolute, instead of relative to each region, and this would not seem to be impossible.

In Great Britain the potential value of such "meso-climatological" studies has long been recognized, especially in the study of frost pockets. For this country there is a detailed rainfall survey, though on a less open scale than Dr. Knoch envisages—half inch to a mile or 1:126,736. The question of a general meso-climatic survey of the country has been considered by the Agricultural Climatology Branch of the Meteorological Office, and the suggestion was made that a series of maps should be prepared to show the probable distribution of the different elements, including soil moisture, over a standard surface, such as bare soil or short grass, with annotations about the effect of different types of vegetation. This would have to be a long-term programme and much preliminary research would be required. The Ministry of Agriculture has in hand a 25-year plan for a soil survey of Great Britain on 1-inch maps, and the climatic survey could well follow, and be linked up with, the soil survey, on the same scale. Once the details of what is wanted had been settled precisely, it should be possible to enlist a good deal of local help from Farm Institutes, Experimental Farms and Agricultural Colleges. Since the prime need at present is to safeguard and increase the food supply, the emphasis must be on the agricultural side, though the maps would also be of great use for other purposes such as health and housing. It might even be practicable, when experience has been gained, to integrate the climatic factors with the help of local crop records, and so build up maps of indices of favourability for special crops—wheat, potatoes, fruit, beet, hay, etc.—which would show at a glance the best crop to plant to suit the soil in any given locality, and so save much wasted effort in trial and error. Even if the idea should turn out to be impracticable, it seems at least to be worth a thought.

C. E. P. BROOKS

HONOURS

The appointment of Mr. W. A. L. Marshall, Senior Experimental Officer in the Meteorological Office, as a Member of the Order of the British Empire was announced in the New Year Honours List.

METEOROLOGICAL OFFICE NEWS

Retirement.—The retirement of Mr. C. W. Lamb, M.C., on November 22, 1951, from an established post in the Meteorological Office brought to an end a period of rather more than 32 years' service. The first three and a half years were spent in Headquarters Branches with a short interlude at Valentia Observatory, but otherwise he worked throughout with the Royal Air Force. For the last eleven years he has been Senior Meteorological Officer at one or other of the Training Groups of the R.A.F.

At a farewell dinner in Mr. Lamb's honour at Headquarters 21 Group, Morton Hall, at which he was presented with a silver spirit-flask, the Air Officer Commanding and Senior Air Staff Officer paid tribute to him both as a Senior Meteorological Officer and as an associate. Later, at an informal meeting at Headquarters, Mr. J. Durward, Deputy Director, on behalf of the Office staff, presented Mr. Lamb with a gold wristlet watch. Mr. Durward emphasized how much the happy personal relations, which Mr. Lamb established with Royal Air Force officers wherever he went, had helped the Office to understand and meet Service requirements. Mr. Durward added that it was not only in his official capacity that Mr. Lamb had made a mark; as a sportsman he had been welcomed wherever his service commitments, at home or abroad, had taken him; though he had engaged in many sports in his time, cricket had been his real love and the game in which he had excelled.

Mr. Lamb has not yet severed his ties with the Office, since he has accepted a temporary appointment in the Branch dealing with special investigations.

Academic successes.—We congratulate Mr. E. T. Stringer, who has been awarded the degree of Ph.D. by the University of Birmingham, also Messrs. P. B. Bonner, H. J. G. Groom and P. D. de la Mothe who were successful in the Intermediate B.Sc. examination of the London University held in November 1951.

Sports.—*Swimming.*—Mr. S. W. Lewis has added to his achievements during the current season by taking first place in both the Air Ministry 100 yards' free style and back-stroke championships, and places in numerous other events. He represented Fighter Command in the recent R.A.F. championships. He is also a water-polo player and his services are much in demand by local teams. Mr. S. W. Lewis is a younger brother of Mr. A. F. Lewis, at present serving in the Falkland Islands Dependencies, who is also a Civil Service and Air Ministry championship swimmer.

Mr. A. R. Hosker gained third place in the Civil Service plunging championship held in London on November 15.

Cross-country running.—In the Air Ministry cross-country championship held at Chingford on November 24, the Office gained 1st and 3rd places in the team race. In the individual event Mr. D. H. Owers was second, Mr. G. F. Burton third and Mr. B. T. Flatley fourth.

Social events.—More than 200 members of the staff, their families and friends came to the Christmas Party on December 18. The highlights of the evening were a conjuring turn by Mr. J. F. Thornton and Spanish dancing by Miss Désirée Jestico and company. Games organized by Mr. G. F. Tindall and dancing, enlivened by swing music played by Mr. H. D. Hoyle, occupied the rest of the evening.

The Social and Sports Committee announce that the Twentieth evening party (Annual Soirée) is to be held from 7.30–11.00 p.m. on Saturday, March 8, in the North Hall, Victoria Halls, Bloomsbury Square, London, W.C.1, and hope to see a large gathering of the staff with their families and friends.

WEATHER OF DECEMBER 1951

The lowest mean pressure of 984 mb. occurred near south-west Iceland. Mean pressure increased south-eastwards, being 1000 mb. from latitude 55°N. in the North Atlantic to central Scandinavia and 1020 mb. from the Azores to central Europe. Mean pressure in the Mediterranean area and North Africa was generally between 1020 and 1025 mb.

Mean pressure was above normal in Europe and the North Atlantic between latitudes 40°N. and 50°N., the excess being about 5 mb. in the Balkans and central Mediterranean. Mean pressure was below normal north of latitude 55°N., the greatest deficit of 17 mb. occurring south-west of Iceland.

Mean temperature was about 15°F. in northern Scandinavia, 30–35°F. in eastern Europe, 35–40°F. in southern Scandinavia, 40–50°F. in the remainder of Europe, 50–55°F. in the Mediterranean region and 70–80°F. in west Africa. Temperature was mainly above normal, the largest excess being about 9°F. in southern Scandinavia.

In the British Isles the weather was dry in the east and south and wet in the west. It was mainly mild, apart from a cold spell from the 10th to the 13th and sunshine exceeded the average except locally in the north-west. Severe gales occurred at times, notably on the 4th–5th, 27th, 28th and 30th.

In the opening days pressure was low to the north-east and high to the west of the British Isles; north-westerly to westerly winds prevailed with showers and sunny periods. During the night of the 2nd–3rd a deep depression approached south-west Iceland and troughs of low pressure subsequently crossed the British Isles causing rain generally. On the 4th another intense Atlantic depression moved to south-west Iceland and thence east to Norway; more rain occurred in the west and north of the British Isles on the 4th and throughout the country on the 5th, while gales were recorded in the west and north, being severe in the Shetlands where a gust of 78 kt. was registered. On the 6th and 7th a small secondary depression moved from north-west Ireland to north-east France; rain fell in most parts but with appreciable sunshine in England. From the 7th to the 9th a deep depression moved from south-west Iceland to a position off south-west Norway. Showery weather prevailed on the 7th, with long bright periods in England and Wales. On the 8th rain fell generally and was heavy locally (2.30 in. at Borrowdale, Cumberland), with

snow or sleet in west and north Scotland and a thunderstorm at Castle Archdale, County Fermanagh. On the 9th there were wintry showers and appreciable snow occurred in parts of Scotland. Gales were registered locally in the west on the 8th and 9th. The northerly winds of Arctic origin behind this system caused a considerable drop in temperature and in the wedge which followed keen frost occurred, notably from the 11th to 13th; screen temperature fell to 13°F. at Eskdalemuir and 14°F. at Dyce on the 11th. During this spell conditions were mainly dry, apart from slight rain in the west and north. Records of bright sunshine were good generally on the 10th and in parts of England and Wales on the 11th, but considerable fog occurred in eastern and midland districts of England on the 12th to the 14th, the fog being dense in places on the evening of the 13th and throughout the night. A period of very mild weather followed with deep Atlantic depressions moving towards south-west Iceland and a mild south-westerly to southerly air stream covering the British Isles. Rain occurred daily in the west and north but in south and east England the rainfall was generally slight, though the skies were mainly cloudy. On the 19th and 20th a shallow secondary depression off south-west Ireland moved north-east across Ireland to Scotland to the west of Norway; rain fell in most places and was heavy locally in the north-west. A very disturbed period ensued which lasted until the end of the month. On the 23rd a deep Atlantic depression moved north-north-east to Iceland and on the 24th a secondary depression moved across Ireland and northern England to the North Sea. Gales occurred locally and rain fell generally, being heavy in some places (2·32 in. at Blaenau Hydfer, Brecon, on the 23rd and 2·72 in. at Dunsop Houses and 2·26 in. at Oughtershaw Hall, both in Yorkshire, on the 24th). On the 25th showery weather prevailed, with local thunderstorms in the west, but the 26th was mainly sunny with scattered showers. On the 27th an intense Atlantic depression moved east-north-east to mid Scotland and later turned north, and on the 28th another deep depression moved east-south-east from south-west Ireland across Cornwall to France. Widespread gales occurred, severe in places in the west; a gust of 85 kt. was registered at Scilly on the 28th. On the 30th another intense depression moved east-north-east along our northern seaboard and an even stronger gale occurred in Scotland, the wind gusting to 94 kt. at Millport, Bute, and 85 kt. at Tiree. Snow fell in west Scotland and Ireland on the 31st and in northern England during the following night.

The general character of the weather is shown by the following provisional figures:—

| | AIR TEMPERATURE | | | RAINFALL | | SUNSHINE |
|-----------------------|-----------------|--------|------------------------------------|------------------------|-------------------------------------|------------------------|
| | Highest | Lowest | Difference from average daily mean | Per-centage of average | No. of days difference from average | Per-centage of average |
| | °F. | °F. | °F. | % | | % |
| England and Wales ... | 59 | 13 | +18 | 100 | — 1 | 123 |
| Scotland ... | 58 | 7 | +08 | 123 | +3 | 120 |
| Northern Ireland ... | 56 | 23 | +09 | 117 | 0 | 95 |

RAINFALL OF DECEMBER 1951

Great Britain and Northern Ireland

| County | Station | In. | Per cent. of Av. | County | Station | In. | Per cent. of Av. |
|-----------------|---------------------------|-------|------------------|--------------------|---------------------------|-------|------------------|
| <i>London</i> | Camden Square ... | 1·80 | 75 | <i>Glam.</i> | Cardiff, Penylan ... | 3·51 | 70 |
| <i>Kent</i> | Folkestone, Cherry Gdn. | 2·57 | 80 | <i>Pemb.</i> | Tenby ... | 4·25 | 85 |
| <i>"</i> | Edenbridge, Falconhurst | 3·12 | 95 | <i>Card.</i> | Aberdovey (Plas Penhelig) | 7·12 | 150 |
| <i>Sussex</i> | Compton, Compton Ho. | 3·98 | 95 | <i>Radnor</i> | Tyrmynydd ... | 8·71 | 106 |
| <i>"</i> | Worthing, Beach Ho. Pk. | 2·74 | 91 | <i>Mont.</i> | Lake Vyrnwy ... | 11·96 | 169 |
| <i>Hants.</i> | Ventnor, Cemetery ... | 2·83 | 84 | <i>Mer.</i> | Blaenau Festiniog ... | 18·34 | 145 |
| <i>"</i> | Bournemouth ... | 2·89 | 74 | <i>Carn.</i> | Llandudno ... | 5·42 | 187 |
| <i>"</i> | Sherborne St. John ... | 2·29 | 70 | <i>Angl.</i> | Llanerchymedd ... | 7·49 | 171 |
| <i>Herts.</i> | Royston, Therfield Rec. | 1·39 | 60 | <i>I. Man</i> | Douglas, Borough Cem. | 6·77 | 137 |
| <i>Bucks.</i> | Slough, Upton ... | 1·49 | 59 | <i>Wigtown</i> | Port William, Monreith | ... | ... |
| <i>Oxford</i> | Oxford, Radcliffe ... | 1·56 | 63 | <i>Dumf.</i> | Dumfries, Crichton R.I. | 7·37 | 172 |
| <i>N'hants.</i> | Wellingboro', Swanspool | 1·75 | 74 | <i>"</i> | Eskdalemuir Obsy. ... | 9·43 | 135 |
| <i>Essex</i> | Shoeburyness ... | 1·35 | 73 | <i>Roxb.</i> | Kelso, Floors ... | 1·64 | 71 |
| <i>"</i> | Dovercourt ... | 1·77 | 82 | <i>Peebles</i> | Stobo Castle ... | 5·02 | 132 |
| <i>Suffolk</i> | Lowestoft Sec. School ... | 1·50 | 64 | <i>Berwick</i> | Marchmont House ... | 1·22 | 43 |
| <i>"</i> | Bury St. Ed., Westley H. | 1·66 | 69 | <i>E. Loth.</i> | North Berwick Res. ... | 1·33 | 62 |
| <i>Norfolk</i> | Sandringham Ho. Gdns. | 1·40 | 55 | <i>Mid'l'n.</i> | Edinburgh, Blackf'd. H. | 2·45 | 105 |
| <i>Wilts.</i> | Aldbourne ... | 2·81 | 87 | <i>Lanark</i> | Hamilton W. W., T'nhill | 5·75 | 133 |
| <i>Dorset</i> | Creech Grange... .. | 3·75 | 85 | <i>Ayr</i> | Colmonell, Knockdolian | 7·46 | 134 |
| <i>"</i> | Beaminster, East St. ... | 3·68 | 77 | <i>"</i> | Glen Afton, Ayr San. ... | 10·60 | 166 |
| <i>Devon</i> | Teignmouth, Den Gdns. | 2·95 | 70 | <i>Bute</i> | Rothsay, Ardenraig ... | 9·08 | 167 |
| <i>"</i> | Cullompton ... | 3·30 | 75 | <i>Argyll</i> | Morvern, Drimnin ... | 10·93 | 139 |
| <i>"</i> | Ilfracombe ... | 4·98 | 103 | <i>"</i> | Poltalloch ... | 10·29 | 171 |
| <i>"</i> | Okehampton, Uplands | 6·12 | 87 | <i>"</i> | Inveraray Castle ... | 14·92 | 150 |
| <i>Cornwall</i> | Bude, School House ... | 3·66 | 84 | <i>"</i> | Islay, Eallabus ... | 8·26 | 139 |
| <i>"</i> | Penzance, Morrab Gdns. | 4·97 | 87 | <i>"</i> | Tiree ... | 7·28 | 139 |
| <i>"</i> | St. Austell ... | 5·02 | 82 | <i>Kinross</i> | Loch Leven Sluice ... | 4·27 | 108 |
| <i>"</i> | Scilly, Tresco Abbey ... | 4·54 | 97 | <i>Fife</i> | Leuchars Airfield ... | 2·07 | 84 |
| <i>Glos.</i> | Cirencester ... | 2·63 | 79 | <i>Perth</i> | Loch Dhu ... | 12·79 | 127 |
| <i>Salop</i> | Church Stretton ... | 3·34 | 95 | <i>"</i> | Crieff, Strathearn Hyd. | 4·85 | 108 |
| <i>"</i> | Shrewsbury, Monkmoor | 2·47 | 101 | <i>"</i> | Pitlochry, Fincastle ... | 4·80 | 119 |
| <i>Worcs.</i> | Malvern, Free Library | 2·66 | 96 | <i>Angus</i> | Montrose, Sunnyside ... | 1·77 | 64 |
| <i>Warwick</i> | Birmingham, Edgbaston | 2·77 | 103 | <i>Aberd.</i> | Braemar ... | 3·48 | 108 |
| <i>Leics.</i> | Thornton Reservoir ... | 1·89 | 74 | <i>"</i> | Dyce, Craibstone ... | 2·27 | 67 |
| <i>Lincs.</i> | Boston, Skirbeck ... | 1·21 | 56 | <i>"</i> | Fyvie Castle ... | 2·53 | 74 |
| <i>"</i> | Skegness, Marine Gdns. | ·88 | 40 | <i>Moray</i> | Gordon Castle ... | 2·31 | 86 |
| <i>Notts.</i> | Mansfield, Carr Bank ... | 2·29 | 79 | <i>Nairn</i> | Nairn, Achareidh ... | 2·98 | 145 |
| <i>Derby</i> | Buxton, Terrace Slopes | 7·77 | 137 | <i>Inverness</i> | Loch Ness, Garthbeg ... | 7·36 | 160 |
| <i>Ches.</i> | Bidston Observatory ... | 3·47 | 131 | <i>"</i> | Glenquoich ... | 19·67 | 134 |
| <i>Lancs.</i> | Manchester, Whit. Park | 5·50 | 170 | <i>"</i> | Fort William, Teviot ... | 15·26 | 150 |
| <i>"</i> | Stonyhurst College ... | 12·57 | 259 | <i>"</i> | Skye, Duntuil ... | 9·18 | 147 |
| <i>"</i> | Squires Gate ... | 6·57 | 211 | <i>R. & C.</i> | Tain, Tarlogie House ... | 3·52 | 124 |
| <i>Yorks.</i> | Wakefield, Clarence Pk. | 1·97 | 81 | <i>"</i> | Inverbroom, Glackour... | 10·71 | 146 |
| <i>"</i> | Hull, Pearson Park ... | 1·76 | 73 | <i>"</i> | Applecross Gardens ... | 10·29 | 160 |
| <i>"</i> | Felixkirk, Mt. St. John | 2·48 | 103 | <i>"</i> | Achnashellach ... | 14·64 | 154 |
| <i>"</i> | York Museum ... | 1·98 | 88 | <i>"</i> | Stornoway Airfield ... | 6·19 | 104 |
| <i>"</i> | Scarborough ... | 2·01 | 84 | <i>Suth.</i> | Loch More, Achfary ... | ... | ... |
| <i>"</i> | Middlesbrough... .. | 3·26 | 168 | <i>Caith.</i> | Wick Airfield ... | 2·44 | 79 |
| <i>"</i> | Baldersdale, Hury Res. | 7·98 | 215 | <i>Shetland</i> | Lerwick Observatory ... | 6·95 | 145 |
| <i>Nor'l'd.</i> | Newcastle, Leazes Pk.... | 1·51 | 64 | <i>Ferm.</i> | Crom Castle ... | 4·38 | 106 |
| <i>"</i> | Bellingham, High Green | 3·76 | 104 | <i>Armagh</i> | Armagh Observatory ... | 4·30 | 137 |
| <i>"</i> | Lilburn Tower Gdns. ... | 1·74 | 66 | <i>Down</i> | Seaford ... | 3·58 | 87 |
| <i>Cumb.</i> | Geltsdale ... | 5·61 | 147 | <i>Antrim</i> | Aldergrove Airfield ... | 3·88 | 113 |
| <i>"</i> | Keswick, High Hill ... | 12·27 | 183 | <i>"</i> | Ballymena, Harryville... | 4·98 | 112 |
| <i>"</i> | Ravenglass, The Grove | 6·82 | 149 | <i>L'derry</i> | Garvagh, Moneydig ... | 5·70 | 142 |
| <i>Mon.</i> | Abergavenny, Larchfield | 4·89 | 110 | <i>"</i> | Londonderry, Creggan | 5·61 | 128 |
| <i>Glam.</i> | Ystalyfera, Wern House | 7·18 | 86 | <i>Tyrone</i> | Omagh, Edenfel ... | 4·65 | 110 |