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KINEMATICAL FEATURES OF DEPRESSIONS

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§ 1—INTRODUCTION

The object of this paper is to examine mainly the kinematical features of some depressions and some high pressure systems. The data desirable for such an examination would be those provided by a network of anemographs, all perfectly exposed, the network becoming closer towards the principal tracks of the depressions. Such a network is never likely to be available, since the principal tracks lie between Scotland and Iceland or even further north. Within recent years the erection of pressure tube anemographs with quite open exposures at Lerwick, Tiree, Butt of Lewis, and Bell Rock has, however, provided additional wind data of considerable value. The two last were erected in 1929 following on a recommendation of the Advisory Committee for the Meteorological Office, Edinburgh. This recommendation had specially in view the provision of data for the study of the depressions arriving from the North Atlantic. Funds for the erection of the additional instruments and for clerical assistance were provided from the Research Vote of the Meteorological Office and made this work possible.

It might be thought that with these records, in addition to those already existing in other parts of the British Isles, the selection of typical depressions for a study of the kinematical field would be a simple matter. Even with some years of record available, this is by no means the case. Most primary depressions cover an area much larger than the British Isles, most pass to northward and many have the complication of secondaries with resulting pressure fields that are anything but simple. The time required to study even one complete case is also considerable. For these reasons the method of investigation has been to examine in great detail two depressions for which suitable data were available, to draw such inferences as appeared to be supported by these data and to test these inferences separately by reference to other cases for which the data permitted partial studies to be made.

Before proceeding to an account of these studies it is desirable to define the position and point of view from which they start. The primary object was to examine the air movement in depressions, allowing that discontinuities of movement and density, without doubt, in general exist; thus it was natural in the first place to see what, if any, general average relationship could be established between air movement and distance from the centre of a depression. The behaviour of the polar air can be studied in some detail because the polar air is always next the ground. For tropical air the relationships cannot always be studied from ground observations, but only in so far as a warm sector exists. In any case, all through the paper, observations are classified according to the air masses to which they belong.

In view of the fact that a considerable section of the paper is devoted to the discussion of the rotational features in cyclones it is relevant to refer first to discussions which took place a number of years ago with contributions by Aitken, W. H. Dines, Rayleigh and Shaw. In 1900 Aitken communicated two papers (1)* (2), and in 1915 a third paper (3) to the Royal Society of Edinburgh on the " Dynamics of Cyclones and Anticyclones ". The papers were illustrated by a series of experiments. The first experiment was to illustrate that if a low pressure area is formed in air or water, no circular or vortical movement will follow unless the air or water has initially a movement relative to the centre of low pressure. The mechanical illustration given on this point by Aitken illustrated two dynamical principles, " first, the constancy of momentum of a rotating system in virtue of which the velocity of a given portion increases as it approaches nearer the centre of rotation ; and,

* The numbers in brackets refer to the bibliography on p. 40.

in the second place, there is increase in the kinetic energy as the rotating water falls to lower levels." He emphasized further that when there is relative movement initially so that the air or water is prevented from moving in radially to the centre of low pressure, but moves spirally so that the inflow is retarded by the centrifugal force then " a greater fall of pressure results, and the energy of the cyclone is increased ; and in addition to this we shall see later that it adds greatly to the efficiency of cyclones considered as circulating engines." By means of a flat circular vessel, with a central outlet in the form of a short pipe he showed that the same amount of water took a half longer to empty when even a slight initial movement was provided to cause it to form a cyclone when emptying.

The experiments in air, though on a miniature scale, are so important as to warrant fuller description. A circular disc 76 cm. in diameter, with three legs 15 cm. high, was placed on a table, thus leaving an air space of 15 cm. between the disc and the table. From the centre of the disc rose a thin metal tube 15 cm. in diameter and about 2m. high. To produce up-draught three small gas jets were fitted inside the tube near the lower end. Light vanes or the fumes of hydrochloric acid and ammonia were used to show the air movement at various points of the area and at different heights above the table under different experimental conditions. If there are initially no air currents in the room then when the gas jets are lit the fumes " move radially towards the hot chimney, moving upwards in even curves, but showing no tendency to rotate round the centre." Even with an initial air current equally strong at all points no cyclonic movement is generated, but if we " cut off the current from one side of the area and allow it to blow on the other, then we have the conditions necessary for producing vortex motion under the chimney. If we examine the fumes rising under these new conditions, it will be seen that they no longer move radially but are in violent cyclonic motion, swirling round and round in the direction given by the tangential current, the rising fumes forming graceful ascending spirals. So strong is the circular motion that at times the gas in the chimney is heard flaring as in a strong wind."

Further—" If there is no cyclonic motion formed when the gas is lit, any light objects lying on the table are not disturbed by the radially moving air, but if a good cyclonic circulation is set up, then any light bodies . . . are seen to be lifted up and tossed about." Coming to questions of detail, " one very marked result . . . is that the air . . . near the surface of the table moves much more radially than the air higher up, and also that the air lying on the surface is drawn into the very core of the cyclone, up which it rises in a rapidly-circling path of small diameter, whilst the air higher up comes towards the centre along a wider rising spiral path, and forms the outer lining of the cyclonic tube. The lower air keeps near the surface until it arrives near the centre of the cyclone and then rises . . . The reason . . . is very obvious. The air near the ground, or surface of the table in this case, has less tangential movement than the air higher up, owing to its motion being retarded by friction. The result of this is that whilst the greater centrifugal force of the upper air keeps it back against the low pressure in the cyclone, the lower air as it moves nearly radially offers but little resistance to the in-draught. Hence . . . it is drawn into the very centre." The data analysed in the present memoir demonstrate that the full-scale cyclones examined can be regarded as having certain points of analogy with the miniature models of Aitken, provided we keep in mind that in the former the centrifugal force becomes of relatively small importance and that the movement is not a balance between pressure gradient and centrifugal force, with molecular friction added at the lower bounding surface, but rather between pressure gradient and the deflecting force due to the earth's rotation, with the larger scale eddy turbulence as a connecting link between the upper air and the frictional effects of the earth's surface ; and also that the angular rate of rotation is almost negligibly slow by comparison with the model cyclones. It is shown that with these substitutions it becomes legitimate to apply some of Aitken's reasoning to certain meteorological situations.

A further point illustrated by Aitken (by means of water vortices) in his first series of experiments is that the direction of the movement of the cyclone as a whole is that of the " tangential current ".

As regards the experiments in air, those in Aitken's first series were, as he admitted, "under very artificial conditions, the centre of low pressure being kept in a fixed position and the ascending column of air protected by solid walls." The second series was devoted to motion in free air. The apparatus used consisted of a small platform the surface of which could be heated to supply the hot air required to make the cyclones. The platform was a shallow tin box 75 cm. square and 1 cm. deep provided with two pipes, one for the entrance of steam to heat it, and another for draining away the condensed water. A wet piece of cloth was laid on the hot surface of the platform and this gave rise to steam which enabled the eye to follow the movements of the air. When a draught of air was arranged across the heated area, and one side shielded by means of a screen, a cyclone was formed at a short distance from the edge of the screen ; as soon as formed the cyclone began to travel away across the hot area in the direction of the tangential air current and before this cyclone had gone far another formed, and so on, cyclone following cyclone as long as there was a heated area and a cross current. To show that the cyclones were not simply eddies from the vertical edge of the screen, a screen with the edge shaped like a magnified comb was introduced with similar results. Aitken remarked, "When the air from the natural draught in the room flows over the hot area at the same velocity at all parts, the rising steam does not ascend far, but keeps close to the hot surface, and is irregular in its movements. But when a cyclone is formed, most of the steam is collected into a rapidly whirling vertical column, which ascends to a considerable height—to a metre or more above the hot surface, and often presents the appearance of a well defined column as it rises through the clearer air."

"In making these experimental cyclones, it was noticed that there must be a definite relation between the amount of heating and the velocity of the cross current. If the heating be slight the cross current must be slow, otherwise the cyclonic movement will not be properly formed owing to the weakness of the ascent, before it is swept off the experimental area ; whilst with the hotter air a stronger current may be permitted, with the result that a more violent cyclonic movement is produced, which penetrates the upper air to a greater height." Similar points were demonstrated with different types of apparatus.

In an additional note Aitken deals with the possibility of determining, from differences in air movement, "whether the cyclones in our atmosphere are convectionally or dynamically driven." In a convectionally driven cyclone the circulation should be "spirally inwards, whereas in a dynamically driven one we would expect it to be spirally outwards," except that in our atmosphere, owing to the motion being retarded by the surface of the earth, there might in the latter case also be in-draught near the surface. Aitken considered that cloud observations on the whole provided evidence in favour of the convectionally driven theory, but proceeded to point out another and more definite way in which we can distinguish between dynamically and convectionally driven cyclones.

"In a convectionally driven cyclone the velocity of movement of the air, both linear and angular, increases from the outside towards the centre, whereas in a dynamically driven one the the reverse is the case, the air in the outer parts moving quicker than the air in the centre." Again Aitken considered that on the whole the meteorological evidence was in favour of the idea that cyclones in the atmosphere are convectionally driven. His reasoning on these points is not, however, convincing and he seems to have overlooked the fact that according to his own experiments the model cyclones depend both for their inception and their continued existence, not solely on the "convectional drive" but also on the "dynamical drive" of the tangential current.

One of the results reached in the present memoir leads to the conclusion that in the cyclones of temperate latitudes a dual causation is fundamental—a convectional inception near the ground, a dynamical drive from higher levels.

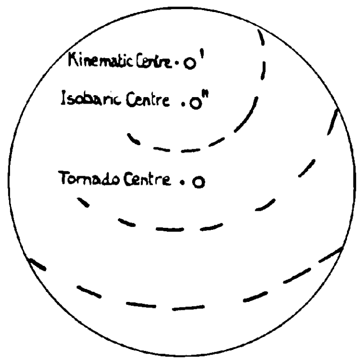
Aitken's third paper (3) appeared in 1915, and was prompted by papers by W. H. Dines in the *Journal of the Scottish Meteorological Society* for 1914 (4), and elsewhere (too well known to require recapitulation here) dealing with the observations from ballons sondes. Two new items of knowledge, namely, that the troposphere on the average is colder and the tropopause lower in cyclones than in anticyclones, appeared to make the convectional theory " utterly untenable ".

With regard to the first, Aitken pointed out that the lower pressure in cyclones more than compensated for the lower temperature, so that on the whole, the air density, level for level, in the troposphere was still less in cyclones than in anti-cyclones. As a preliminary to dealing with the second difficulty he called attention to a well-known physical principle adequately demonstrated in the laboratory and in engineering practice and inevitably, in his view, applicable in the atmosphere. " The points to be kept in mind," he says, " are that gases moving from a higher to a lower pressure lose potential energy and gain velocity, and that gases having velocity gain pressure while losing their velocity." (The complete principle is really that, taking any mass of gas, the total energy, which is partly kinetic, partly potential, and partly intrinsic, changes at a rate equal to that at which work is done on the boundary by pressure from without. Some illustrations of the applicability of the principle in the case of polar surface air currents moving from high to low or low to high pressure were given by the writer a number of years ago (5).) Aitken's idea was that air which moved from regions of higher pressure into cyclones and ascended gained speed in proportion as it lost pressure and that ultimately " while its centrifugal force confers upon it a quasi-horizontal pressure which enables it to act against the side pressure, it has no corresponding vertical pressure, hence the descent of the stratosphere in that area. On the other hand, the low-pressure air with high velocity flowing out of the upper part of the cyclone towards the anti-cyclone loses its velocity and regains sufficient pressure to enable it to enter the upper part of the anticyclone, where it gives rise to an increase of pressure which tends to push the isothermal layer higher than the mean. It would thus appear that the change of energy from potential to actual and back again to potential gives the explanation of the lowering of the isothermal layer over cyclones, and its rising over anticyclones." Aitken admitted, however, that if these ideas were correct the cyclone must receive energy from outside sources and that it was not easy to see whether " convectional effects, the latent heat of water vapour and increased absorption of solar radiation " could suffice.

Aitken's experiments moved Rayleigh (6) to contribute to the Royal Society a mathematical paper on the theory of fluid revolving about a vertical axis ; the rotation of the earth was, however, neglected. Rayleigh afterwards encouraged Aitken to further experiment in a letter dated June 7, 1917 expressing some of his own difficulties and suggesting that it was a case where careful physical experiment and observation might accomplish more than calculation.

On June 21, 1917 in a paper to the Royal Society on " Revolving Fluid in the Atmosphere " Shaw (7) " explained that a disc of travelling revolving fluid would be represented on a map, not by a series of circular isobars like a travelling cyclone, but by a distortion of the isobars of a large cyclone such as we are accustomed to call a small secondary . . . Two examples of revolving fluid of this character were suggested and represented by the weather maps for March 24, 1895, when a very destructive small secondary, a very large column of revolving fluid, swept across the British Isles from the south-west of Ireland to Norfolk, and for October 27, 1913, when a most violent tornado of very narrow dimensions did great damage in South Wales . . . we may accordingly call the centre of ' revolving fluid ' a tornado centre to distinguish it from the centre of a travelling cyclone. The difference between the motion in the two cases is of fundamental importance in meteorology. In the case of the tornado we have a disc of fluid revolving in rings round its axis, while by some means the whole is simultaneously transported bodily along, with the velocity of translation of the tornado ; and in the case of the travelling cyclone we have a distribution of winds which is at the moment arranged symmetrically in rings, but which, for a reason which will be explained later, is not free to go on moving in the circles which it marks out but develops a like distribution about a new centre in advance of the old. Of course, if the centre of the cyclone is stationary, the motion persists in the circles, and we have a case of fluid revolving about a fixed axis."

The above is a quotation from *Geophysical Memoirs* No 12 where Shaw (8) goes into greater detail. He proposed that if a disc of air is rotating like a solid with uniform angular velocity ζ and the whole disc at the same time travelling from west to east with velocity V, then the centre about which the relative motion is symmetrical should be called the tornado centre, and the centre about which the instantaneous velocity is symmetrical should be called the kinematic centre. The latter is at a distance V/ζ northward of the former. Thirdly, there is still the isobaric centre, which he proposed to call the dynamic centre. The position of this centre depends upon the earth's rotation and it would lie at a distance $(V/(2\ \omega \sin \phi + \zeta))$ southward of the kinematic centre. The positions are illustrated diagrammatically below.



$$00' = V/\zeta.$$
$$0'0'' = V/(2\ \omega \sin \phi + \zeta).$$

Shaw considered that "colourable examples . . . might be adduced from actual maps, and the recognition of the dissociation of the kinematic centre from the centre of isobars makes the regularity more apparent, but the phenomena of the more central region which may be affected by convection are still a subject rather of conjecture than of observation." Here and in the "Manual of Meteorology" he treated several examples of the nature of secondary depressions.

Aitken returned to the controversy in a fourth paper (**9**), this time to the Royal Society of London, but an early statement in this paper suggests that he ignores the effect of the earth's rotation in determining the run of the isobars and takes account only of the centrifugal force of the wind. His chief point, however, is that the mathematical assumption that a cyclone might be treated as an eddy with a closed lower end is, in general, so wide of the truth that results based on it would not be applicable in nature. He wishes to insist that the incoming (surface) air "does not belong to the cyclone, and does not possess the same motion as the air in the cyclone. It is new matter coming in which will ultimately take up cyclonic motion, but approaching the centre cannot be considered to have true cyclonic and translational motion. . . . If the cyclone were a closed system, it would, in pushing its way through the atmosphere, cause the streamlines of the surrounding air to be quite different from what they are. If we are to find winds whose direction of motion relatively to the earth is a compound of their rotational and translational velocities, then we must look for them at higher elevations, where the air has acquired a true cyclonic motion." He objects to the analogue of the vortex ring even for eddies and small revolving storms, because these are open at the lower end and need not be capped at the upper end and thus can be fed and grow. The latter part of Aitken's paper is devoted to "the penny and the pin" forms of revolving fluid. These, he thinks, cannot be distinct types of motion because a tropical cyclone of the "pin" diameter on the coast of Florida can, after crossing the Atlantic, acquire the "penny" diameter. Experimentally he showed, by means of a siphon tube and a water cyclone, how by increasing the rate of the upward outflow the cyclone could be contracted to small diameter, and by decreasing the outflow the cyclone could be expanded and made less violent; also that with a steep gradient the expanded type appeared with widening at the lower end, whilst with a slight gradient the narrower vertical type appeared.

Though the above discussion on revolving fluid and particularly on Aitken's experiments has been given in advance of the discussion of the data dealt with in the body of this memoir that was not the order followed in the course of the investigation. Rather it was that the results of the investigation as they emerged emphasized the importance of certain points upon which Aitken had greatly insisted and of other points, notably the details of the central region of cyclones, to which Shaw called attention as not yet having been adequately investigated by study of the meteorological data. It was decided from the beginning to make no attempt to correct theoretically either the speed or the direction of surface winds, and in the first instance, to make no assumptions as to balanced relationships with the barometric gradient or even with that plus isallobaric conditions, and not to neglect the possibility of vertical motion being present. The earlier part of the memoir (§2–§8) is a study of surface winds as recorded at well-exposed stations, upper winds as measured by pilot balloon ascents, or directions of cloud movements as observed at various stations.

To complete the theoretical discussion on revolving fluid, reference should be made to a paper by Brunt (10) which amplifies Rayleigh's results by taking account of the rotation of the earth. Rayleigh had shown that if fluid is removed at the axis of a body rotating as a solid with angular velocity ζ the effect of convergence towards the axis is to superpose upon the rotation as a solid body a simple vortex of intensity A, so that the speed at any point is given by

$$v = \zeta r + A/r$$

where r is the distance from the axis of rotation. Brunt showed that the effect of the rotation of the earth was to increase the strength of the superposed vortex by the inclusion of a term depending on $\omega \sin \phi$. For example, if the effect of the removal of the fluid is to cause a cylinder of radius R_o to shrink to radius R then the speed is given by

$$v = \zeta r + (\zeta + \omega \sin \phi)\ (R_o^2 - R^2)/r$$

Thus the intensity of the added vortex, other things being equal, is proportional to the total amount of fluid removed from the region of the axis. The present memoir deduces from observations a result in general agreement with this mathematical result, namely that in two October depressions (1929 and 1930) of about the same depth as measured by the lowest isobars on the synoptic chart (and this roughly is an indication that in some earlier stage the same amount of " fluid " had been removed from each), but otherwise not conspicuously similar, the " outer vortices " are of closely similar intensity.

In addition to the question of revolving fluid a second matter to which reference is made in the memoir is that of cell action. The dynamical theory of this was worked out by the late Lord Rayleigh (11) in 1916. If, for example, a large flat dish containing a fluid is heated from the bottom, the first effect is to render the bottom layer of fluid warmer and thus lighter than the layer next above it and thus to disturb the equilibrium of the vertical arrangement of the fluid. Rayleigh discussed the motion which would ultimately result. It may be described as a set of cells arranged side by side, the fluid rising in the middle of each cell, and descending round the walls. In Rayleigh's problem for motion in water, the horizontal diameter of each cell was about three times the depth of the fluid. As Jeffreys has pointed out, any reduction of pressure arising from this process alone would be of too small an order of magnitude to correspond to that found in cyclones.

The cell theory has, however, been successfully applied by Walker (12) and Mal (13) to explain the forms of certain stratified clouds. It has also been extended by Durst (14) to explain a certain type of wind structure found over level country. The cells found by Durst are of the order of 3 to 5Km. long and 1 to 2Km. deep. More recently the present writer (15) in a discussion of wind structure as recorded at the uniquely exposed anemograph on the Bell Rock Lighthouse, has provided evidence that the wind structure characteristic of these cells is found in highly developed form in unstable polar currents over the sea. In this case the cells require to be of the order of 25 to 30Km. in horizontal diameter and perhaps as much as 4Km. deep.

A third matter to which reference is made is that of waves in the atmosphere. V. Bjerknes put forward the proposition that the cyclones of temperate latitudes originate as waves in the polar front considered as a slightly sloping surface of discontinuity between cold and warm currents. Such waves, on a relatively small scale, were proved possible dynamically by Helmholtz. The present writer (16) has discussed this matter also, in two papers, and has shown examples which fit in with the dynamical theory in the sense that they show both the pressure and the wind effects which theory would indicate to be expected at ground level and also fit in with the cloud effects to be anticipated in higher levels. Further, in the Bell Rock memoir to which reference has already been made, he has shown that such waves are in fact associated with surfaces of discontinuity or isothermal layers in the upper air and that they only occur in characteristically stable conditions; also their period so far as can be observed never exceeds a magnitude of the order of one or two hours, nor their length an order of 30Km. It has in fact never been demonstrated that any waves of irrotational type can develop to phenomena with the dimensions and characteristics of full-scale cyclones.

§ 2.—THE DEPRESSION OF OCTOBER 1–3, 1929.—WIND IN RELATION TO DISTANCE FROM ISOBARIC CENTRE

The first case examined was the depression of October 1–3, 1929 (Fig. 1). The position of the low pressure centre, i.e. the isobaric centre or dynamic centre

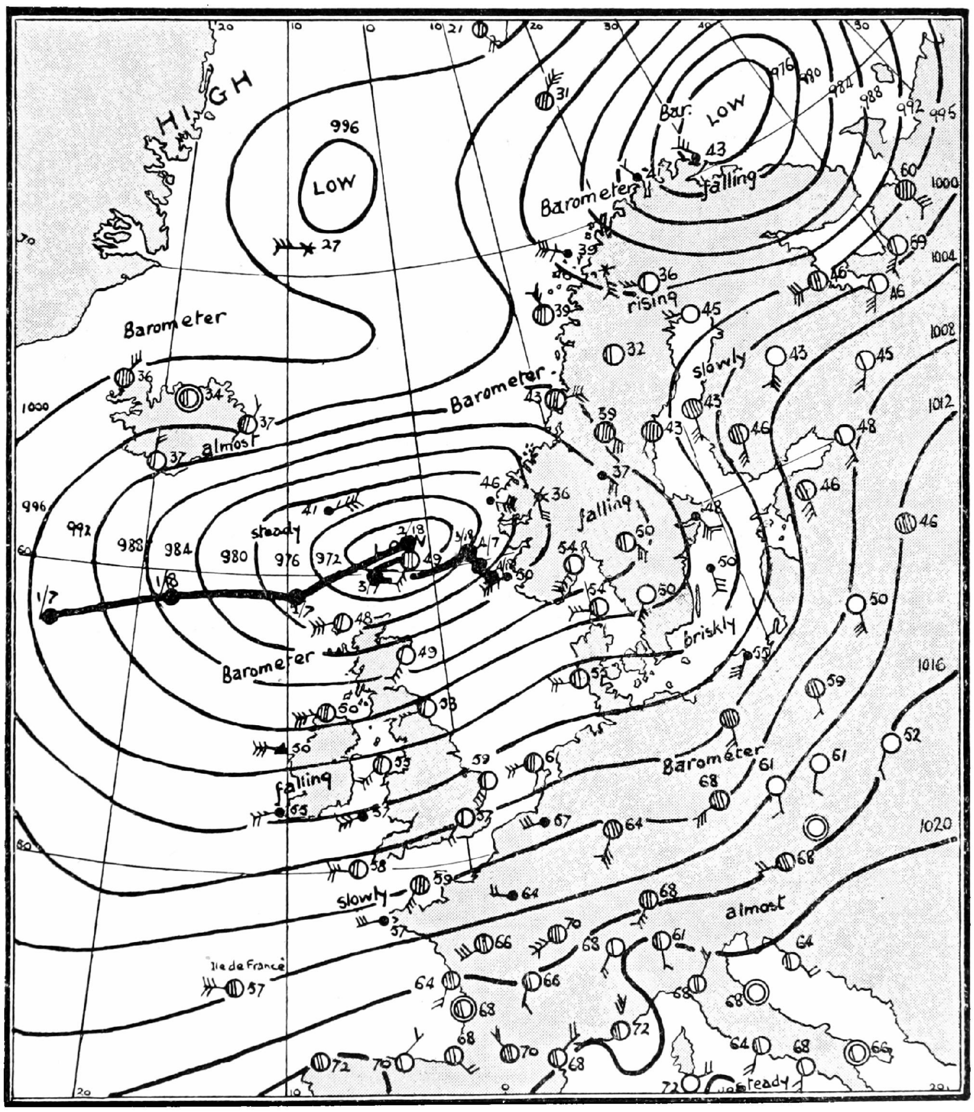


FIG. 1.—SYNOPTIC CHART, 18H. OCTOBER 2, 1929, SHOWING MOVEMENT OF DEPRESSION CENTRE FROM 7H. OCTOBER 1, TO 18H. OCTOBER 4.

as Sir Napier Shaw calls it, as nearly as could be determined at various times from 18h. on the 1st to 18h. on the 3rd, was marked on the synoptic charts. Then measurements were made of the distance of Bell Rock from the centre at fixed times and of the mean hourly wind speed at Bell Rock at these times. The same was done for Butt of Lewis, Tiree, Lerwick, Holyhead, Scilly and Valentia. In this way 86 sets of values of wind speed and distance from centre were obtained, of which 38 lay in polar air and 48 in equatorial air. As might be expected, the individual values show a fair amount of scatter. The dotted curves of Fig. 2 are those obtained for cold and warm air respectively when mean speeds are taken for distance in groups 0–160Km., 160–320Km., 320–480Km., etc. These curves actually run fairly smoothly. The two continuous thin lines on Fig. 2 are drawn from the formulæ $V = 5 + 11$ d/400m./sec. for values of d from 0 to 500Km. and $V = 10800/\mathrm{d}$ m./sec. for values of d from 600 to 1200Km. From the manner in which these continuous lines derived from the formulæ fit the dotted curves derived from the observations, we see that, roughly at least, the polar sector of the outer part of the depression, i.e. beyond a radius of some 500 or 600Km., appears to rotate as a " simple vortex ", whilst the polar part of the inner core, i.e. within a radius of some 500Km., appears to spin like a solid. The word "appears" is used advisedly as we have not yet taken account of direction and the possibility of convergence. The rate of spin of the polar core is such that a complete rotation would be effected in 63 hours. The translational motion of the core, indicated by the above formulæ, is at the rate of 5m/sec. and this agrees closely with estimates—made from the synoptic charts—of the rate of movement of the centre of the depression under examination.

For the outer vortex the only motion indicated is that relative to the centre. This suggests that the outer vortex consists of air—continually new air (cf. Aitken's results)—that is being drawn in to the depression from surrounding regions, and that its motion has been developed as the result of approach towards the centre.

Given the above rate of spin and the translational motion we should deduce the position of the instantaneous centre as being about 180Km. to northward of the isobaric centre, the latter in this example apparently being at least to a first approximation identifiable with the tornado centre.

According to the dynamical theory, however, as developed by Sir Napier Shaw (8) and others, if there is solid spin the isobaric and tornado centres should be separated by a distance given by

$$\frac{V}{\zeta} - \frac{V}{2\,\omega \sin\phi + \zeta}$$

where V is the rate of translational motion. In the present case this should amount to about 150Km., whilst the isobaric centre should be only 30Km. from the kinematic centre. The observational data, however, suggest rather that the isobaric and tornado centres are the same and lie 180Km. distant from the kinematic centre. The explanation is that we are not justified in regarding this as a case of solid spin.

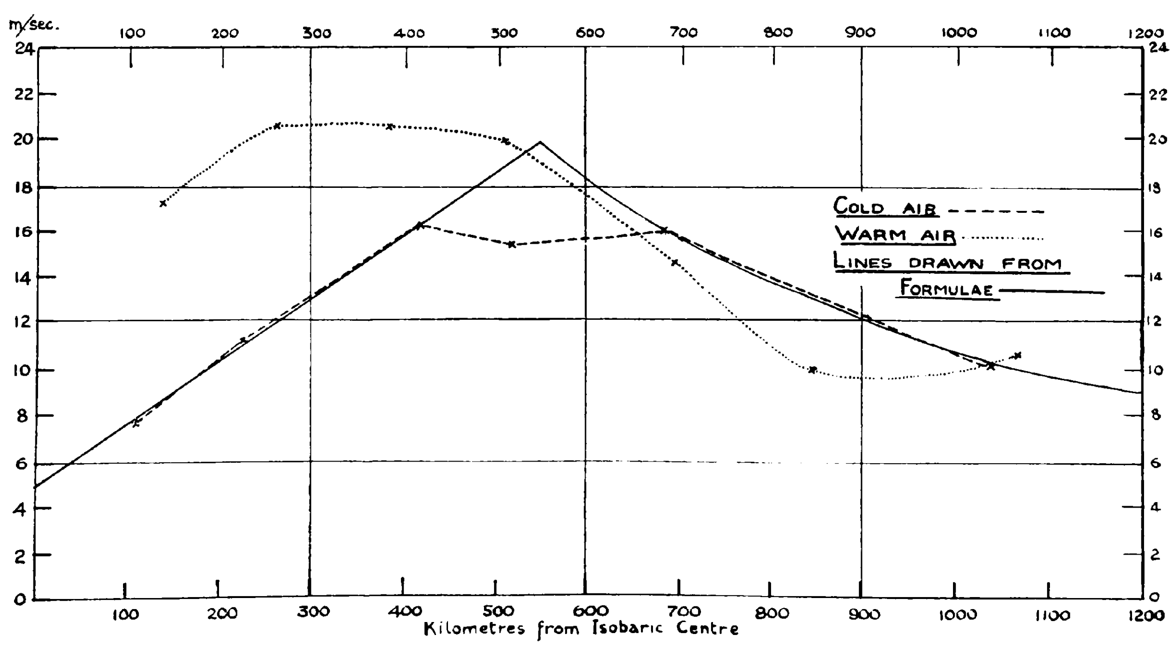


Fig. 2.—Depression of October 1–3, 1929.

In the diagram of Fig. 2 the wind direction has not been taken into account but only the wind speed. Actually, it is a case where there is not true circular motion of the same air mass, but where the wind has everywhere some incurvature towards the centre of low pressure. Even in this central region, with what at first sight looked like solid spin of a mass of polar air, it is actually more nearly the kind of case dealt with by Aitken in his convectional experiments, where, as he emphasized, new air is continually being drawn along the surface into the depression. In other words the eddy must not be treated as if it were closed at its lower end. However, we shall leave this aspect of the case aside for the moment and deal next with the tropical air.

Such of the tropical air as approaches within some 500Km. of the centre maintains a high speed, and one cannot say whether there is any tendency to " solid " rotation unless possibly very near to the centre. Outside of a radius of some 600Km. from the centre, the speed of the warm air drops quickly to a mean speed of rather under 12m/sec., and there is little evidence of any important change in this mean speed up to 1200Km. from the centre.

Another method was used to study the central region in more detail. If for a few hours around a given " zero " time a depression remained unchanged in structure and moved west to east with a steady rate of (say) 10 m.p.h. then the wind record one hour later than zero time could be regarded as giving conditions which prevailed 10 miles to the west of the station at the zero time, the record two hours later would give conditions 20 miles to the west and so on. In this way, with several hours of record from each of a limited number of autographic stations it would be possible to build up a map of the depression in regard to wind, pressure, temperature, rainfall as it existed at a given zero hour. The advantages of such a map over an ordinary synoptic chart are (a) it need have no blank areas (b) all the west–east sections are from continuous records from well exposed stations so that the information about discontinuities is perfectly positive (c) comparative work even in the north–south direction is also rendered more positive, being dependent not on a few eye observations but on sections of several hours of continuous record for all the stations available. The difficulty, for which allowance can to some extent be made, is that depressions do gradually change in structure and in rate of progression. By building up cross sections of the warm sector in the above manner (the method is more fully developed later in Fig. 8) it was possible to see that the motion in the warm air had the following important features. Towards a line running roughly west–east through the centre of the depression, there was strong convergence. Then, from a parallel line, some 400Km. farther south in the warm sector, there was marked divergence. On the south of the line of convergence there was definitely movement across the isobars towards the low pressure ; to the south of the line of divergence there was slight movement outward across the isobars. These features will be remarked on more fully later in connexion with the depression of October 7–9, 1930.

Returning to the polar air, it has been mentioned above that the dot diagram showed a fair amount of scatter. Considering that the values cover two days of the life of the depression this is not surprising ; also some of the highest dots belong to the front and the majority of the lowest dots belong to the rear, i.e. for equal distance from the centre the speeds were rather higher in front and rather lower in the rear of the depression. In passing we may mention that this is not always the case but that the reverse sometimes happens.

An attempt was made to determine whether the rate of spin of the polar air in the inner core varied in any important degree during the life of the depression. Values of $\frac{1}{1000} \cdot \frac{V-5}{d}$ were calculated and found to be as follows :

October	2, 7h. and 13h.	25 28 28	Mean	27
,,	2, 16h., 18h. and 21h. ..	28 50 69 18 21 17	,,	32
,,	3, 1h. and 4h.	19 17 42 26 ..	,,	26
,,	3, 7h. and 10h.	21 15 21 38 31 ..	,,	25
,,	3, 13h, 16h. and 18h. ..	25 27 23	,,	25

There is thus not a great variation in the means, though, if the figures are a reliable guide, the rate of spin reached a definite maximum about the evening of October 2, i.e. about the time when the full depth was first attained.

An inspection of many cases of anemograph records more or less in the line of advance of depressions shows that the approach of a depression is first indicated sometimes by a gradual change in the wind, but in some cases the onset is signalised by a definite discontinuity in the wind record (see Fig. 3 where just before 16h. there is a sharp rise of wind speed from about 4·5m/sec. to about 11·5m/sec.). The discontinuity is not a recognised " front " in any existing theory ; it is scarcely to be expected on the wave theory, unless it means that the cyclone has passed beyond the wave stage and has become a vortex. It suggests rather that a change in the circulation has already been going on above the place of observation and that the surface wind is suddenly being swept into the new circulation. This occurs in the outer vortex of polar air some distance in advance of the warm front. The dynamical aspects of the question are discussed in Appendix I. The deduction is made that the movement of " old cold air " in advance of an approaching depression is consistent with the idea of a pressure field superposed from above.

§ 3.—THE RELATION BETWEEN WIND SPEED AND BAROMETRIC PRESSURE

Another method of studying the structure of the depression is to consider diagrammatically for an individual station the relation between wind speed and barometric pressure. The results for Bell Rock and Butt of Lewis are set out in Figs. 4 and 5. The Bell Rock diagram can be interpreted in the following way. From 1h. on the 1st (when the diagram begins) polar air is passing over the station ; for several hours no important change takes place ; then from about 9h. to 15h. both pressure and wind speed fall slowly. A significant change takes place before 16h. in fact, from the time where the anemogram indicates a discontinuity in the form of a sharp rise from a mean speed of about 4·5m./sec. to one of about 11·5m./sec. ; this was regarded as the time when the surface air at Bell Rock comes definitely within the influence of the outer vortex of the depression. From this time speed increases and pressure decreases in a remarkably steady relationship until about 22h. when the warm sector is approached.

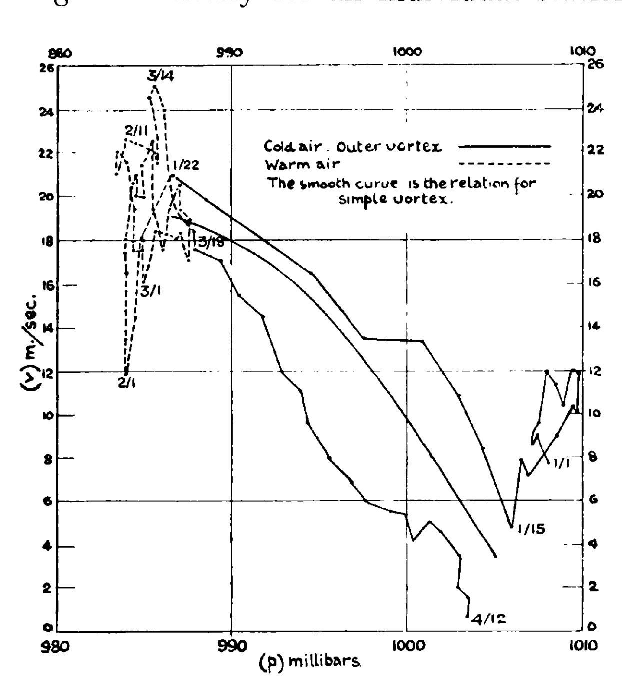


FIG. 4.—BELL ROCK, MOVEMENT OF AIR, OCTOBER 1–4, 1929.

About 2h. on the 2nd the warm air has properly arrived. In all this period and until the evening of the 3rd the relationship between wind and pressure is entirely different. Pressure varies little, whilst wind fluctuates in speed in a manner indicative of diurnal variation in that minima are attained at 1h. on the 2nd and 1h. on the 3rd, whilst maxima are attained at 11h. on the 2nd and 14h. on the 3rd. Actually it is likely that here we have an example of the way in which the diurnally varying turbulence can exert an influence on the behaviour of a depression. During the greater part of this period the station lies between 400 and 500Km. from the centre of the depression, i.e. at a rather smaller distance than the periphery of the polar core. The speed varies between the rather wide extremes of about 12 and 25m./sec., but for by far the most part is between the much narrower limits of 17 and 23m./sec. From about 18h. on the 3rd the station comes again into polar air, this time in the rear of the depression ; speed and pressure from then until 12h. on the 4th exhibit a relationship parallel to that shown when the station was formerly in the outer vortex, but with a difference, namely, that for

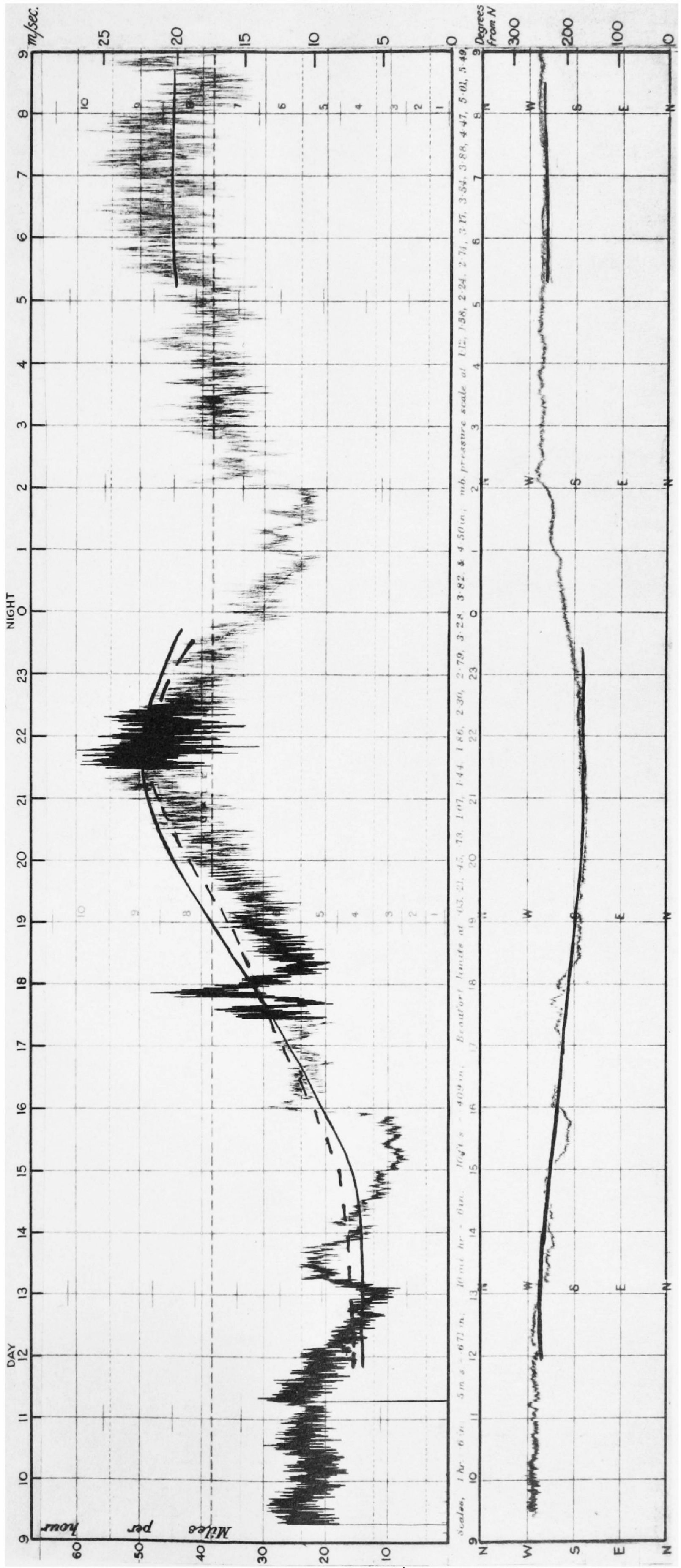


Fig. 3. Pressure Tube Anemogram, Bell Rock, 9h. 15m. October 1, to 9h. October 2, 1929.

a given pressure the speed is reduced by something of the order of 5m./sec. or, alternatively, for a given speed the pressure is reduced by the order of 5mb. The lower speed for a given pressure is perhaps connected simply with the movement of the depression, but it may also be because the cold air is passing out with less energy than it went in ;* in this period also the depression is filling up and moving less quickly so that the progressive changes in speed and pressure in respect of time take place at only about half the former rate.

Fig. 5 shows the sequence of wind and pressure changes at Butt of Lewis. In this case a part of the period is passed in the inner core of polar air, i.e. in this period

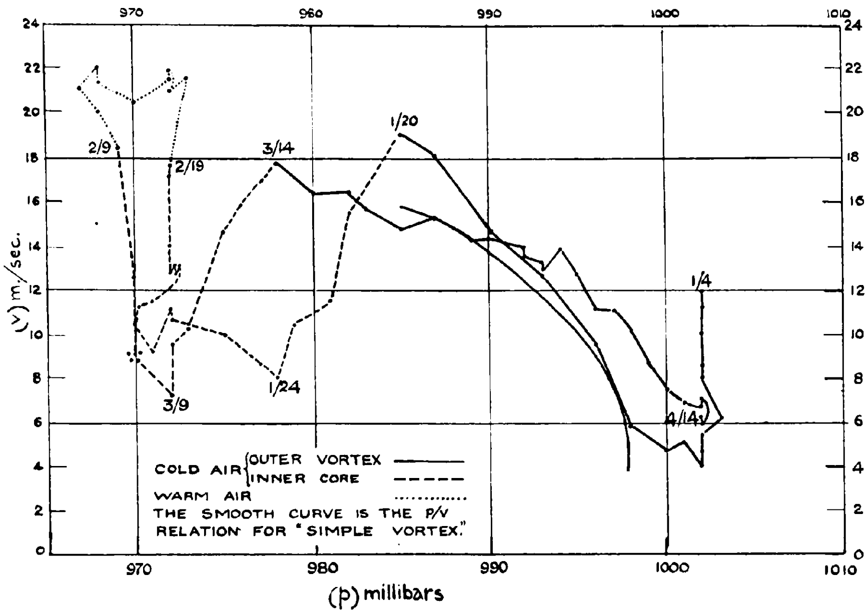


FIG. 5.—BUTT OF LEWIS, MOVEMENT OF AIR, OCTOBER 1–4, 1929.

pressure and wind speed decrease together or increase together. The type of relationship between pressure and wind speed shown in Fig. 5 for the polar air is similar to that found in Fig 2. These pressure-wind speed diagrams can be quite quickly constructed and so permit numerous cases to be studied. They show that the type of relationship indicating an outer region in which wind increases as pressure decreases, is one of such great frequency that one must conclude that it is a normal one in this part of the depressions. The type showing the inner core with the opposite type of relationship as well as the outer region is not so general, and it seems likely from examples studied that it should be regarded as representing a later stage—possibly the final stage—in the life of a depression. One of the cases to be studied later, namely that of October 7–9, 1930, is a case of a vigorous depression with scarcely any evidence of the inner region.

From these diagrams it is not possible to say categorically that the two regions are respectively cases of simple vortex and solid spin. For a simple vortex we require to have $V \propto 1/r$. If we could assume that v was in balance with pressure gradient (i.e. ignore allowance for curvature of the path of the air and ignore accelerations) then we should also have $v \propto dp/dr$. From these relations we derive an equation of the form

$$\log v = -k p + k'$$

where k and k' are constants. In order to show how far the diagrams in Figs. 4 and 5 approximate to this type of relationship a logarithmic curve has been drawn on each.

In the same way and with the same assumptions, which would not in this case be quite warranted, we should derive an equation of the nature

$$p = c v^2 + c'$$

for the inner core, where c and c' are constants.

* See footnote to p. 37.

Thus the diagrams cannot be regarded as establishing the exact law of variation of speed with distance from centre, but only the general nature of it.

Fig. 5 has a feature in common with five such diagrams (not reproduced here) which were constructed for the depression of October 7–9, 1930. This feature is that at each station the approach of the depression is first signalised by a steady drop of wind speed for several hours during which pressure undergoes practically no change. This is the usual preliminary to the entrance into the outer vortex.

§ 4.—THE DEPRESSION OF OCTOBER 7–9, 1930

Another example studied in detail was that of the depression of October, 7–9, 1930. On the 7th at 7h. this large depression was centred at a point on the Atlantic roughly 1100Km. westward of Valentia. The centre moved on a notably regular and slightly curved course, just touching the north of Ireland, then across the mouth of the Forth, on to the Skagerrak, and was just northward of Stockholm by the afternoon of the 9th. (See Fig. 6). The position of the centre at each of the synoptic

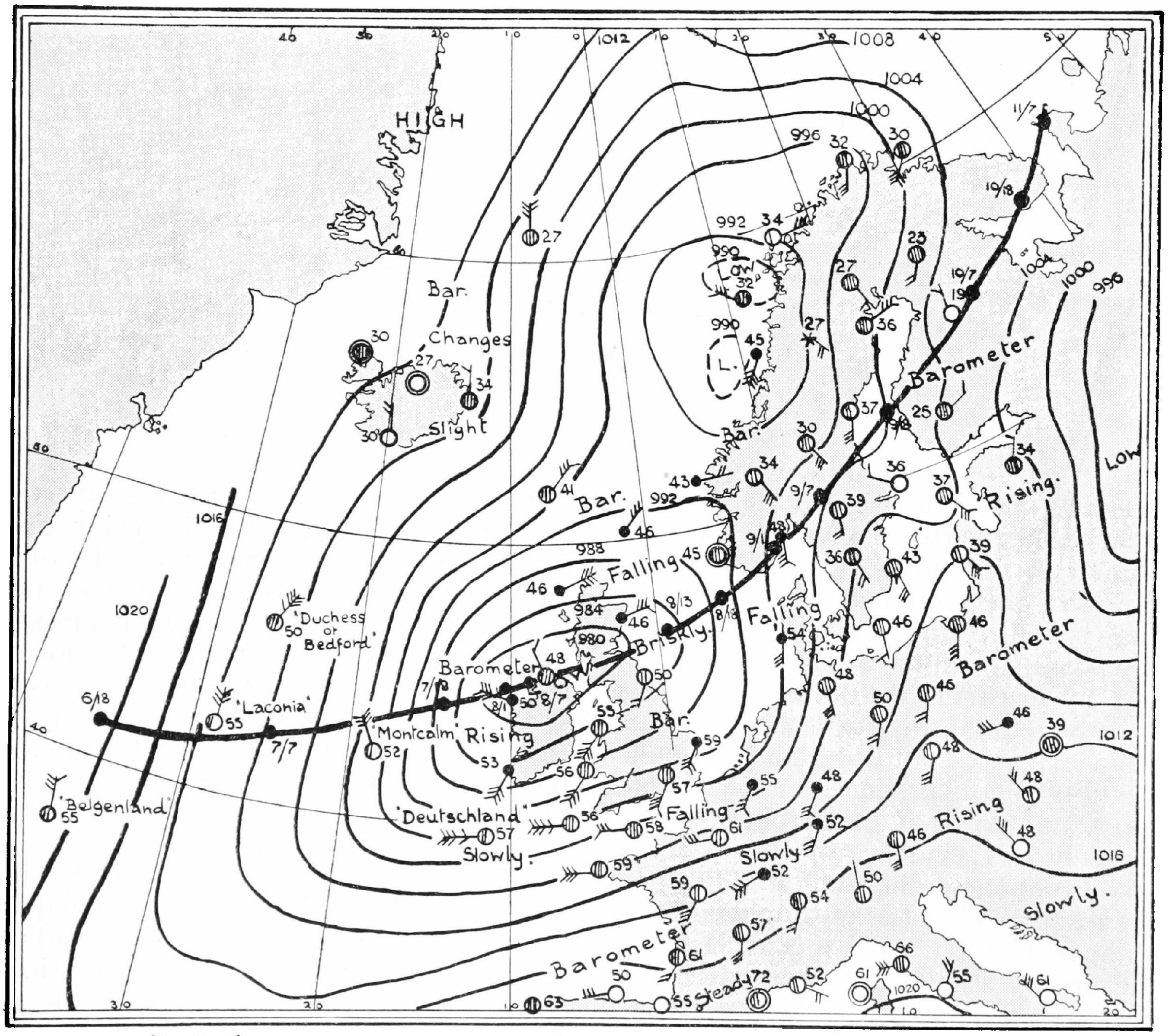


FIG. 6.—SYNOPTIC CHART, 7H. OCTOBER 8, 1930, SHOWING MOVEMENT OF DEPRESSION CENTRE FROM 18H. OCTOBER 6, TO 7H. OCTOBER 11.

hours was marked on a chart and its position at the intermediate hours was obtained by interpolation. The rate of movement of this depression was at first about 15m/sec. and it afterwards increased to about 17m/sec.

Taking the five anemograph stations (of which two—Bell Rock and Tiree—lay almost on the path of the centre) it was possible to measure up a large number of wind speeds and central distances, rather over 200 indeed. These were separated into (a) those in cold air with steady or rising pressure, (b) those in cold air but in a region of falling pressure in front of the depression, (c) those in warm air, pressure rising or steady, (d) those in warm air, pressure falling; when meaned they led to the curves shown in Fig. 7. The few individual values near the centre give just a slight suggestion of the central " solid " core, but this has not been shown on the

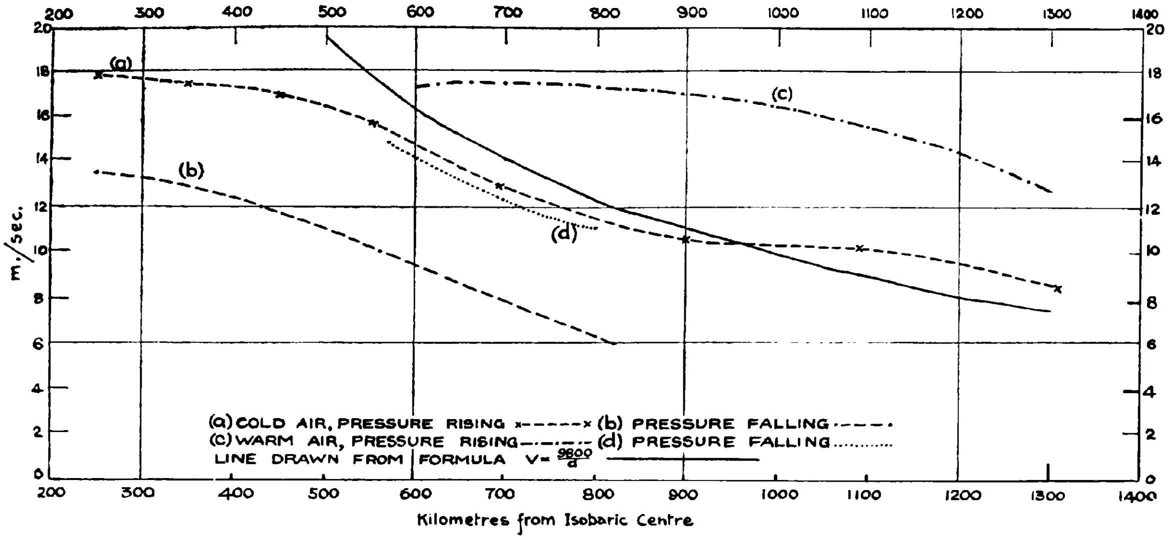


FIG. 7.—DEPRESSION OF OCTOBER 7–9, 1930.

diagram. There is again, however, a very definite indication of the outer vortex, and the vortex to which the curve (a) approximates has a vorticity only a little less than the depression of October 1–4, 1929. Though not otherwise similar the two depressions were about the same depth in the matter of pressure. In other words the amounts of air requiring to be removed from an area at normal pressure to produce two such depressions would be about equal. The fact that they had therefore almost equal vorticity in their outer regions is an important empirical demonstration of the mathematical result of Brunt (referred to in the Introduction) that the vorticity arising in the earth's atmosphere in consequence of removal of " fluid " is proportional to the amount of fluid removed. The vortices in these two depressions satisfied the criterion of stability in that the vr product increased slightly with distance from centre, but that of October 1930 looks more symmetrical on the synoptic charts. As to the suggestion of a central rotating core, if there is one, the translational movement in the latter case accounts for nearly all the air speed, and there is a relatively small rotational motion. In fact the rate of rotation would be only once in about 185 hours, so that if there were solid rotation the instantaneous and tornado centres would be separated by an enormous distance. In this case, therefore, we can leave " solid rotation " out of the picture.*

The larger amount of data available in the second case, by permitting classification, brought out that the polar air in front of the depression never attained speeds of the same order as the rest of the polar air. The curve (c) also brings out that the equatorial air, though at any given place it undergoes but little pressure change, showed very definitely and consistently the same feature. For any given distance from the centre the mean difference of speed in falling pressure as compared with speed in rising pressure is about 5m/sec. In the former case the centre of the depression is advancing towards the air under consideration and in the latter case the air has to pursue the depression. If we could regard the whole system as travelling bodily the speeds in falling and in rising pressure would therefore be expected to show some difference, the magnitude of which would depend on the speed of the depression. Winds of all directions are included in Fig 7, so that the exact difference does not lend itself to calculation. Considering, however, that the centre of this depression was advancing at a mean speed of 16m./sec. the actual difference of speed in front and rear seems of a smaller order than one might have expected from this cause. Moreover, the depression of October 1929, a slow

* In a very intense depression—for example a deep secondary—the development of the vortex up to a relatively short distance from the centre would give to the central area a much higher speed of rotation than that shown by either of the primary depressions mentioned above. In that case it would appear, there must exist a tornado system with revolving fluid characteristics as described by Sir Napier Shaw. See also §11.

moving one, showed exactly the opposite feature, in that it gave lower wind speeds, in proportion to pressure, in its rear than in its front.

In both cases part of the difference between front and rear will certainly arise from the effects of changing pressure distribution. Brunt and Douglas (17) have examined "the modification of the strophic balance for changing pressure distribution." Neglecting friction they give a method of computing the departure of the wind on this account from the geostrophic value. The method (they say) gives results of the right order, but in theory it requires to be based on charts of instantaneous isallobars so that its application to the individual values of a group of over 200 observations in a rapidly changing pressure field is out of the question. The wind changes for the depression of October 1–3, 1929, as recorded at the excellently exposed station at Bell Rock have therefore been treated by themselves (in Appendix I), and compared with the changes deduced theoretically by another method. In this latter method the mathematical discussion is directed to the changes in speed and direction experienced by the same mass of air followed along its trajectory, surface friction not being neglected. It will be seen that the results recorded are in reasonable harmony with those deduced from the assumptions made, i.e. that the movement of surface air in the forward part of and into a depression, once the depression is established, is consistent with the idea of an overhead travelling pressure field. This does not, however, prove anything as to the processes taking place whilst a depression is in actual process of formation.

In the case of the depression of October 1930 also a trajectory of air was selected at points along which speeds could be taken either directly from the anemograms, or estimated from the close proximity of anemographs. This trajectory related to air which passed into the rear part of the depression and then out again. This air arrived from the north at Lerwick at 18h. on the 7th, travelling at 12–15 m.p.h. initially, its pressure for 24 hours or so previously having been about 996mb. (It started between a small depression centred off the Norwegian coast and a high centred somewhere to the north-west of Iceland). Next, accelerated by the large depression now under review, it took a course which passed round the west of Ireland, reaching a speed of about 38 m.p.h., and a pressure of 984mb.; early on the 9th it was again moving from northward just to the west of the Scilly Isles. By the same evening it was feeding an anticyclone over the Bay of Biscay and its pressure had risen to 1020mb.

The air of this trajectory after being drawn in to about 300Km. from the centre —the zone of maximum speed as it happens—was thrown out again at a speed very considerably above the mean speed in the surrounding vortex and, by the time its speed had fallen to the original value, its pressure had risen by 12mb., and was to rise even a further 12mb. It went to feed the small high shown over the Bay of Biscay at 18h. on the 9th, a high which appeared to travel rapidly on as if in attendance on the depression. There can be no reasonable doubt that a great mass of polar air is transferred in this way from north to south of the path of a large depression, the air passing in the rear of the centre and going to help in the formation of a high pressure farther south. The net effect of this depression on the air mass considered was actually to leave the mass compressed to a pressure some 24mb. higher than it had originally. The depression in fact did work on this air mass; it probably did most of the work needed to form the small attendant high.

Thus in the case of October 7–9, 1930 the higher total energy of the cold air which left the depression in its rear is explained by the fact that the depression did more work on this air than on the old cold air which entered the forward part of the depression. It was not possible to examine the conditions in the depression of October 1–3, 1929 so fully, since that depression was centred too much to the north of the area for which detailed information is obtainable, but it was a dying depression and the cold air was presumably giving up energy and doing work (see footnote on p. 37).

§ 5.—CROSS-SECTIONAL STUDY OF THE DEPRESSION OF OCTOBER 7–9, 1930

The structure of this depression was investigated by the method of cross-sections already described, but in this case the observations permitted greater detail to be achieved; the results are described below as they have features that are probably common to many deep and vigorous systems.

The autographic records of Lerwick, Butt of Lewis, Tiree, Bell Rock, Holyhead and Scilly were used in this case to give six sections across the depression in the direction of its motion. In transforming a record of the meteorological elements against time in this way into a cross section in space it is assumed that, over the time considered, the depression maintains an approximately constant rate of movement and does not change to any important extent in other respects. (Actually this depression was gradually growing deeper.) It was thus possible to construct a picture, if only an approximate one, of the instantaneous wind system over an area about 2400Km. from west-south-west to east-north-east, and about 1000Km. from north-north-west to south-south-east. The diagram, Fig. 8, shows the results.

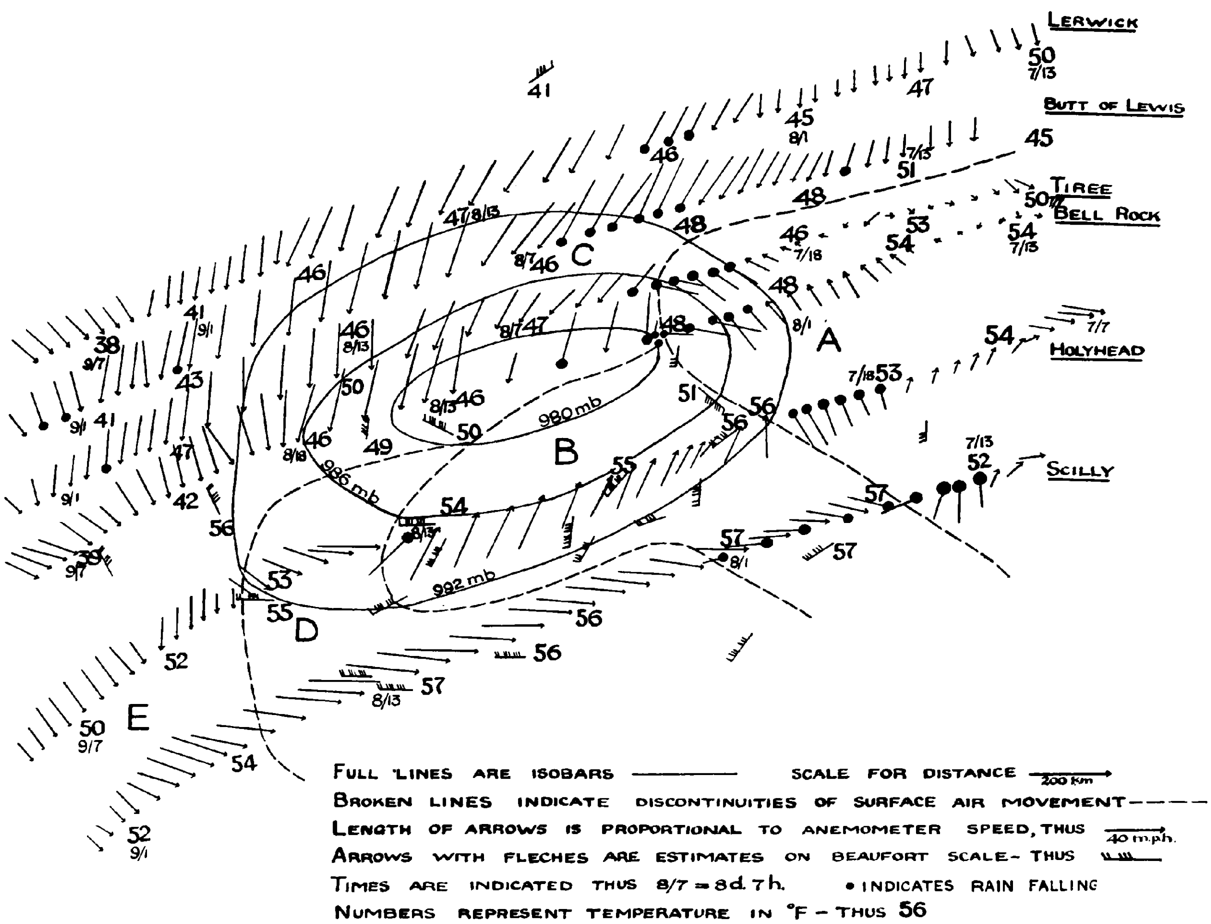


Fig. 8.—Cross sections of depression of October 7–9, 1930.

By means of this diagram, supported by the details of the autographic records, it was possible to draw in the lines of discontinuity. It will be seen that five regions, marked respectively, A, B, C, D, E, are thus delimited. A is a sector of old polar air separated by the warm front from B which is tropical air, C is fresh polar air, E is probably maritime polar, and D again is tropical. The reality however of a line of demarcation between the areas B and D is supported (i) by discontinuities in the anemograms of Holyhead and Scilly, especially definite at the latter station, and (ii) by another consideration which will be referred to later.

The following notes are compiled from the barograms and other autographic records and the weather diaries. Tiree lay just to the north of the path of the centre and the warm air at ground level never reached it. It had a symmetrical and continuous barograph trace, without marked discontinuities. The wind direction trace however does show a slight discontinuity at 2h. 40m. on the 8th, just north of the tip of the warm sector B, the wind changing from E. to ENE. at this point, and becoming more steady in direction; this may be taken as meaning that the east-north-east (and afterwards north-east and finally north) current was in all probability more solid in the vertical direction. The time of minimum pressure at Tiree was not characterised by any sharp change of wind direction. (About 17h. on the 7th there was a considerable drop of temperature at Tiree).

In regard to precipitation the conditions were as follows:—Rain started at Tiree at 22h. on the 7th, and went on to 3h. on the 8th (about 9mm.), i.e. until the homogeneous north-easterly current C flowed over the station. After that there was no rain until 23h. 10m. on the 8th, when a brief slight shower fell, and then no more until 22h. on the 9th when a showery period of some 6 or 7 hours started. This however belonged to quite another system. Lerwick had 1mm. on the 7th, 7h. to 18h., and 2mm. from 18h. of the 7th to 7h. of the 8th, 2mm. from 7h. to 18h. of the 8th, and 2mm. from 18h. of the 8th to 7h. of the 9th, the last being far to the rear of the depression.

At Butt of Lewis there was a shower and a fall of temperature at 15h. 40m. on the 7th. Continuous rain started at 0h. 50m. on the 8th, and lasted until about 7h. on the 8th, but the amount was small, 4mm. in all.

Taking Leuchars as representing what occurred in the Bell Rock cross section we find 2mm. of rain recorded from 7h. to 18h. of the 7th; 15mm. from 18h. of the 7th to 7h. of the 8th, and after that only 0·3mm., i.e. the rain was practically all (as at Tiree) within some 200 or 250Km. of the main front, and over the sector marked A.

At Holyhead we find 2mm. from 18h. of the 7th to 7h. of the 8th; then 1mm. from 7h. to 18h. of the 8th, and 7mm. from 18h. of the 8th to 7h. of the 9th. Holyhead thus gave only 2mm. within the region just mentioned above, whilst most of the rain (7mm.) fell far in the rear of the depression at a secondary cold front. Scilly had 4mm. from 7h. to 18h. on the 7th, i.e. in front of the warm front, then 3mm. from 18h. of the 7th to 7h. of the 8th apparently in the warm sector, and at the first cold front, and after that practically none.

We have thus no difficulty in locating the greatest rainfall as being near the tip of the sector marked A, and the chief rain area as being in its normal place along the north-east side of the warm front. The wind chart also indicates the tip of the sector A as a region of great convergence. This point is dealt with in detail below.

The preliminary picture to which all considerations lead us is that most of the current in sector C maintains its position and its course along the earth's surface, being, however, accelerated considerably as it passes through the depression area, and much of it goes finally to feed a high pressure farther south. This latter point was confirmed by the trajectory dealt with in the previous section.

Reasons are developed below for regarding the surface air in sector B as an air mass destined to leave the surface and ascend first on a north-easterly course and then on an easterly course (that is upsliding finally over sector A) to upper levels. This sector B has the least dense air of any and the natural course would be for it to be displaced upwards by the surrounding air masses. The depression did in fact grow deeper by some 8mb. within the succeeding 24 hours.

Fig. 9(a) shows the surface movement of air in relation to the centre of the depression. It has been constructed by compounding with all air velocities a velocity equal in magnitude and opposite in direction to the mean movement of the centre of the depression. This figure shows clearly great convergence from both north and south towards the line marked *ab* and great divergence towards both north and south from the line marked *cd*. Even on the ordinary synoptic chart (7h. of the 8th) these loci of convergence and divergence are definitely evident on examination. These features have already been noted as existing in the depression of October 1–3, 1929, also along lines some 400Km. apart. Taking first the convergence, we must keep in mind that, since the air in sectors A. and C is much colder than that in B, the westerly component of the wind in B will increase rapidly with height so that even at 2 or 3Km. height the convergence will be directed more towards the tip of sector A. This is all much as one would expect to find. The fact that there is such marked divergence along the line *cd* is, however, more remarkable. Below Fig. 9(a) there has been drawn a diagram, Fig. 9(b), showing in a vertical section taken along the line NS, the vertical structure that would be required to fit in with the horizontal movements on the surface. There is convergence of surface air from both sides towards the line *ab*. We can be certain however that there is no accumulation of air here because the depression, at the time under review, was actually growing slowly deeper. The

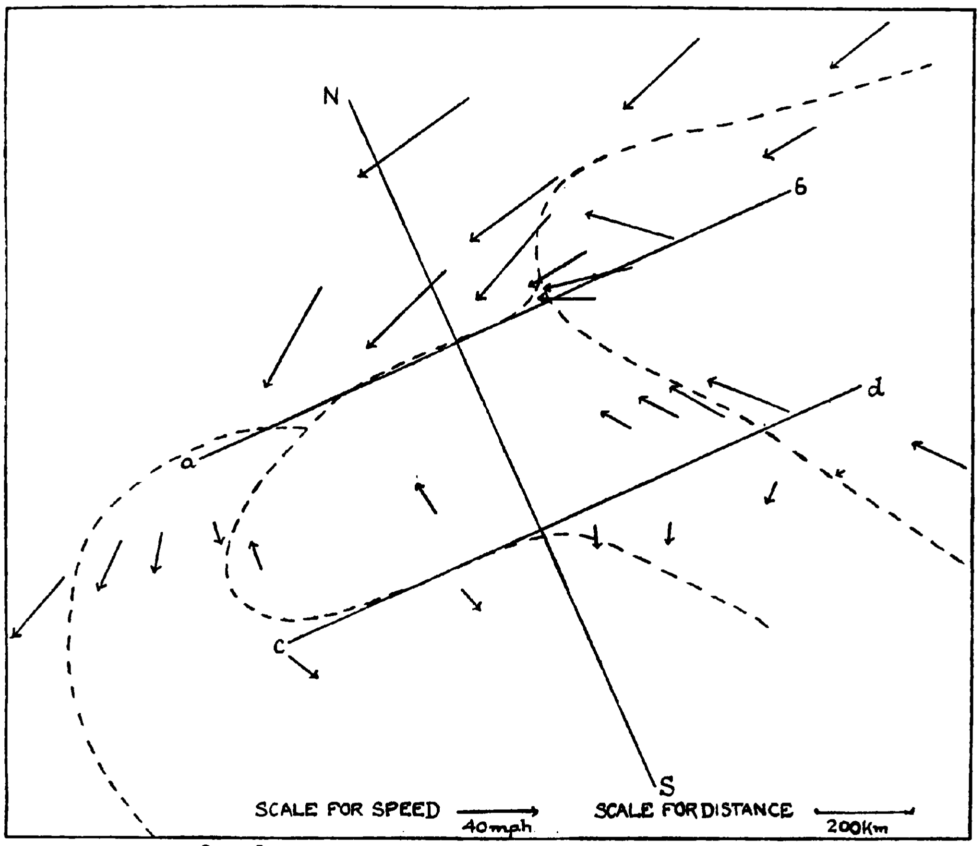


FIG. 9(a)-SURFACE MOVEMENT OF AIR RELATIVE TO CENTRE, OCT. 7-9, 1930

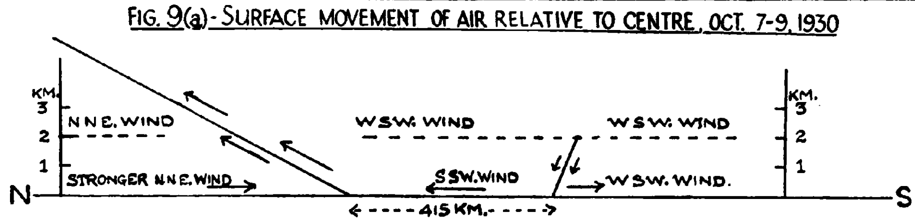


FIG. 9(b).- VERTICAL SECTION SHOWING WIND STRUCTURE.

converging air must therefore be passing upward and—at some higher level—passing out of this area. Taking next the line *cd*, the divergence from this line on both sides could be explained either by the pressure getting lower in this region or by a supply of air coming down from above or by a combination of these two effects. With regard to the first possibility it did seem—on the synoptic chart of 7h. on the 8th—as if a secondary depression were about to develop along this line, but this did not actually happen. Instead, pressure over the whole central area grew gradually lower. Consideration of temperature and humidity in the region of the line *cd* confirms the likelihood of slight, but only very slight, downward motion. The relative humidity was of the order of 90 per cent. The principal effect therefore was gradual evacuation of the air and chiefly the surface air between the lines *cd* and *ab* towards *ab* and thence upward. Also, as commonly happens, sector B became narrower in the west–east direction. The vertical arrangement is shown diagrammatically in Fig. 9(b), but certain details in that diagram depend on points which are discussed later.

According to the vertical section we have in effect a much flattened vortex with horizontal axis somewhere above the line *ab*; to northward of this another subsidiary vortex rotating in the opposite sense, and to southward a third vortex, the second and third induced by the frictional action of the first. Corresponding to the vortex associated with the line *ab* there should, at some height in the upper air, be winds with northerly components. Evidence of this northerly wind is frequently found in advance of a warm or occluded front, at heights between 3 and 9Km. In " Forecasting Weather " Shaw points out the tendency for northerly winds over southerly or south-easterly to be followed by the formation of a secondary. Also, J. Durward (23) dealing with the drift of pilot balloons in relation to Gold's Weather Types, shows that in Types 2, 4, 5, 5a and 15, in the south and south-east sectors of depressions there is movement divergent from the centre at great heights.

That the divergence along the line *cd* is relatively superficial is supported by upper wind measurements. Pilot balloon ascents at various points in sector B and the eastern part of D show that at a height of 1 or 2Km. the wind in both sectors was practically in agreement with the isobars, i.e. WSW. and, as nearly as could be determined, approximately in agreement with gradient as to speed. Thus it is only below the 2Km. level at most, and chiefly below the 1Km. level, that the divergence exists, and it is notably movement of surface air in sector B away from the line *cd*.

Here we have an insight into the mechanism of the occlusion of depressions. The air in sector B, below a height of about 2Km, is all moving towards the centre of the depression and thence upward, so that the patch marked B ultimately narrows or disappears from the surface map. No really satisfactory explanation of occlusion seems hitherto to have been advanced,* but the structure indicated here shows why occlusion must ultimately take place and why it usually takes place beginning near the centre. It also explains the motion of the lower layers of cold air following a cold front ; in an unpublished discussion of a special case Harwood showed that the cold air " cascaded " as if rushing in to fill space vacated by the warm air.

If we take the whole central area extending from the line *cd* in the south to a line about the same distance on the other side of *ab* in the north and consider it in relation to the horizontal and vertical motions as deduced above we find a type of " cell " action on a large scale. The action here is represented by surface movement from both sides towards the line *ab*, thence upward movement ; then again in the higher layers, somewhere between 3 and 9Km., there is (at least above sector B) divergent movement from the region *ab*. Whilst attention is called here to a cell-like action, the action in this case is characterised by convergence towards a line and not towards a point. It has already been mentioned that cell action, in itself, does not lead to depressions. The best example of this is found over the oceans within a few degrees of the equator, where there is every evidence of local instability, leading to rains and thunder but not to the formation of cyclones. It is only some degrees distant from the equator, where the forces due to the earth's rotation become appreciable, that tropical cyclones of even relatively small horizontal diameter develop. The explanation of this failure to develop depressions close to the equator is provided by the analogy of one of the models proposed by Aitken where he showed that any relative movement given to a vessel of liquid which is emptying its contents through an aperture in the bottom leads to rotational movement, to the prolongation of the process, and to a greater fall of pressure and adds greatly to the efficiency of the system considered as a circulating engine. In the earth's atmosphere over the equator, the absence of any relative motion about a vertical axis allows local convergence to proceed unhindered and to make good immediately any deficiency of surface pressure which might arise from convectional circulations due to local heating.

A further example is to be found in the cell action which, as remarked in the Introduction, is sometimes observable in polar currents. Some very good examples occur in northerly polar currents as recorded at Butt of Lewis, with squalls and sometimes showers. Here, however, the whole action is within a broad polar current which as a whole has a fairly uniform mean forward motion ; and thus the factor of relative motion upon which Aitken insisted is still lacking.

I. M. Cline, whose studies on tropical cyclones are well known, has recently (18) published a diagram of a ground plan of a tropical cyclone. It has been " made by combining the actual wind directions and velocities and precipitation in four

* cf. D. Brunt.—Physical and Dynamical Meteorology, p. 330.

travelling tropical cyclones having diameters of more than 450 miles, on one chart." The diagram, since it is based on data for four cyclones, may have lost a certain amount of detail in so far as discontinuities are concerned, but it is possible to identify on it the regions corresponding to A, B, C, and D of Fig. 8 of the present memoir.

In order to compare Cline's diagram further with Fig. 8 we shall regard the direction of propagation of his average tropical cyclone as being towards the east. We can say then that the easterly current in sector C shows the similar acceleration in passing through the cyclone, the air of sector B is converging in this case rather towards the centre than towards a line drawn through the centre, the greatest precipitation is eastwards of the tip of sector B and there is an indication of divergence all round the curved line dividing B from D. The scale of Cline's diagram is not definitely indicated, but if the whole area portrayed be taken as 450 miles in diameter then the central distance of the curved line of divergence varies from 200 to 300Km. This applies to the larger tropical cyclones and about them Cline gives also the information that " the lower clouds not more than half a mile above the earth's surface move around the centre of the cyclone but are not inclined towards the centre. The altocumulus and altostratus clouds recorded in the front of the larger cyclones are inclined away from the cyclonic centre." He concludes also, from cloud observations, that the total height of the cyclones of smaller diameter is less than those of larger diameter. Thus with the difference that convergence approximates to point convergence rather than line convergence and that the total diameter is less it will be seen that some of the cell action characteristics noted above for the central region of the cyclones of temperate latitudes are to be found also in tropical cyclones.

Incidentally an analogy with Aitken's models will be noted here, for Aitken suggested that with a wind gradient slight in proportion to the intensity of surface heating (as is the case in tropical regions) the narrower and more vertical type of cyclone is developed.

The depression of October 1–3, 1929 differed from that of October 7–9, 1930 in having no region corresponding to the northern lobe of sector D in Fig. 8. The former, at the time studied, had reached the stage when it was progressing little and was filling up, whilst the latter had still a long and vigorous course to run. These differences are worth noting, though we cannot, on the basis of the two cases analysed in detail, say whether the features noted are in general connected.

At this point we return again to consider surface wind conditions. Diagrams similar to Figs. 4 and 5 enable us to determine the times of entry into the outer vortex as being approximately as follows: Scilly about 12h. on the 7th, Butt of Lewis, Tiree and Holyhead about 13h., and Bell Rock about 16h. At Lerwick the entry of surface air into the horizontal vortex and the exit from it show no discontinuity on the wind records. The lowest hourly mean speed is 11 or 12 m.p.h. and the direction definite. At Butt of Lewis, considering the wind record only, there is not a very definite suggestion of entry; the wind never becomes uncertain in direction or falls below an hourly mean of 14 m.p.h.

At Tiree and Bell Rock, relatively close to the line of advance of the centre of the depression, we find behaviour different from that noted at Lerwick and Butt of Lewis. At Tiree, which, as already remarked, lies just on the north side of the path, we find a WNW. wind falling very light; then from 14h. on the 7th it becomes uncertain in direction and finally, shortly after 19h., a definite ESE. direction is assumed and a steady rise in speed commences. At Bell Rock, almost exactly in the line of the isobaric centre of the depression, the sequence of events resembles in its general features that at Tiree. A WNW. wind falls light and from 12h. on the 7th becomes uncertain in direction; then about 16h. an ESE. direction becomes fairly definite and the rise in speed commences. The first maximum of speed—just over 30 m.p.h. in the mean—is attained about 5h. 30m. on the 8th; the speed then falls quickly to almost zero at 7h. 10m. when a sharp discontinuity occurs and the direction changes from E. through S., W. and N. to N. by E. By 8h. speed is already on the rise again and another maximum, about 46 m.p.h., is attained about 14h., followed by a very gradual fall. Bell Rock apparently lies a little to the north of the path of the kinematic centre. The lack of symmetry evident in its record is, however, common to the other records, i.e. there is much higher speed in the rear of the centre than in front of the centre of the depression.

The warm air of this depression never reaches any of the four stations with which we have just dealt, yet the two last (Tiree and Bell Rock) as we have seen, show quite a different sequence of events from the two more northerly stations, Butt of Lewis and Lerwick. Thus in Fig. 8 we consider it justifiable to show a line of discontinuity between the regions marked A and C. Its reality is further confirmed by the data of synoptic stations lying approximately on the same line. This line approximates closely in direction with the course of the depression, though displaced bodily some 200Km. to the north of the path of the centre. It is a line of cleavage in the air in advance of the approaching depression. It is parallel to the line of convergence *ab* and to the horizontal axis of the vortex pictured as existing in the upper air.

§ 6.—ANALOGY WITH AITKEN'S EXPERIMENTS

The isobars have also been drawn on Fig. 8, and the relation of the surface wind to them shows some curious features which support deductions already made. In certain parts of the depression the directions of the surface winds are in close agreement with the directions of the isobars, viz., in the part of sector A nearest to the centre, in sectors D and E, and in the most westerly part of sector C.

In sector B, however, and the eastern part of sector C and also in the part of sector C nearest to the centre of the depression the surface wind blows very considerably across the isobars and, as we have said, there is in fact very considerable convergence towards one line (*ab*) between the main horizontal vortex line and its northern subsidiary and divergence from another line (*cd*) between the main vortex and its southern subsidiary. The point about this convergence being limited mainly to lower levels can now be discussed further. Such upper air information as is available for the current in sector C shows that this current diminished in speed up to a height of 1Km. or at least did not increase in the way that the wind usually increases within this level. (Unfortunately information for higher levels in this sector is not available.)

In sector B, on the other hand, the wind, with increasing height, veered round to be nearly in agreement with the isobars in direction at a height of 2Km. and averaged there about 60 m.p.h. which is about 5 m.p.h. over the speed appropriate to the gradient, if the gradient is measured at ground level. The increase of gradient with height in this sector, allowing for the south–north thermal gradient which actually existed between this sector and the colder one to the northward and applying the formula, $34{\cdot}2\,\frac{p}{\theta}\left(\frac{\Delta\theta}{\theta}-\frac{\Delta p}{p}\right)$ per Km. increase of height (where p denotes pressure, θ temperature and Δp, $\Delta\theta$ the differences in the horizontal direction) amounts to the equivalent of an increase of 7 m.p.h. in the gradient wind in the first two kilometres. Whilst it would not be desirable to attach too high an order of accuracy to pilot balloon wind measurements or to estimates of horizontal temperature gradient in the upper air, the result of the calculation broadly is to confirm as nearly as the data allow, agreement of the actual wind with the actual barometric gradient both in direction and in speed at the 2Km. level.

Thus the motion across the isobars of the air in sector B and its convergence towards the line *ab* is determined as nearly as possible as being entirely in the lowest 2Km. and chiefly near the ground. About sector C we cannot say more than that the convergence, so far as the upper air observations enable us to tell, is also chiefly near the ground.

It will now be appreciated that these features of the depression of October 7–9 are well illustrated by Aitken's experiments (described in the Introduction) on miniature cyclones developed in air over a table by convection, or in a vessel of water by the suctional effects of a siphon tube. We recall that Aitken emphasized " that the air near the surface of the table at all parts of the area moves much more radially than the air higher up, and also that the air lying on the surface is drawn into the very core of the cyclone . . . whilst the air higher up comes towards the centre along a rising spiral path, and forms the outer lining of the cyclonic tube." He referred to the lower air being retarded by friction and thus having less tangential movement than the air higher up, so that it was drawn along the surface into the very core, whilst the greater centrifugal force of the upper air keeps it back against the pressure gradient. In the full scale depression (as compared with Aitken's models) the difference is that the upper air is more nearly than the lower in geostrophic balance with the pressure gradient. The cyclostrophic terms will not greatly affect the air movement in the full scale cyclone of temperate latitudes though they will do so in tropical cyclones of great intensity and small diameter where the curvature of the paths of air masses is considerable and the rate of angular rotation higher.

The simple vortical type of air movement in an outer region with convergence of the lower air in the central area across the isobars towards the centre was further confirmed by study of the depression of March 18–19, 1933 which is referred to in a later section in connexion with the question of groups of associated vortices.

§ 7.—DIVERGENCE AS SHOWN IN THE DEPRESSION OF JANUARY 1–2, 1930

Other examples than those of October 1929 and October 1930 dealt with above can be adduced of the existence of a region of divergence to southward of the centre of a depression. One of these is the case of January 1–2, 1930 when a secondary depression passing the north of Scotland deepened considerably. In this case the period of most rapid fall of pressure at Butt of Lewis practically coincided with a period of divergent wind at Butt of Lewis as compared with Tiree, the wind at the more northerly station having backed from WSW. to S. at the beginning of this period, with a preliminary check in its speed, whilst the wind at the southerly station continued to blow from WSW. and also rose continuously in speed. During the passage of this secondary the pressure at Butt of Lewis fell (and subsequently rose again) by about 25mb., that at Tiree fell and later rose again by about 15mb. The changes of pressure and wind at Butt of Lewis and Tiree during the passage of this secondary are set out in Fig. 10. Beginning at 13h. we have parallel flow of air at the two stations ; from about 15h. to 22h. there is rapid separation, the

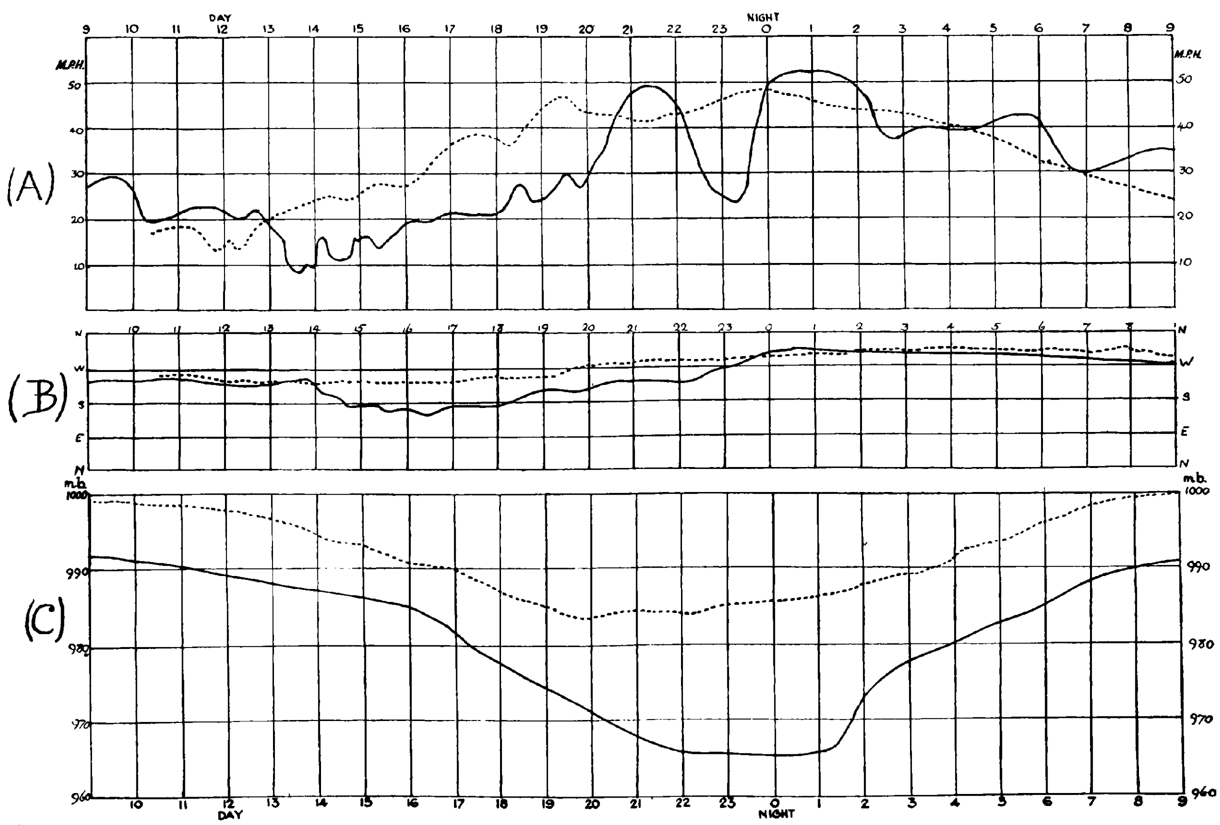


FIG. 10.—WIND SPEED (A), WIND DIRECTION (B), PRESSURE (C) AT BUTT OF LEWIS (———) AND TIREE (...........), JANUARY 1–2, 1930.

air flow at Butt of Lewis diverging considerably towards the left. At 1h. and 2h., i.e. just where a rapid rise of pressure occurs at Butt of Lewis, conditions are reversed, the flow at Butt of Lewis converging relatively to the flow at Tiree, though to a less important degree than it had previously diverged. In the case of the rising pressure, however, we have also the contributory effect of the lower temperature of the incoming north-westerly current to explain the steepness of the rise compared with the previous rate of fall of pressure.

Unfortunately the examination of cases by means of sets of anemograph records is a slow and cumbersome process even when the distribution of stations renders it possible. An attempt was made to identify such lines of divergence in other cases directly from the synoptic charts, but with rather unsatisfactory results. It is obvious that with observations which are mostly the more or less momentary personal estimates of observers at the different stations the possibilities of comparative work are greatly reduced when the element of wind—subject to constant short period fluctuation in speed and direction—is under consideration. Two further cases, detected in this manner, are therefore mentioned with appropriate reserve.

In the depression of November 2, 1930 the synoptic charts indicated the line of divergence at 7h. as lying between 400 and 600Km. distant from the line of advance of the centre. The depression became deeper by the same evening, developing two centres.

In the depression of September 24, 1935 at 18h. divergence was indicated from a line some 400Km. distant from the line of advance. In this case also the depression became deeper in the ensuing half-day.

Divergence has been referred to also in §5 in connexion with tropical cyclones.

§ 8.—SECONDARY DEPRESSION OF OCTOBER 17–18, 1930

The small depression of October 17–18, 1930 first appears on the chart of 7h. of the 17th to south-south-west of Valentia as a secondary to a large depression then lying over the Atlantic to southward of Iceland. Thereafter it moved on a north-north-easterly course, the centre just skirting the western Irish coast, and the depression growing deeper until 7h. of the 18th when it was centred near the Faroes; it then became rather less deep. The path was normal in the sense that it was in the direction of the warm current in this small depression. In Fig. 11

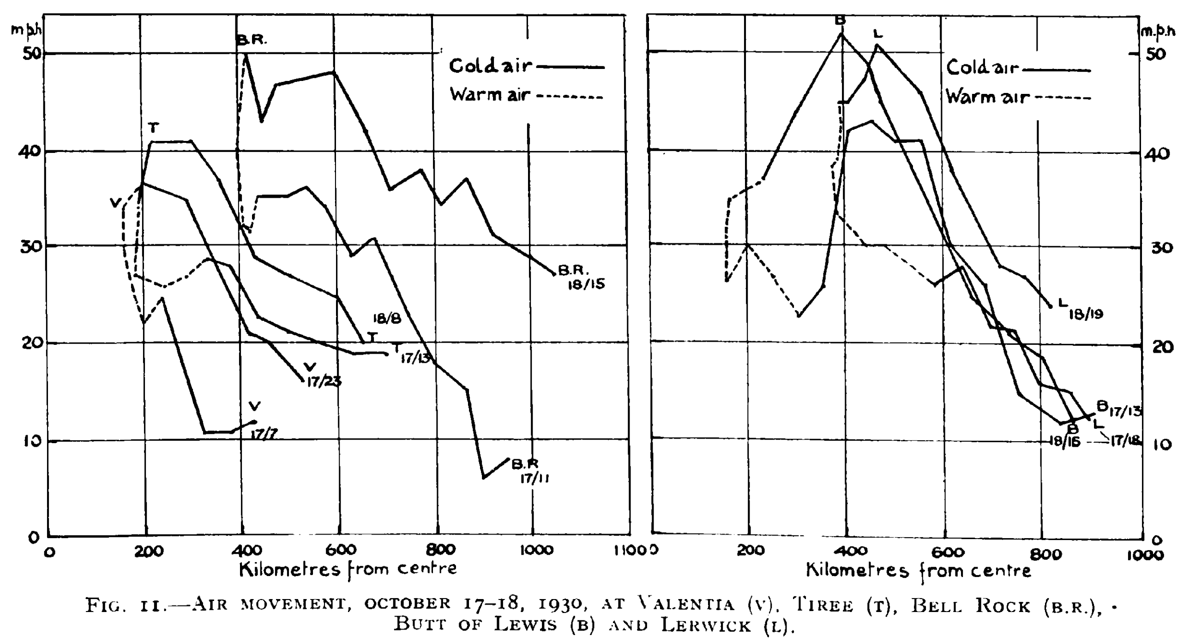


FIG. 11.—AIR MOVEMENT, OCTOBER 17–18, 1930, AT VALENTIA (V), TIREE (T), BELL ROCK (B.R.), BUTT OF LEWIS (B) AND LERWICK (L).

are curves showing, from the Valentia, Tiree, Butt of Lewis, Lerwick and Bell Rock records, the wind speed in relation to the distance of the station from the centre. The curves are similar to others already shown in having definite maxima at a certain distance from the centre. The chief point of interest here however is how the ring of maximum speed increases in radius with time, i.e. as the depression moves

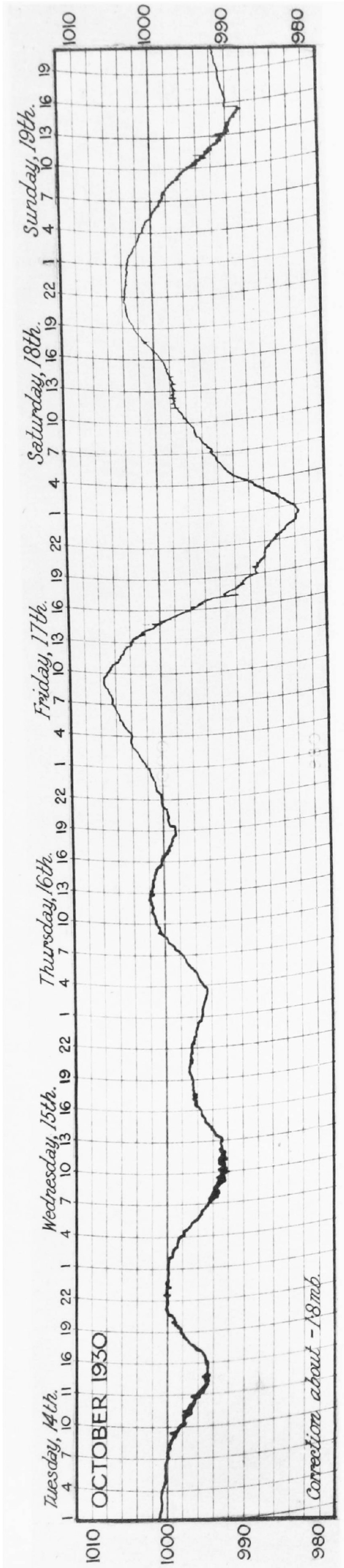


FIG. 12. BAROGRAM, TIREE, 1H. OCTOBER 14 TO 19H. OCTOBER 19, 1930.

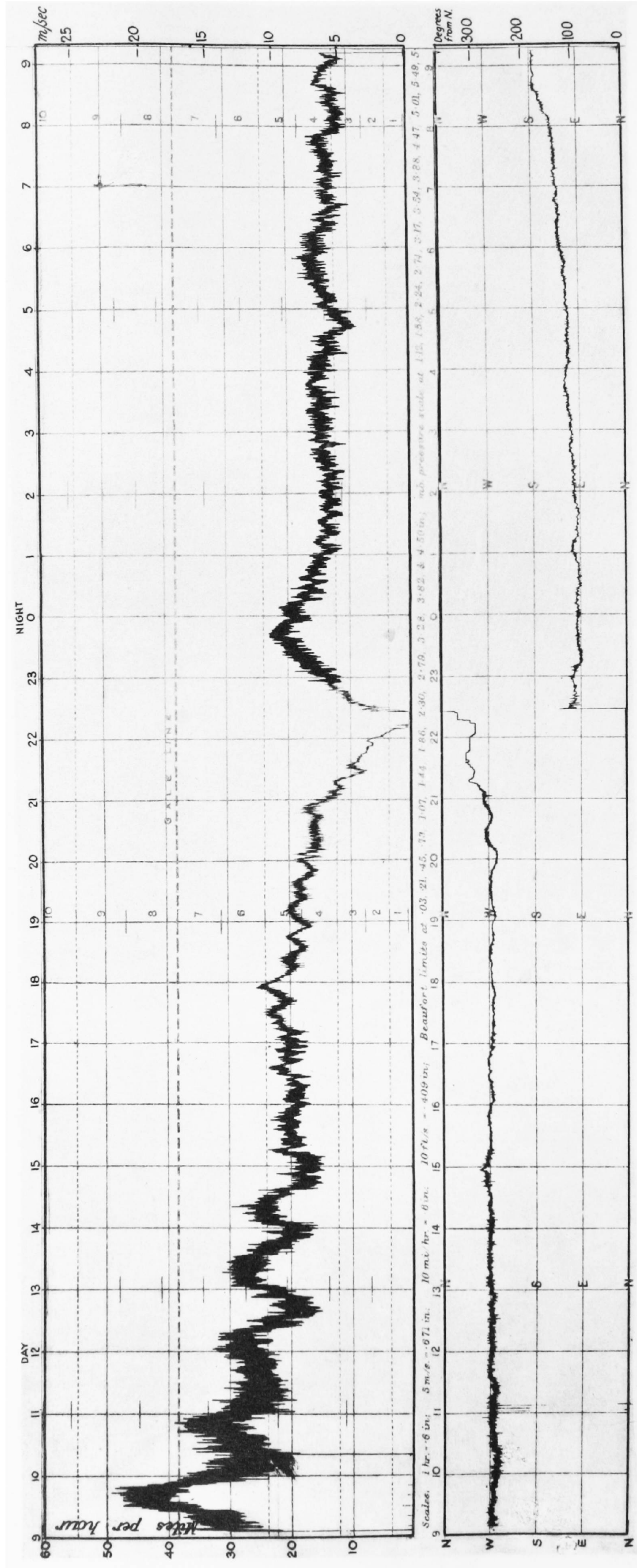


FIG. 13. PRESSURE TUBE ANEMOGRAM, BELL ROCK, 9H. 6M. SEPTEMBER 2, TO 9H. 4M. SEPTEMBER 3, 1929.

northward. At Valentia maximum speed was attained at 16h. on the 17th, namely 37 m.p.h. at 200Km. from the centre of depression. At Tiree maximum speed, some 41 m.p.h., was attained about 2h. 30m. on the 18th, at a distance of about 260Km. from the centre ; at Butt of Lewis the maximum came about 7h. on the 18th, namely 52 m.p.h. at 400Km. from the centre ; at Lerwick the maximum came about 12h. namely 51 m.p.h. at 470Km. from centre. The centre of this depression never came near enough to Bell Rock for that station to experience the maximum wind of the depression.

We have here a very definite example of a growing vortex. Butt of Lewis shows the full development, with, in addition, some of the inner cold air in apparent "solid rotation". The centrifugal tendency of the ring of maximum speed was for a time fairly constant and then fell off rapidly. Thus we have :—

v^2/d for maximum speed recorded at	Valentia	6·84
,, ,, ,, ,, ,, ,,	Tiree	6·79
,, ,, ,, ,, ,, ,,	Butt of Lewis	6·78
,, ,, ,, ,, ,, ,,	Lerwick	5·50

At Tiree 20mm. of rain fell from 13h. 45m. to 19h. 15m. and mainly before 17h. 20m. ; then showers to the extent of 4·5mm. during the night. At Butt of Lewis 10·5mm. of rain fell from 16h. 30m. to 21h., then showers at 0h. 30m., 1h. 45m., and from about 4h. 40m. These amounts of precipitation indicate the disturbance as being one of considerable intensity, when regard is had to the fact that neither of the stations mentioned is subject to orographic effects.

Another interesting feature of the small depression of October 17–18 was the train of pressure changes which immediately preceded its formation, namely a series of small waves or secondaries from the 14th to 16th. These were all in the same way secondary to the parent depression centred to southward of Iceland. The Tiree barogram for the period 14th to 19th is shown in Fig. 12. It will be seen that there are successive fluctuations of pressure with minima about 15h. on the 14th, 11h. on the 15th, and 4h. and 19h. on the 16th, before the more intense secondary with minimum about 24h. on the 17th. At Valentia the corresponding fluctuations are just perceptible but very little developed. At Butt of Lewis the development was much the same as at Tiree, the minima occurring at the Butt about an hour later than at Tiree.

These fluctuations look like pressure waves but the last of them developed definitely to a vortex and terminated the wave-like behaviour.

The chief point to notice about this example is that though the preliminary phenomena may have been waves, once a vortex started, the system developed rapidly to a disturbance of altogether different order. The inner core at the same time grew in diameter up to a certain point and finally the intensity of the disturbance as a whole subsided again as it travelled away northward.

§ 9.—GENERAL SEQUENCE OF EVENTS, OCTOBER, 1930

The sequence of events after the passage of the depression of October 7–9 1930 is typical for weather of unsettled type and has many points of interest, which it is desired to emphasize. When this deep depression was centred near Stockholm another depression, in some ways appearing to be secondary to the first, lay between Iceland and Greenland. This second depression moved eastward until at 7h. on October 12 it was centred near the Faroes and had increased a good deal in intensity. Extending to south-westward of it there was a trough of low pressure with two secondaries. By next day (13th) one of these had developed greatly and become the chief centre of activity on the map. Its centre was at about the same place in the North Atlantic as was the centre of the depression of October 7–9 when on October 7 its great development took place. On the following day (14th) the depression now under review became decidedly more intense and by 7h. on the 15th the centre had moved northward and was then in long. 23° W. about 500 miles southward of Iceland. During the next two days certain changes occurred which ended in the development of the intense secondary of October 17–18, whose history and structure also have been discussed in detail in §8.

Whilst the deep secondary developed the parent depression diminished slightly in intensity. The secondary moved on northward and when it was centred near the Arctic Circle the parent depression began to rotate round the secondary and then became rather more intense again as it was brought further south. The intensification, however, took place in step with the intensification of another depression lying over north-east Labrador and Davis Strait. With the deepening of these two depressions there was intensification of wedges of high pressure over Greenland and the North Atlantic, but it cannot be said whether the intensification of the highs preceded or followed the intensification of the lows. This simultaneous increase of intensity however of two main features on a map is not unusual and connotes either a direct connexion or the widespread effect of some common cause in the upper air not otherwise evident at ground level. The nature and probable extent of the direct connexion between the depressions and the wedges of high pressure is dealt with later in § 12.

By October 22 the Canadian depression and its secondaries were dominating the circulation over the North Atlantic and western Europe. By 7h. on the 23rd the centre of lowest pressure had been in turn transferred to one of these secondaries then centred over Iceland, and for at least the next three days this depression controlled events over the North Atlantic and western Europe. It moved at first slowly east-south-east and the strong north-west current in its rear flooded across western Europe and, as is customary in these cases, gave rise to a fairly deep secondary over Italy and the western Mediterranean. On the 26th, pressure in this secondary was as low as in its parent depression which was then centred over Scandinavia. By the next morning (27th) the parent and the secondary, still about equally deep, had both moved north-eastward. Under what influence this occurred is not clear from the charts in the *Daily Weather Reports*, but the chart of 7h. of October 28, shows that two depressions formerly lying over the North Atlantic and formerly apparently shallow had by then become very intense. One of these, centred near the Faroes on October 28 at 7h., in turn controlled the events over western Europe for some days, absorbing others into its system. This depression, having become the chief centre, moved north-north-east until November 2, 7h. when its centre was south of Spitsbergen. Within the preceding 24 hours, however, one of its own secondaries, centred to westward of the British Isles had been becoming much more intense and within a further 24 hours, viz. by 7h. of November 3, we must in turn regard this secondary, which had then reached the North Sea, as controlling the circulation over western Europe. The parent retreated on a south-westward course and was gradually swallowed up in the new circulation.

The chief deduction from any such examination of a sequence of events of (say) a month is that the movements of air masses and the positions and outlines of any obvious fronts are determined by the major circulating systems existing at the moment ; in particular the biggest " eddy " existing controls the changes of the field for the time being, shapes the " fronts " and controls the movements of the smaller " eddies ".

There is another point and a very important one, namely, the tremendous accessions of energy which at certain times or in certain places come to particular centres of low pressure and enable them to develop to the point of becoming the dominating circulations over a considerable part of the northern hemisphere for the time being. Two of the notable cases already mentioned were on October 6–7 and again on October 12–13, when quite small depressions centred over the North Atlantic some 800 miles westward of Ireland showed surprising development. Another was on October 20 when the depression over north-east Labrador and Davis Strait developed greatly. Developments of this kind are found frequently to have a geographical bias.

L. D. Sawyer (19) has shown that the parts of the North Atlantic most favourable for the birth or development of depressions are the neighbourhoods of (1) Nova Scotia and Newfoundland, (2) Davis Strait, and (3) the Iceland to Greenland region, with an extension southward to the west of Ireland. The Davis Strait region is effective mainly in late autumn and early winter.

All these are regions where outflow of cold air over warmer sea occurs in winter and where there exist at all seasons fairly steep gradients of temperature, both of air and surface. They are therefore regions where any balance of movement that may have existed initially between cold and warm air currents is going to be destroyed by surface warming and humidifying of the colder air current, with subsequently some degree of mixing and the possibility of upward air movement at the original bounding surface between the currents. Cooling of the warmer current by a cold land or sea surface has much less effect, because the first result is to cool the surface layers of air, thus rendering the lower levels more stable in the vertical direction and thus limiting enormously the rate at which eddy conduction can cool the whole mass.

Thus in these cases it is highly probable that the great accession of energy appearing on our surface charts is somehow released by the ascent of warmed and moist air of mixed origin, the ascent having been started by the warming of the cold air along the boundary between the two currents. It has to be remarked, however, that there was apparently a closed isobaric system already in existence in each case before the accession of energy came. A depression, as we have seen, appears to arise mostly as a secondary thrown off by some other depression and the subsequent diminution of pressure from ascent of relatively warm air is physically possible, only provided there is an agency by which the ascending air could be removed from the region.

A readily available store of energy is also required as it can scarcely be regarded as feasible in temperate latitudes for any local warming which produces the initial ascent to be much more than the trigger action for the release of the large amount of energy which the winds of a cyclone develop at ground level. This matter is discussed in the next section.

Apart from the influence of local conditions in leading to development, diurnal conditions have been found to affect the behaviour of cyclones. Though it is still uncertain whether the diurnal conditions affect initial development there can be no doubt that they affect the incidence of precipitation at the surfaces of discontinuity. This has been shown by the writer in an earlier memoir (20) and is further explored in one just published (21). In the case of warm fronts there is a definite tendency for the rain to reach its maximum in the latter part of the night or the early morning ; and, particularly in summer and over land, the rain may cease in the middle of the day and early afternoon, or at all events fall off considerably. In the case of cold fronts, on the other hand, there is a very marked tendency indeed for most of the rain to occur in the afternoon, and there is a slight tendency to a secondary maximum about 4 a.m. It is found that both frequency and intensity are affected. In §3 of the present memoir reference is made to the diurnal variation of surface wind speed in the warm air. The higher surface wind in the daytime means greater eddy connexion between surface and upper air and thus a greater surface frictional drag on the warm air current as a whole. Thus (more especially if we accept the conclusion reached later in this memoir, that the warm air current supplies most of the driving force to rotate the whole system) the activity of the depression is slightly damped during the day as compared with the night. This conclusion would be in accord with the view of some practical forecasters that depressions frequently deepen more notably during the night hours than during the daytime.

Given suitable conditions, a mountain range may be the local cause leading to the formation of a depression. The Alps afford a good example ; a high northwesterly wind across the Alps at the 5Km. level has been noted by the writer to be the prelude on several occasions to the formation of a low pressure system over northern Italy.

§ 10.—DYNAMICAL CONSIDERATIONS

On the question of energy the writer takes the same view as Ryd (22) namely, that the rapid developments sometimes observed in cyclones indicate that " they are supplied from stores where the energy is present in a form more easy of approach than the potential one. Now there exist inexhaustible deposits of kinetic energy from which the cyclones may be supplied, namely the west–easterly motion of the upper air." In the cases now under discussion it can be shown that neither about removal of ascending air nor about supply of energy ready in kinetic form is there any difficulty.

The months of October 1929 and October 1930, like most other months of the name, were characterised by a great difference of temperature between air of polar and air of sub-tropical origin. A normal condition of the month, therefore, would be a great increase with height in some component of wind speed, usually the west-south-west component. The extent of the increase may be calculated theoretically. In the early part of October 1930, for example, the observations from aeroplane ascents showed that the temperature differences between cold and warm air ranged from about 6° F. to 10° F. at the surface, then rapidly increased to some 15° F. at the 2Km. level and were some 20° F. at the 6Km. level. If we consider these changes as taking place in the width of (say) a 300Km. wide zone running parallel with a principal front whose general direction is from west-south-west to east-north-east and if the barometric gradient at surface level be taken as corresponding to 30 m.p.h., then the barometric gradient at the 6Km. level, computed according to the formula already quoted, will be about 110 m.p.h. The increase may continue even to higher levels and the conditions quoted above are by no means exceptional.

Thus in the conditions existing near fronts we can have winds of extremely high speed at high levels, higher than anything experienced at ground level in the most severe depressions of our latitudes.* Observational proof of the existence of these extremely high winds, in the westerly circulation south of regions of low pressure has been found in the drift of pilot balloons. J. Durward (23) quotes an October case where a balloon travelled 570 miles in four hours, representing probably speeds of the order of 80, 100 and 180 m.p.h. at heights of 10,000, 15,000 and 35,000 feet respectively. Enormous kinetic energy must indeed be available in general, at least during the winter half of the year in the warm air above most principal fronts. Thus, if any patch of surface air near the boundary between polar and sub-tropical air were made sufficiently warm or humid to rise relatively to the polar air, it would be carried away very rapidly in the strong upper warm current, leaving an area of lower barometric pressure at the locus of the ascent. In such a case we should be able to identify, on the chart, lines of convergence and divergence as shown in the depression of October 7–9. Also, a relatively small proportion of the energy of higher levels, if communicated to the surface, would account for all the kinetic energy ever displayed on the surface ; such communication however will arise and can only arise when some local surface heating (or sufficient obstruction), by causing vertical movement in lower levels of the atmosphere, provides the action required to disturb the smooth flow of the high speed upper air.

According to Aitken's idea the rate of progression of the cyclone as a whole is determined by the momenta of the air masses entering into it. To test this proposition we should require to know the speeds and densities of the tropical and polar currents at all heights and the proportions in which these currents contributed air at each height to the cyclonic system. The observational material is far from being complete. Approximate estimates of the density can be made, and we have already made, for the case of October 7–9, 1930 an approximate estimate of the speed in the tropical air at 6Km., namely 110 m.p.h. ; the speed at 2Km. is known from pilot balloon data. Assuming that from 6Km. to 9Km. the speed remains at 110 m.p.h. and interpolating values for lower levels between 2 and 6Km. an estimate has been made of the momentum of a current of tropical air 9Km. deep. It is found to be equivalent to that of a current of mean density equal to that at 2Km. moving at a uniform speed of 56 m.p.h. (The mean density of air over England at 2Km. is 1·014 grammes per cubic metre). The motion is in the direction of the movement of the depression as a whole.

As to the polar air we have much less information and can only make a rough assumption which will be that, since it occupies a large portion of the lower levels of the depression and the component of its speed in the direction opposed to that of the movement of the depression is about 15 m.p.h. its momentum is equivalent to that of a current of the same mean density (as was adopted above for unity),

* It is relatively seldom even at well exposed anemograph stations that hourly mean values of wind speed attain 50 m.p.h. whilst an average speed of 70 m.p.h. is very exceptional indeed.

moving at a uniform speed of 15 m.p.h. Knowing that the mean speed of the progression of the depression is about 36 m.p.h. we can from these data make an estimate of the proportions in which polar and tropical air would require to enter into the depression in order to determine the observed rate of progression. The result is one part of polar air to $2\frac{1}{2}$ parts of tropical air.

This proportion is high ; for comparative purposes a second assumption has been made, namely that polar air up to a mean depth of 6Km. enters into the depression and that in this polar air there is with height a gradually increasing WSW. component, so that at 6Km. the speed is WSW. 60 m.p.h. The result of this second assumption is to give the polar air a momentum equivalent to 19, and in this case the proportions of polar to tropical air come out as 20 to 17.

Looking at the matter from another aspect, but still on the assumption that rate of progression is determined by the momenta of the air masses entering the depression, it is obvious that an increase in the proportion of polar air will slow down the rate of progression and diminish the total kinetic energy and *vice versa*. Now this is actually what happens. It is a fact of observation that when a depression becomes occluded, that is entirely surrounded by polar air at lower levels, it dies and at the same time its rate of progression falls notably. And conversely increase in the warm sector, increase of activity and increase of speed on the whole go together. In this aspect therefore of the behaviour of depressions the facts are consistent with Aitken's proposition as to rate of progression. Aitken's proposition in fact, added to the idea that the energy of a depression is drawn largely from the energy of the warm air, offers a generalized explanation of a group of empirical rules, of which it will be seen that the well known Bergen rule for the direction of movement of a depression is one particular case.

A serious objection to the idea of a depression as approximating in any way to a solid rotating disc or column is that its top as a rule would soon be sheared off by the upper currents, since these greatly exceed the rate of progression of the depression. Such a depression could thus not continue in being for several days as a quasi-constant system. The conception of the depression rather as an absorbing and discharging eddy obviates this difficulty.

If the rate of progression of depressions is determined as Aitken supposed, it is still not unlikely (more especially if cold and warm air enter into them in about equal proportions) that on the average during any given season of the year the rate would approximate to that of a general current corresponding to the spacing and direction of the average isobars for the season.

In this connexion it may be recalled that Sir Napier Shaw (24), speaking of "the Case for Revolving Fluid, in General Terms", points out that the travel of tropical revolving storms is in general in agreement with the idea that they are carried along in a current represented by the normal isobars, and he quotes, in support, the behaviour of those of the West Indies, the Bay of Bengal, the China Seas and Mauritius. He also points out that the depressions of middle latitudes, on the average, travel over Great Britain with a speed of the same order as that indicated by Teisserenc de Bort's isobars for the 4-kilometre level. In particular, however, referring to the extraordinarily high correlation found by W. H. Dines between changes of temperature and changes of pressure in the levels between 4 and 8Km. of height, he remarks—" it follows therefrom that there is at least a presumption that, at a height of 4Km. from the surface within each well-marked cyclonic system there is symmetry in the distribution of pressure and temperature such as we might expect in the case of the tropical revolving storm. If, then, the lack of symmetry of the winds is explained by the surface friction and the super-position of the velocity of translation upon that of rotation, and the lack of symmetry of temperature by irregularities of the surface-temperatures which do not extend beyond 4Km. we reach the conclusion that, so far as any horizontal section between 4 and 8Km. is concerned, our cyclones may be examples of revolving fluid carried along in the main current, which have the portion nearer to the surface distorted and made unrecognisable by differences of temperature peculiar to the lower layers and by friction of the surface.

" Considering, then, cyclones to be dynamical systems of revolving air formed in a flowing current, it seems hardly possible to find any source except convection, re-inforced by the latent heat of condensation, for the vast amount of energy which they develop. The velocities are so much greater than anything which occurs outside their spheres of action that the attempt to derive their energy from pre-existing air currents is not encouraging."

It must now be emphasized that in temperate latitudes the last remark applies only to surface conditions. It is now practically certain that large depressions never occur without the associated condition (discussed above) of extremely high speeds of warm air at great heights. Further in the case of the depression of October 1–3, 1929, it was found that the gradient impressed upon the polar air in front of the advancing depression approximated closely to that existing in the warm sector. Figs. 2, 4, 5, and 7, also show that the speed of the warm air, over a considerable area, approximates to and mostly rather exceeds even the maximum speeds of the cold air. (It is admitted that the speed of the cold air may in certain cases be the maximum speed attained at the surface in a depression, but it appears that this could arise, as shown in Appendix I, through speed very temporarily overshooting the value appropriate to balance with gradient after allowance for ground friction.) The general excess of warm air speeds over cold air speeds has also been demonstrated by the writer in an earlier memoir (20), where the average winter speed of tropical air over Scotland at a height of $\frac{1}{2}$Km. is shown to be of the order of gale force.

The fact that the highest gradient values in the cold air in general just fall short of the gradient in the warm air, together with the fact that the warm air must be uppermost when both overlie the same area, and the above remarks on the high speed of the warm air at high levels, all suggest that it is for the most part the warm current which determines the surface gradients subsequently attained.

We have already demonstrated (§ 6) that one characteristic feature of Aitken's model cyclones, namely that convergence of air is mainly along the surface, is applicable to the full-scale depression. It seems convenient at this point to emphasize that two initial conditions, which he showed to be necessary to the formation of his model cyclones, have now also been demonstrated as existing in general when depressions form in our latitudes. One is the local bias favouring the formation of depressions whenever cold currents pass over warmer sea, so that they can be heated from below; the other is the existence of high speed in an adjacent warm current (and particularly in the upper levels of this current), corresponding to Aitken's "tangential current".

It has long been recognised that one of the most characteristic features of depressions is the existence running through them of what are nowadays known as "fronts" or surfaces of discontinuity. One of the original propositions of V. Bjerknes was that the depressions originated as waves in a main front between the cold air of the polar calotte and the warm south-westerly air flowing from subtropical regions. Much work of the highest value has been done by the Bergen school and others on the structure of depressions, and much is now known about "fronts", but the actual wave origin has never been demonstrated satisfactorily.

At one time it appeared to the writer that the development of waves from those of the two-hour or shorter period category to those of the dimensions of cyclones was at least a possibility, but it has not been possible to trace such a development. There is also the fundamental difficulty about the stability of the conditions at the discontinuities in connexion with which the smaller waves occur, these being characteristic "inversions" of temperature which is in contrast to the conditions referred to below obtaining normally in cyclones. In Appendix II the possible relation of the wind structure of the depression of October 1–3, 1929 to a wave is dealt with, but it is shown that the type to which this depression might be regarded as approximating is definitely not an irrotational but a rotational type of motion, in the genesis of which the unequal application of heat or moisture may most probably be considered to have played a part.

The question of the precise nature of the polar front in depressions was explored some years ago by L. H. G. and W. H. Dines (25). They showed that inversions are not as a rule found in depressions and that indeed almost the only generality that can be established statistically, is that, in cases where barometric pressure is notably low, the lapse rate of temperature in the first three kilometres is steeper than usual. Further, Douglas (26) in 1929 gave numerous examples showing that warm fronts are characterised not by inversions but by layers of reduced lapse rate, the surface of discontinuity being in these perhaps a kilometre thick in the vertical direction. His examples show also that there is often a considerable thickness of nimbus cloud below the discontinuity and the ascents on the whole mostly indicate a lapse rate about the saturated adiabatic. These results all confirm the view arrived at above mainly from kinematic considerations, namely, that at any main front, wherever there are depressions, there is upward movement of the cold air as well as the warm air from surface levels and that there is considerable mixing at the boundary. On the basis of the results just quoted Douglas was apparently inclined to the view that there are two types of depression, one of which formed entirely in polar air with the assistance of instability acquired in passing over progressively warmer surfaces and another type which formed on a polar front. It will probably be granted generally that the formation of the polar air depression is largely a question of acquired instability, but it seems further, according to reasoning set out above (§ 9) that the main polar front is a potential locus of instability, for the quasi-stability between the air masses will be upset and instability will develop wherever surface conditions are such as to warm and humidify the fringes of the polar air and to induce mixing along the boundary. It has already been emphasized that the convergence towards the fronts of a depression is in any case chiefly of air occupying the lowest two kilometres, so that all the conditions for the convergence and ascent of air are prepared if the lowest two kilometres are warmed to the extent of instability. Important confirmation as to the conditions existing at a principal front where a depression did actually develop is obtainable from upper air data given in an important work by Bergeron and Swoboda (27). A diagrammatic representation is there given of a meridional section of the isothermal and isentropic surfaces across a principal front at which a depression originated on October 10–12, 1923. The diagram shows a maximum concentration of energy in the mixing zone of the principal front 25 times as intense as in the next most important latitude zone and 100 times as intense as in any other zone. It is important to remark that what is referred to as the next most important zone to the main front is the adjoining zone of the polar air.

§ 11.—THE MAIN POLAR FRONT AS A HORIZONTAL VORTEX LINE

We should like to introduce here the theoretical conception of the main polar front as a vortex with horizontal axis. It is certainly this potentially since the application of heat at its surface fringes is liable to upset the stability of the air masses and induce circulation about a horizontal axis. We have also shown that horizontal and vertical components of air movement appropriate to this structure exist in actual depressions. Now Fujiwhara (28) gave numerous examples of the tendency of a vortex with horizontal axis parallel to a fixed bounding surface,—as in particular the surface of the earth—to break up into other vortices each becoming symmetrical and having its axis perpendicular to the fixed surface. These vertical axis vortices are links in the dissipation of the available energy and he looks upon the principle of tendency towards symmetry in this way as belonging to the same category as the second law of thermodynamics. It seems that, in the atmosphere, given the main vortex with horizontal axis, then local surface conditions can and do determine the points where vertical axis vortices will develop. Certainly cases arise which very definitely fall into this type and where the idea of travelling waves is very difficult to apply, even though the individual depressions show in their actual structure the ordinary Bergen picture of events.

As an example of such cases we take the period March 18–19, 1933. At the beginning of this period the distribution of pressure over Scandinavia, most of the British Isles and the part of the Atlantic lying to westward of our Islands was most irregular. At 18h. on the 18th a trough with several low pressure centres ran roughly west-south-west to east-north-east across western Europe. To northward of our islands there extended a great belt of north-easterly wind and to southward of our islands a great belt of westerly wind. In the intervening region of irregular pressure distribution no fewer than six low pressure systems are marked on the 7 a.m. synoptic chart of the International Section of the *Daily Weather Report*. One of these, centred near Lewis at 18h. on the 18th, looks small and comparatively innocent. A surprising amount of precipitation (it was partly rain and partly snow) was associated with the line of advance of this small centre ; actually over two inches were recorded at Butt of Lewis, but even in the southern parts of the same island the amounts were much smaller. There was much rainfall or snowfall also in the Orkneys and north-east Scotland, and smaller, but appreciable, amounts of rain all over Scotland, at the same time. These were associated with an occluded front which, with the help of the autographic records, can be traced as belonging to the small depression and probably connecting it with others of the system and as sweeping across Scotland and the north of England during the night of March 18–19. The manner in which this front swept round is strongly reminiscent of a type of eddy in a fluid as portrayed by Fujiwhara (28). (The case is of interest also because, without the autographic records, the extent of country directly affected by this front would probably be underestimated, and the precipitation some distance away from the centre of the depression might seem to be of casual and local type. Also, the considerable development attained by another small centre which passed over the south of England a day later is less surprising, when it is remembered that the first mentioned member of the system, namely the depression near Lewis, though small, possessed the energy associated with over two inches of precipitation). So far as can be deduced from the autographic records this depression also approximated to a simple vortex with maximum speed of some 40 m.p.h. about 60 to 70Km. from the pressure centre. As in the case of October 7–9, 1930, there were north-easterly winds to north and even to north-east of the centre and these were blowing considerably across the isobars towards the low pressure.

A most interesting further point about this case of March 18–19, 1933 is that the whole system of depressions or line of eddies (all of similar depth) did not travel appreciably in the west to east direction but swung round bodily until the line was roughly south to north ; then the depressions finally filled up more or less in step with one another. Fewer centres are shown on later maps, but this need not mean that there were actually fewer centres. That point, however, is not so important as the feature that a common cause or common causes apparently governed both the depth and the behaviour of all the members of the system. One common cause, operating to cause diminution of intensity, might be that the separate centres passed on to land or inland waters and were then drawing upon an air supply less nourishing to their energy than that obtained by the centres near north Scotland and south-west England, a day or two earlier.

The swinging round of the whole system, however, is a different effect,—something that we must attribute to the general circulation. Taking this with the feature that there was but little tendency of the various lows to advance along fronts, we are induced to think of the lows in this case not as waves but rather as members of a line of vortices, surface intersections with the contortions of one long upper air vortex or potential vortex, the general run of whose axis was horizontal.

Another not unusual feature of depressions suggests that they are of the vortical eddy nature, namely, the occurrence, in the outer areas, of small disturbances of eddy type. For example, at Bell Rock on October 5, 1929, in front of a large depression than centred over south Ireland, the anemogram indicated the passage of a small disturbance in which wind backed from SW. to S., then—in the course of about 3½ hours—veered through W., N. and E. to about SSE. as if a small cyclone had passed over the station.

There is another matter which has a bearing on the conception of the polar front as a horizontal vortex line, namely, the events associated with occlusions and seclusions. In a recent paper on the rainfall of depressions (21) the writer has pointed out the frequency with which high rates of rainfall occur at occlusions, higher rates on the whole than are associated with either warm fronts or cold fronts. Also, as we know, secondaries with their heavy rainfall and frequent evidences of " rotating fluid " originate on occlusions. Again, as W. H. Pick (29 has shown.

the English tornadoes of October 27, 1913 and June 14, 1931 were each associated with the passage of the line of occlusion of a depression. Now, if an occlusion represented only a catching up of cold front processes with warm front processes, as generally understood and frequently in a dying depression, one would rather expect a certain degree of diminution of the violence of upward air movements. If, however, a vortex or even potential vortex with horizontal axis is actually doubled back on itself, we have two linear loci of upward motion approaching close together, with consequently additionally powerful uplift of the air between and underneath. Not only so, but any lack of homogeneity of the intervening air along the surface trace of the line of occlusion will result in localized uprushes at the points where conditions are least stable, for example over land areas in calm summer conditions or over sea areas in winter. We thus have in an occlusion, and especially in summer over land and in winter over sea, the possibility that convergence towards a line—which we may regard as the normal feature of the large depressions of temperate latitudes—may be replaced by convergence towards a point. Normally, this would mean a secondary with all the evidence of vortical motion, but in particularly violent forms it might mean disturbances of tornado type. Actually it is in the south-eastern sectors of large depressions, i.e. where the line of occlusion normally lies, that the tornadoes of the United States are most usually formed. It is of further interest to observe that A. Wegener (30) and G. T. Walker (31) have developed the theory that the vital part of a tornado is a vortex with horizontal axis, usually directed from north-west to south-east, with the south-easterly end of the vortex prolonged at times and bent down to the ground. The circumstances attending their occurrence seem equally to support the suggestion that secondaries and tornadoes should be regarded as singularities on a line of occlusion, regions where the long horizontal vortex, doubled back on itself, leads to point convergence locally.

§ 12.—DESCENT OF AIR AND DIVERGENCE

If we are to regard depressions as vortical systems, in the initiation of which vertical motion has played an important part, the question arises as to where the corresponding descent of air occurs. Some descent of air has been found to occur in the warm sectors a few hundred kilometres southward of the centre of the depressions of October 1–3, 1929, January 1–2, 1930 and October 7–9, 1930, and this may be a general feature of developing depressions ; but this would not account for all the tropical air which goes up near the centre, and along the warm front. There must also be descent of polar air, and on an important scale, somewhere in the outlying regions of the polar air to compensate for the great convergence of polar air towards the central area of the depression. This descent must therefore be looked for in the wedges and ridges between the depressions. Actually both these conclusions about descent of air are in accord with the results found by Lempfert and Shaw (32) in the " Life History of Surface Air Currents ". They say " We have failed to identify the central areas of well-marked anticyclones as regions of origin of surface air currents. The areas of descending air seem to be (a) the shoulders or protuberances of anticyclones, in particular the regions of comparatively high pressure between two consecutive cyclonic depressions, and therefore also between two anticyclones, or the extension of an anticyclone, between a depression and its secondary ; (b) the trough lines of travelling V-shaped depressions and parts of the central area of travelling circular storms. The latter have not been identified sufficiently well for them to be specified in a precise manner, but there is too much evidence in favour of the descent of air within the region of approximately circular isobars for the exchange of air between the surface and the upper layers in these regions to be disregarded."

Having already dealt rather fully with the central areas of depressions we may inquire what other evidence there is that wedges and ridges should be regarded as boundary regions associated with descent of air and divergence, lying between different circulations of cyclonic type. The weather experienced in them is certainly in a general way evidence of subsiding air movement. The winds, however, at well-exposed sea stations, also show discontinuities of a type which verifies this suggestion.

A typical case is that of September 2, 1929 when the Bell Rock wind record showed at 22h. a complete and quite sharp reversal of wind from W. to E. with the passing of a ridge of high pressure separating two depressions centred respectively over Scandinavia and over the Atlantic to westward of the Bay of Biscay. When the corresponding change had occurred at Tiree it was less sharp but quite marked,—NNW. wind to calm, then E. then SE. This case is dealt with in more detail below. An almost exactly similar situation occurred curiously enough on September 2, 1930. In this case the change of wind, in the centre of the ridge, from a definite WNW. to a definite ESE. wind occupied half an hour.

Another case of a sharp change in a ridge occurred at Bell Rock on September 16, 1929 near midnight. October 1, 1929 mentioned in the early part of this paper, affords another example of discontinuity of wind in a wedge. Again on November 4, 1929 at 4h. the Bell Rock record showed the sharp change of wind from one depression system to another occurring in the middle of a wedge.

The ridge of high pressure of September 2, 1929, if we may reckon from aeroplane ascents made when it was passing over south-east England, consisted of cold air in the lowest 2 or 3Km., with an isothermal layer about a kilometre deep and then warm air above about 3Km.; the wind was in the lower part from about WNW. and above 3Km. it was from about WSW. The available pilot balloon ascents show that the change of wind direction as the ridge passed, was greatest in the lowest layers where it was a change from WNW. to SE., whilst at the 3Km. level the change amounted only to a slight backing from WSW. to about SW. The change of surface wind from W. to E. is shown on the anemogram of Fig. 13 (facing p. 25) for Bell Rock. It will be seen that the W. wind, whilst gradually falling in mean speed, had impressed upon it a series of waves of the regular and symmetrical type associated with a discontinuity in the upper air and conditions of general vertical stability.

Another typical case showing the passage of wedges accompanied by these regular waves in the surface wind at Bell Rock was the period October 12–14, 1924 when also there was an inversion at about 2Km. level with warm air above. The frequency of inversions at about this level is in fact notable, and has elsewhere been remarked upon by the writer (16). Peppler (33) has shown that, excluding surface inversions, the level of greatest frequency is about $1\frac{1}{2}$ to $2\frac{1}{2}$Km. and that the frequency becomes very small above 4Km.

Considerable divergence is indicated in the case of September 2, 1929 along the centre of the ridge between the westerly and easterly currents. It does not appear that one of these partially overlay the other but rather that the warm WSW. and later SW. stream overlay both. Thus the divergence can be accounted for only by subsidence or leakage away of the cold air composing the lower currents, coupled with the inflow of warm air at higher levels. That this was the process is supported by the fact that a day later, in the rear of the ridge, the warm air had got down to the 1Km. level. The structure of the ridge is shown diagrammatically in Fig. 14.

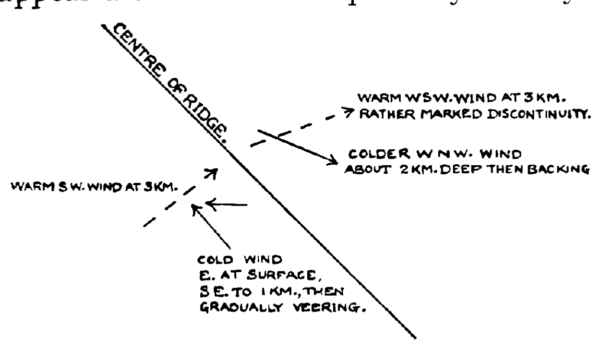


FIG. 14.—TYPICAL STRUCTURE OF A RIDGE OF HIGH PRESSURE.

§ 13.—DISPOSAL OF AIR ASCENDED IN THE CENTRAL AREAS AND AT THE WARM FRONTS OF DEPRESSIONS

Experience gained from pilot balloon ascents shows that the places where pressure is rising, i.e. the rear of a depression or the front of a wedge, are in general places where the wind backs with height in the first two or three kilometres or even higher,—typically a WSW. wind overlying a WNW. wind; the places where pressure is falling, i.e. the rear of a wedge or the front of a depression are conversely, in general, places where wind veers with height,—typically a SW. or WSW. wind overlying a SE. wind. These relationships appear to be almost fundamental to rising and falling pressure regions respectively and in indicating the (surface) regions of subsiding and of ascending air respectively. We may regard the Bergen structure of warm and cold fronts as particular cases of this more general type of relationship, and from pilot balloon data we may say that in general up to the middle levels of the troposphere these conditions hold.

It is clear that, if there is not to be accumulation of air at higher levels and if there is to be no penetration of the tropopause and still more so if there is to be actual " eviction ", there must be outward movement of the air with respect to the cyclone from the upper levels of the troposphere. According to an idea proposed by Aitken and already quoted in the Introduction, the converging and uprising air, as a dynamical consequence of loss of pressure, acquires speed sufficient to cause considerable centrifugal action in higher levels. In the Introduction also it is already mentioned that this is not a complete statement of the case ; part of the loss of pressure of any uprising mass is reflected in an adiabatic fall of temperature. Whilst observational detail is far from sufficient to enable a complete picture to be built up we can deduce certain probable consequences. The general drift of air at the two or at least at the three kilometre level above sectors B and A (see Fig. 8) is about WSW. and thus much of the converging surface air from both of these sectors must be carried eastwards and upwards by the escalator or upsliding action at the warm front. That the upper air structure in this particular region points to such a mechanism is supported by the conditions quoted in § 10 from Bergeron and Swobada's work and is confirmed in an indirect way by the characteristic distribution of precipitation. Whilst this method of eviction of air from the central area may be partly penetrative movement by air which actually started from surface level, it is more likely to be in large part in the form of a consequential general and slow upward displacement of the central core of the depression, with a maximum of upward velocity near the warm front surface of discontinuity. Such a movement would be in accord with the average statistical results from upper air data in low pressure regions.

Here however is a movement which, though it may have owed its initiation to some convectional action in the surface levels could not, in the fully developed state and at higher levels, be maintained out of such beginnings. The only source of energy, so far as can be seen, from which the necessary contribution could be made is again the kinetic energy of the fast moving air. Without this the movement would quickly achieve an equilibrium and come to rest. Such a contribution could be made in the following way. The tropopause is known to be on the average lower over low than over high pressures and yet it constitutes so great a barrier to penetration by air from below that such cannot be contemplated as occurring. The uprising air would thus require to spread outward on reaching the higher levels of the troposphere or it would add to the pressure in these levels. If it did the latter the result would be to reduce the pressure gradient in these levels and thus to leave the air speed in outer zones of the depression in excess of that appropriate to geostrophic balance. If this happened outward movement across the isobars would at once result until some measure of equilibrium was again restored. Then, in turn, latent energy released by condensation of water vapour from the continued upward movement of air could assist so that, given favourable conditions, the depression could continue in being. We cannot however say from observational evidence whether outward motion across the isobars, i.e. the isobars at these levels, occurs, i.e. whether there is anything analogous to Aitken's " centrifugal action " at these levels. It is difficult to get exact observational evidence on this point, partly because the chief depressions pass to northward of the British Isles and partly because upper air data tend in any case to be scarce in depressions. The numerous cloud observations in the Upper Air Supplement to the *Daily Weather Report* do however afford qualitative evidence of outward movement from the centre of depressions at high levels, i.e. outward with respect to surface isobars. One such case is that of November 5–6, 1930. At this time a centre moved from the south-west of Ireland to west France. Five observations of cirrus, cirrostratus or alto-cumulus cloud over England on the morning of the 5th showed definitely divergent movement with respect to the surface isobars on the east side from the depression towards a ridge, whilst two further observations of altocumulus cloud on the 5th and 6th showed divergent movement on the north side of the depression. Numerous further cases may be quoted. Divergent movement from depressions towards ridges is shown in nephoscope observations of altocumulus on November 7 and 9, and in several high cloud observations on November 12, and again in observations on November 18, 19, 25, 27 and 30.

Douglas (34) has given examples of the cirrus movement above depressions at various stages of their development. An excellent example of divergent movement in the upper levels in the warm current of a depression, as shown by a balloon, is also quoted by Douglas (35). On December 9, 1909, a sounding balloon sent up from Crinan fell at a point 112Km. in a direction S. 67° E. from its starting point though there was a south-westerly gale at the surface and tropical air throughout the whole ascent, the tropopause being (characteristically for tropical air) at a height of over 12Km. Thus in this case in the higher levels there was considerable drift outward from a region of low pressure around Iceland and over the North Atlantic across the isobars (as shown for surface level), towards a wedge of high pressure over France.

In the forward part of tropical cyclones also, Cline (as already quoted in a passage in § 5) has noted that the movement at higher levels is divergent with regard to the centre.

We may therefore extend the statement, though mainly on qualitative evidence rather than exact measurement, and say that a veer of wind from the surface right up to cirrus levels appears to be associated as a rule with the forward parts of travelling depressions and the rear parts of ridges, and conversely a backing is associated with the rear parts of depressions and the forward parts of wedges and ridges. A veer arises as the effect of the inflow of layers of lower density than those originally overlying the place under discussion, a backing as the effect of inflow of layers of higher density. This point is dealt with dynamically in Appendix IV.

§ 14.—ANALOGY TO THE CENTRAL " CELL " ACTION IN DEPRESSIONS

It may be useful here to point out a meteorological analogy on an intermediate scale between Aitken's miniature cyclones and the full scale depression. Consider the case of sea breezes on a south coast. The diurnal heating of the air over the land bulges up the isobaric surfaces and causes a flow-off of air at perhaps 1000 feet from north towards the sea. In turn the increased sea-level pressure over the sea causes a flow of surface air as a south wind towards land. Towards evening the sea breeze in well-developed cases veers to W., i.e. becomes parallel to the coast ; and during the night the surface wind changes to the northerly land wind. The total upward motion in general is at most only such as to produce cumulus cloud. If we could have, over the sea only, the tangential wind postulated by Aitken it might, with suitable adjustments, lead to small closed horizontal circulations. If we regard the whole sea breeze system as a cell-like action we have a depth of perhaps one kilometre in a north-south extension of perhaps 20 or 30Km.

Coming to the full-scale depression we may regard polar air overlying a warmer sea as the equivalent of the land air in the sea breeze analogy. To southward and also overlying the edge of the polar air we have tropical air with presumably at least adequate " tangential " (i.e. westerly wind) speed. In addition to the warming of the polar air from below we have it humidified. As a first development we should have the bulging upward of the isobaric surfaces in the troposphere as the polar air is heated from below, and a superposed component in these and higher levels from north to south ; as the second step the backing of the westerly wind to a more southerly point. In this case the cell, within which the action occurs—the central area of the depression to which we referred in §5— is probably initially 2 or 3Km. deep and perhaps 100Km. in horizontal extent if we take the relation of the vertical to the horizontal dimensions as being about the same as in the sea breeze phenomenon. The energy available in particular cases would determine whether development would continue until a large depression was formed with a central cell consisting of a width of perhaps 400Km. of the warm sector and perhaps 200Km. of the cold air on the north side of the centre.

The analogy with the sea breeze cannot however be carried very far. In the full scale depression upward air movement leads to, and its continuation is assisted by, precipitation and, by interfering with the high speed flow of air in higher levels. it brings the energy of the latter into the system ; and the combined effect of this action in the central cell is then to induce convergence and cyclonic circulation in the lower layers of surrounding regions, with divergence in the upper layers of the troposphere and necessarily—since the stratosphere rests upon the troposphere —in the lower stratosphere also. The depression process, if it proceeds successfully, is not reversible, it is mainly a dissipation of energy, though the opposite process, for example, leading to the formation of continental anticyclones in winter, does occur under the appropriately reversed conditions.

§ 15.—CONSISTENCY OF THE RESULTS WITH ESTABLISHED KNOWLEDGE OF AVERAGE UPPER AIR CONDITIONS OVER LOW AND HIGH PRESSURE SYSTEMS

In connexion with the formation of depressions the statistical result that depressions are relatively cold in the layers from 4 to 9Km. has frequently been advanced against the idea that convection can be an important factor. Cases of young and vigorous depressions, when the centre is not cold, can be quoted, but the general statistical result which applies to depressions in their later stages is capable of explanation. The formation of cumulus clouds is undoubtedly started convectionally yet the air in them is frequently colder than the air of the immediate environment. In both cases the difficulty of explanation probably exists only as long as attention is confined to an isolated part in the complete thermo-dynamical system. In both cases the central region of upward movement is relatively small in relation to the whole cell which is in action, so that, once the movement has started, it is by no means necessary that its continuance should depend on the conditions then found to be existing in some particular part of the rising core. Also, the upward movements in the atmosphere, whether in convectional clouds or in cyclones, are relatively localized and have smaller cross-sectional area and higher mean speed than the compensatory downward movements, which in general consist of gradual subsidence over relatively wide areas and are therefore difficult to explore. Most important however to the maintenance of the cyclone is the fact that the initial exchanges of air between surface and higher levels bring into action at surface levels some of the enormous kinetic energy which the tropical air current, especially in its higher levels, possesses.

It can now be proposed that the following is the mechanism by which this energy can be transmitted and expended in continuing to raise the central core in the later stages of the depression's life when the core has, through ascent, already become relatively cold. We have found that depressions in a later stage of their existence have a central core in which air speed is proportional to distance from the centre and that nevertheless in the lower two kilometres there is convergence of air towards the centre. If the moment of momentum of this air about the centre were conserved in the same manner as it is in the outer vortical region we should have a continuous increase of the air speed with approach to the centre. Since this does not occur we must conclude that in all depressions and very notably in the later stages of their life the air below 2 Km. in the inner core is giving up its energy by doing the work required to lift the overlying mass. Thus we have a sequence of events in which an initial convectional impulse brings into play the great energy of the upper air ; transmitted pressure change then sweeps in air in surface levels from the outer regions towards the centre, and this air, when it comes within some 500Km. of the centre in turn gives up its kinetic energy to help the upward movement of the middle layers of the troposphere.*

It has been found (§4) that some of the air drawn in on the north side of a

* A calculation has been made to confirm this. Assume the air at the periphery of the inner core (500Km. in radius) to be moving at 20 m./sec. and converging at an angle of 25° to the isobars round half the periphery, with no convergence or divergence on balance on the other half ; also take these conditions as holding up to the 2Km. level. Then the equation of continuity requires that at the 2Km. level there should be a mean upward movement at the rate of ·036 m./sec. The energy required to lift the core at this rate, assuming the mean temperature in the core to be 7° C. lower than in the environment (roughly the average of W. H. Dines' results for old cyclones) has been calculated and found to be approximately half the total inward flux of energy in the case specified above.

cyclone and thrown out on the south side has had work done upon it by the cyclone, emerging with a speed, in relation to pressure, higher than that with which it entered, —and further that this air is thus rendered capable of doing work in pushing under other air and helping to form a high pressure system. The air diverging from the centre in the cirrus levels above a cyclone must also be capable of doing considerable work before it comes to rest. It has a high speed,—the speed in fact may in general exceed the gradient value, though that cannot be proved by any means of observation available so far ; we know that it cannot readily penetrate the tropopause because of the high degree of "resiliency" at that level, and it must therefore travel approximately horizontally and make room for itself under the stratosphere. This its kinetic energy makes possible and as it gives up the kinetic energy both its pressure and its temperature will be raised. In the regions where it comes to rest (or even again into equilibrium with the gradient), the troposphere will have been increased in thickness and the stratosphere raised. This piling up of air in the upper levels leads in turn to divergence of other air in the surface layers, apparently below 2Km. according to § 14, so that we have a complete cycle of events, though not a cycle of the same air. Any descent of the air is more appropriately described as subsidence, associated with leakage at the bottom.

There are thus apparently two distinct ways in which anticyclones may be formed by dynamical action as part of a cycle in which cyclones play an essential part by providing kinetic energy to be turned into potential energy, namely (1) by insertion of additional air at the bottom of the troposphere and (2) by insertion of additional air at the top of the troposphere. The first type of anticyclone may have a considerable depth of cold air and will in general be small and move relatively quickly, i.e. at a speed of the same order as cyclones. It may here be recalled that Hanzlik a number of years ago proposed to classify anticyclones into two types, those which were warm and moved slowly and those which were cold and moved fast. A third method of formation of anticyclones arises more directly from thermal causes operating over large areas, namely the formation of continental anticyclones in winter or ocean anticyclones in summer. The first two processes appear to be in harmony with the general statistical features established by W. H. Dines as characterizing high pressure systems.

We have referred above to the raising of the stratosphere over anticyclones by the air thrown out from the higher levels of cyclones. With this is associated necessarily a circulation in the higher levels of the stratosphere from the regions above the anticyclones to the regions above the cyclones with downward movement of stratosphere air above cyclones and upward movement of stratosphere air above anticyclones. This is exactly the circulation pictured by W. H. Dines (36) as capable of explaining his statistical result that air in the stratosphere over cyclones is relatively warm for its level and air in the stratosphere over anticyclones relatively cold for its level.

According to the scheme described above the energy to develop the cyclone is drawn mainly from the energy of the equator to pole planetary circulation. The most marked evidence of this energy in kinetic form in temperate latitudes is the high speed motion of the tropical air, more especially in the upper air above the main polar front. The interchange of the tropical and polar air might (somewhat remotely), conceivably take place without cyclones forming, were it not that the main polar front is a surface where small inequalities may easily arise and destroy stability. More specifically any local warming or humidifying of the surface polar air produces conditions and introduces vertical motion leading to the formation of the central cell of a cyclone and bringing the great store of energy above into action at lower levels. We have then the formation of a cyclone in a manner analogous to that described by Aitken in his model experiments, except that in the full scale cyclone of temperate latitudes it is mainly geostrophic rather than cyclostrophic considerations that apply or fail to apply throughout.

§ 16.—SUMMARY AND CONCLUSIONS

The low and high pressure systems dealt with in this memoir show the following characteristics and lead to the following conclusions.

1 Excluding a central area we find that both in the forward and the rear parts of depressions and notably in the cold air the average surface air motion is approximately that of a simple (vr = const.) vortex. Two cases treated in detail which were of similar depth had closely equal vorticity.

2 In the polar air part of the central area of depressions there is sometimes, but not always, an approximation of the average speed to direct proportionality to distance from centre. It is found, however, not to be solid rotation. There is in general considerable incurvature and—in the large primary depressions examined—the dynamical conditions for a disc of air spinning like a solid and having a general translational motion are not satisfied ; the probable existence of solid rotation in intense secondaries is accepted. So far as can be seen, such of the tropical air as approaches the centre maintains a fairly uniform high speed, and it shows little if any indication of proportionality between speed and distance from centre.

3 There is evidence that the central polar area, characterized by the approximate v/r = constant type of motion, increases in diameter with the age of the depression.

4 The above are average relationships between speed and distance from isobaric centre. A more detailed analysis of the conditions throughout the central area reveals a cell-like structure with convergence of air, both the cold and the warm, below the 2Km. level towards a length of the main front running through the centre of the depression, and thence upward motion. The analogy with a feature of Aitken's model cyclones is indicated. The convergence here in turn explains how the vortical nature of the air movement has developed in the outer regions of the depression.

5 In the two cases examined in great detail a line of divergence is found lying in the warm air some 400Km. south of the warm front. Divergence is also established in a third case examined. An explanation of the process of occlusion is advanced.

6 From a consideration of the places and circumstances in which depressions originate or develop increased intensity, and of data relating to temperature and wind in the upper air it is concluded that a dual causation is indicated, in which (a) the energy required is drawn mainly from the high speed of the tropical air particularly in the higher levels (that is, in effect from the planetary circulation) and (b) the immediate initiation—which in some cases may be little more than trigger action—is the warming and humidifying of the polar air along its fringes at a warm front. Two further analogies with Aitken's model cyclones are indicated.

7 The sea breeze is suggested as an analogy, on an intermediate scale, in which, owing in general to the absence of Aitken's "tangential wind", the phenomenon does not develop to the cyclone stage.

8 Using partly the results of earlier investigations by the writer it is concluded that discontinuities of the type at which irrotational waves with periods of two hours or less are sometimes set up must be unfavourable, being characteristically stable, for the development of greater waves and cannot in themselves lead to disturbances of the nature or magnitude of depressions. A case of approximation to a wave of rotational type is shown. No evidence is found that gravity waves have any determining part in depression formation.

9 The structure of wedges is studied, the regions of divergence at the surface, and the evidence of divergence in the higher layers of the troposphere. The bearing on the formation of anticyclones of two types is discussed.

10 The conception is supported of the main polar front as having theoretically the properties of a horizontal vortex line, any portion of which, when the stability of the arrangement of the cold and warm air masses is disturbed from below by suitable local conditions, is the potential locus of line-convergence, i.e. of a depression. The conception is extended to regarding a line of occlusion as a main vortex line doubled back on itself and as being—again given suitable surface conditions—the potential locus of point-convergence, i.e. of a tornado with strong rotational features.

11 The general conclusions about the mechanism of low and high pressures are shown to be consistent with the statistical relations established by W. H. Dines as applying between temperature and pressure in the troposphere and in the stratosphere ; it is shown how a cyclone in later life can still for a time raise a central core already cooled.

12 To avoid misconception it should be added that the studies support in a general way the Bergen structure of the warm and cold fronts of depressions and the association of the chief precipitation areas with the fronts ; at the same time the point of view is reached (though further studies are required to explore it) that this typical structure is a result of the circular and converging motion which is impressed upon the edges of the polar air mass by the depression process and that the depression process—though liable to be started off whenever local conditions are favourable to its initiation—is but a stage in the dissipation of the kinetic energy of the planetary circulation.

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APPENDIX I.—MOVEMENT OF AIR IN RELATION TO BAROMETRIC GRADIENT IN THE FORWARD AREA OF AN ADVANCING DEPRESSION.

The object of the note appended here is to consider the variations of wind speed and direction as recorded at an anemograph station in the old cold air in advance of an approaching depression. It can be shown that these variations are such as are indicated by calculation on the assumption of a barometric gradient gradually impressed from above. Whatever theory is held as to the manner in which the change of gradient is brought about, if the motion of the old cold air (except close to the warm front) is developed as the result of convergence towards the central area of the depression, its motion is controlled by mass movements in and around the depression generally, and therefore by a changing transmitted pressure. The variations in surface wind speed and direction have as a rule certain well-known characteristics, in particular the gradual backing of wind at first with rise of speed, sometimes to a definite maximum, and then some fall in speed before the warm front arrives. It is therefore of interest to examine the process in detail, taking account of the effect of surface friction on the moving air.

Taking the case of October 1–3, 1929 the barometric gradient measured from the chart at 13h. on the 1st, was W. 9 m/sec. in the region of Bell Rock. The approaching depression soon afterwards began to impress a different gradient on this region. At 13h. on the 1st, the actual speed at Bell Rock was only 60 per cent of the gradient value, an unusually low proportion. By a process of interpolation from the synoptic charts the gradient is estimated as having become SSW. 25·5 m/sec. by 21h. 30m. (The gradient in the warm air reached about 29 m/sec.)

It is noteworthy that this new gradient approximated closely to that existing in the warm sector which arrived shortly afterwards. To effect a dynamical discussion of the sequence of events let us suppose that originally there existed in the cold air a westerly gradient of value $\Gamma = 9$ m/sec. and that the wind was in accordance with this gradient and a ground level coefficient of friction μ. Suppose then that a southerly gradient is gradually impressed upon the area so that at time t its value is $k\,\Gamma\,t$. Taking the x axis pointing north and the y axis pointing west, the equations of motion of the air are :—

$$\ddot{x} - \Omega \dot{y} = -\mu \dot{x} + \Gamma$$
$$\ddot{y} + \Omega \dot{x} = -\mu \dot{y} + k\,\Gamma t.$$

where $\Omega = 2\,\omega \sin \phi$, ϕ being latitude and ω the angular rate of rotation of the earth. Multiplying the second equation by i, adding and putting $v = \dot{x} + i\dot{y}$ we find

$$\dot{v} + (\mu + i\,\Omega)\,v = \Gamma + ik\,\Gamma t = \Gamma\,(1 + ikt)$$

of which the solution can be shown to be

$$v = \frac{i\,k\,\Gamma}{(\mu + i\,\Omega)^2}\left\{e^{-(\mu + i\,\Omega)\,t} - 1\right\} + \frac{\Gamma\,(1 + i\,k\,t)}{\mu + i\,\Omega}$$

Now strictly speaking the changes in v in this equation are the changes undergone by the same mass of air, i.e. they should be compared with the speed variations recorded along a trajectory of air if that were possible. A close network of perfectly exposed anemographs does not exist, but in the present case examination of the records of Bell Rock, Tiree and Holyhead suggests that the speed variations of the trajectory of the air which reached Bell Rock at 21h. 30m. were somewhat like the dotted line in Fig. 3, i.e. not greatly different from the Bell Rock speed record. From records so widely spaced only a rough representation is possible. But in such cases—and an examination of trajectories of comparable type in Lempfert and Shaw's "Life History of Surface Air Currents" supports this view—the speed variations along a trajectory are often not greatly different from those recorded at a fixed station, always supposing that the record is entirely within the same air mass. At 12 noon this air was probably in the Holyhead region and affected by a barometric gradient not greatly different from that which will be assumed for the air at Bell Rock one or two hours later. The value of v attains a maximum at a time given by $\Omega\,t = \pi$ i.e. t approximately 7 hrs. for $\phi = 58°$.

Now in the actual case the maximum is attained at 21h. 30m. We shall therefore suppose that the southerly component of the gradient begins to be impressed on the moving air seven hours earlier, i.e. at 14h. 30m. and that this component attains its maximum of 3 Γ by 23h. 30m. (the westerly component of Γ persisting throughout this time and thus giving a resultant of about 28·5 SSW. for the maximum value reached) and shall then compute the course of v and the direction. This has been done for values of t corresponding to

$$\Omega\,t = 0,\ \frac{\pi}{2},\ \pi,\ \frac{5\pi}{4}$$

i.e. corresponding to the times 14h. 30m., 18h., 21h. 30m., and 23h. 15m. Also the values of v in the warm air have been added and the whole plotted on the anemogram. The result is seen to be in general agreement with the trajectory and thus of course not much different from the actually recorded values at Bell Rock. The gap from 23h. 15m. to about 5h. 30m. corresponding to the passage of the warm front cannot be subjected to theoretical calculations, because the details of gradients and of how the different air masses are being mixed are unknown. It seems however that we are justified in saying that the surface (cold) air at Bell Rock, for nine hours or thereabouts, followed very much the course which it would have been expected to follow if it had been moving under the influence of a gradient impressed from above in the way supposed. Other examples can be found where, in front of a depression, wind seems to rise, as if overshooting the gradient and then fall away with a suggestion of a 14-hour period. One such was the depression which set in at Bell Rock and Butt of Lewis on November 18, 1929. The winds in the cold air before the warm front, at both stations, were actually the highest reached in the depression, though in this case it would seem that the strongly flowing warm air did not really get down to ground level. (Leuchars, Renfrew and Aldergrove pilot balloon ascents show speeds on the 20th of the order of 60 m.p.h. at the 2Km. level).

Another depression with its strongest wind SSE. was that of January 23–25, 1930. These look like cases where the gradient in the old cold air is set up by the action of an agency quite external to the old cold air. If sufficient time is available, the cold SSE. surface current may have an opportunity to overshoot the gradient speed for an hour or two. It appears that at such times, and only at such times, its speed can exceed temporarily the mean speed of the warm air. The fact that the highest gradient value reached in the old cold air only just falls short of that in the warm SW. or SSW. current gives ground for believing that it is the warm current which most likely is the external agency responsible in some way for controlling the gradient in the old cold air in front of the depression. The diagrams of Fig. 2 point to a similar conclusion, in that the periphery of the core of cold air rotates at a speed closely approaching but just under that of the warm air. We conclude indeed that it is the upper warm current that supplies the greater part of the energy to set up the gradient that draws in the old cold air in front of the depression and to rotate the cold core.

It may be remarked that at Bell Rock in the case of the tropical air the actual speeds recorded ranged around 85 per cent of the gradient value, and were highest when the centre of the depression was nearest.

Appendix II.—THE RESULTS IN RELATION TO THE THEORY OF A WAVE ORIGIN.

The velocity results of the case of October 1–3, 1929 were considered from the point of view of a wave origin for the depression. Following Gerstner and Rankine (see Lamb, "Hydrodynamics" 5th edition, pp. 396–8), and taking the axis of x as parallel to the polar front and that of y as perpendicular thereto, the motion of a particle (additional to any translational effects of the whole field) may be specified on the Lagrangian plan by the equation :—

$$x = a + \frac{1}{k} e^{kb} \sin k\,(a + ct)$$

$$y = b - \frac{1}{k} e^{kb} \cos k\,(a + ct)$$

where a, b are parameters serving to identify the particle. The actual paths are circles of radius $r = e^{kb}/k$ and the speeds are given by $v = c\,e^{kb}$.

Thus v/r = constant $- ck$.

Now in the above mentioned depression of October 1–3, 1929 we have $c = 5$m/sec. and $v/r = 11/400$ v and c being expressed in m/sec. and r in kilometres

therefore we find $\lambda = 2\,\pi/k$.
$= 1140$Km.

As it happens the diameter of the inner core is pretty nearly as great as this, so that these formulæ altogether gave a reasonable representation of the average motion.

Thus if the depression could be regarded as some sort of wave, the diameter of the inner core would correspond to the wave length. A point of importance however is that though any motion that can be expressed by the above equations satisfies the equation of continuity, the motion is not irrotational, but rotational. It cannot therefore be originated from rest, (or destroyed) by the action of forces derivable from a potential. Lamb points out that for the genesis of such waves "by ordinary forces, we require as a foundation an initial horizontal motion, in the direction opposite to that of propagation of the waves ultimately set up, which diminishes rapidly from the surface downwards," and further, "it is to be noted that these rotational waves when established, have zero momentum". An easterly polar current, if its speed increased with height, might therefore be regarded as a possible foundation for a rotational wave travelling from west to east. But equally the motion could arise with the assistance of convection currents generated by unequal application of heat or humidity or from some cause which altered the relationship of density to pressure. If therefore we have ground for believing that primary depressions do not as a rule develop to considerable intensity unless over relatively warm water surfaces, then there is reason to suppose that the special motion of the air has in fact been set up with the assistance of the second means mentioned above.

Appendix III.—POSSIBLE GEOGRAPHICAL EFFECT OF THE BRITISH ISLES IN ORIGINATING SECONDARIES

The possible geographical effect of the British Isles and North Sea area is of interest. The indications of Fig. 8 may be compared with the mean winter conditions over the British Isles. The Table below gives mean values, for the four months November–February, of the direction of the isobars, the inclination of the surface drift of air to the isobars, the percentage relation of surface drift to geostrophic wind, and the mean temperature for the four stations, Deerness, Holyhead, Great Yarmouth and Scilly. The values in the first three columns have been computed from data given by Sen (37).

	Direction of Isobars	Inclination of Surface Drift to Isobars	Relation of Surface Drift to Geostrophic Wind	Mean Air Temperature
	°	°	%	°F
Deerness	248	43	49	40·1
Holyhead	248	16	40	43·4
Great Yarmouth ..	253	45	19	39·9
Scilly	255	3	62	47·1

Here there is very little variation in the direction of the isobars, but at the two eastern stations Deerness and Yarmouth the inclination of surface drift to isobars is considerable, owing in part probably to the effect of land friction, whilst at Scilly it is conspicuously small. The proportion of surface drift to geostrophic wind is nevertheless relatively high at Deerness—though small at Yarmouth. These differences and the mean temperatures tell a consistent story, i.e. that Scilly experiences the tropical air and lies with high frequency near a line of divergence of a depression ; Yarmouth mostly experiences continental or cold polar air, and the tropical air seldom reaches it ; Holyhead fairly frequently has tropical air ; and Deerness with a relatively high temperature for its latitude, also fairly frequently experiences tropical air, but differs from Scilly and Holyhead in that it is frequently in a region of strong convergence. The effects on surface wind speed and direction are such as would be anticipated from geographical conditions, but there is at least the possibility that the topographical conditions would exercise some favourable action in the formation of depressions or secondaries.

Appendix IV.—UPPER AIR STRUCTURE WHEN PRESSURE IS CHANGING.

In § 13 reference has been made to the frequent association of falling pressure at ground level with a wind which veers with increasing altitude and the association of rising pressure at ground level with a wind which backs with increasing altitude. Now a veering wind, interpreted in terms of barometric gradient, means inflow, at higher levels, of air of less density and a backing wind means inflow of air of higher density than that which previously occupied the space. The general aspects may be examined dynamically.

Let us assume that above some definite level H (say 20Km.) there is no substantial variation of pressure.

We have then

$$p = \int_0^H g\,\rho\,dz \qquad \text{for the variable part of pressure,}$$

$$\text{and} \quad \frac{\partial p}{\partial t} = \int_0^H g\,\frac{\partial \rho}{\partial t}\,dz \qquad \text{for a given place.}$$

Further, let us consider only the regions where air is moving horizontally and so that any given mass of air does not change its density

$$\text{i.e.} \quad \frac{\partial \rho}{\partial t} + u\frac{\partial \rho}{\partial x} + v\frac{\partial \rho}{\partial y} = 0$$

This automatically excludes the central regions of depressions where upward movement, change of density or level cannot be neglected.

Thus we have

$$\frac{\partial p}{\partial t} = -\int_0^H g\left(u\frac{\partial \rho}{\partial x} + v\frac{\partial \rho}{\partial y}\right)dz$$

$$= -\int_0^H \left\{\frac{g\rho}{p}\left(u\frac{\partial p}{\partial x} + v\frac{\partial p}{\partial y}\right) - \frac{g\rho}{\theta}\left(u\frac{\partial \theta}{\partial x} + v\frac{\partial \theta}{\partial y}\right)\right\}dz$$

where θ denotes temperature.

Now, as we have noted earlier, above a height of 2Km. geostrophic conditions prevail, at least very approximately.

Thus the above expression becomes,

$$-\int_0^2 \left\{\frac{g\rho}{p}\left(u\frac{\partial p}{\partial x} + v\frac{\partial p}{\partial y}\right) - \frac{g\rho}{\theta}\left(u\frac{\partial \theta}{\partial x} + v\frac{\partial \theta}{\partial y}\right)\right\}dz + \int_2^H \rho u^2 \Omega \frac{\partial}{\partial z}\left(\frac{v}{u}\right)dz$$

where $\Omega = 2\,\omega \sin\phi$, ω being the rate of angular rotation of the earth and ϕ the latitude.

The second integral, representing the contribution of the levels from 2 to HKm., is proportional to the square of the west-east component of wind speed and to the total veer of wind speed. For a veering wind this second integral gives falling pressure and for a backing wind it gives rising pressure.

The first integral is one which cannot be exactly evaluated without further assumptions, but contains elements depending on (a) the extent of the departure from geostrophic conditions in the first two kilometres and (b) the speed and the veer of wind in the first two kilometres.

In the case of high or low pressure systems travelling without change or development the second integral alone should give a close approximation to the total pressure changes. In the case of developing systems the first integral representing the contribution of layers below 2Km. would become relatively more important.

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