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ESSAY ON FRONTOGENESIS AND FRONTOLYSIS

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Part II. Deformation field and circulations in the vertical plane

Subsidence is generally considered as a frontolytic agency. Frontal lines of discontinuity in the horizontal plane tend to disappear in the accompanying (horizontal) divergence, and clear skies and sunshine favour modification of the shallow layer of cold air in the lowest levels by surface heating.

Nevertheless convergence in the vertical plane will tend to sharpen existing discontinuity (e.g. frontal) surfaces aloft wherever air subsiding from higher levels meets either vertical up-currents or air masses rising at a slanting angle. The same effect will be present where subsiding air descends upon another body of air which is sinking less rapidly, as the air layers next the earth's surface are normally compelled to do in regions of active subsidence. Namias[8] has given diagrammatic illustration of these points (see also Chromow[9]). Conversely, frontal surfaces associated with general upward motion (as at normal, active fronts with horizontal convergence in the lowest layers) tend to weaken and become diffuse aloft.

It is a curious fact that, when horizontal divergence supplied by downward motions in an anticyclonic situation weakens a front on a surface map, subsidence tends to maintain and sharpen the discontinuity surface aloft. The vertical analysis will sometimes show these sharpened discontinuity surfaces maintaining their identity aloft throughout the life of an anticyclone and eventually becoming involved in renewed horizontal convergence and uplift when the anticyclone breaks down. Upgliding cloud sheets of thin stratus, altostratus or cirrostratus, then appearing in the region of general fall of pressure far ahead of any surface fronts, may give rainfall, sometimes well within the decadent anticyclone. Such cloud systems tend to be located at the surviving discontinuity surfaces aloft, themselves beginning to be deformed by the convergence and vertical expansion of the lower air layers.

An example of the maintenance and sharpening of discontinuities aloft in the vertical convergence associated with subsidence may be followed through all stages of the process in Fig. 9, which shows a vertical analysis (time cross-section) of the lower atmosphere over Downham Market, Norfolk, during the life of an anticyclone centred over England between April 17 and 20, 1945. The time cross-section has been given a time scale that reads from right to left so that the motion of winds and frontal surfaces from west to east may be read in normal fashion from left to right across the paper. The anticyclonic centre first

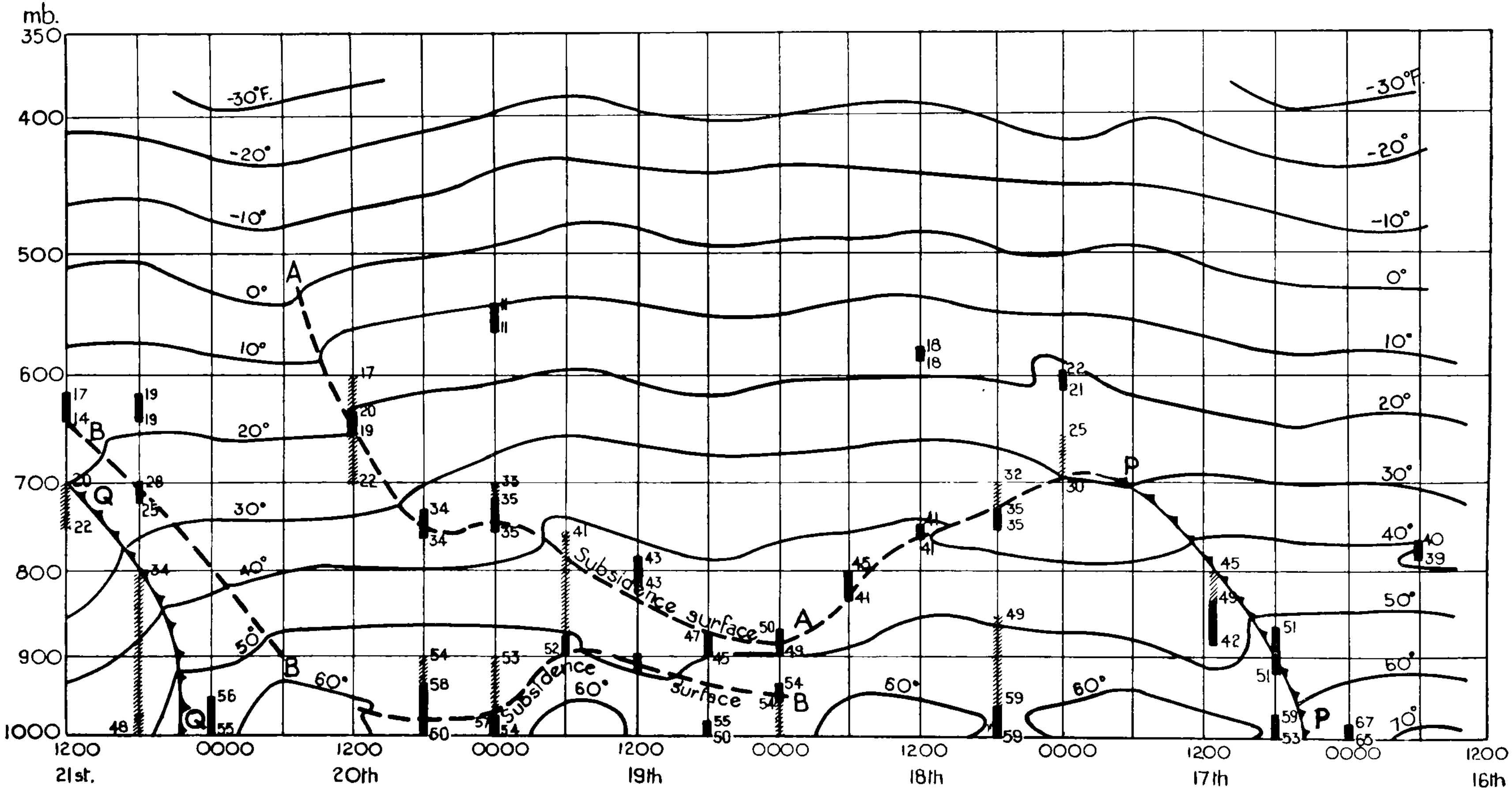

FIG. 9—VERTICAL CROSS-SECTION THROUGH THE ATMOSPHERE OVER DOWNHAM MARKET DURING THE LIFE OF AN ANTICYCLONE, APRIL 16–21, 1945

Vertical lines correspond to successive soundings. Observed temperatures are shown at the top and bottom of stable layers only. Inversions and isothermal layers are marked with thick black lines, stable layers with hatching.

appeared on the 17th in the mouth of the Bristol Channel after the decadent remains of cold front P, which had been well enough marked over Scotland and Ireland the day before, had passed east-south-east. This front was so weak as to be virtually impossible to follow across East Anglia on the surface maps of the 17th. The isotherms on Fig. 9 show it from the temperatures observed on successive soundings between the 950-mb. and 650-mb. levels. It was also shown by a wind shift which was sharpest near the ground, though somewhat blurred by a thermal trough in the isobars ahead of the front on the 16th. Between the 800-mb. and 700-mb. levels the incursion of the colder air mass was shortlived: the temperatures at each level returned in 24 hours or less to the earlier, higher values, rising approximately 3°F. as the frontal surface sank on the 18th and 19th. The frontogenetic sharpening process working on the subsidence surface A, which is the continuation of the cold-front surface P, eventually produced an inversion layer on the 18th–19th where only an isothermal state had existed in the cold-front upgliding stage on the 16th–17th. Temperatures rose 2–4 F at each height with the downward passage of the subsidence surface and later they fell 3–7°F when the same sharpened discontinuity surface was lifted again on the 19th–20th. From the 19th onwards subsidence sharpening seems to have made a distinct discontinuity, designated subsidence surface B, out of the top of the ground turbulence layer; and this too can be traced through the uplift phase as the anticyclone collapsed before the advance of the cold front Q from the north-north-west. An interruption of surface B on the afternoon of the 20th is attributed to convective turbulence resulting from the high ground temperatures in the afternoon at Downham Market. Analysis of the aircraft-ascent readings at the neighbouring coastal station of Langham, where less ground heating occurred, shows surface B without interuption. The anticyclone collapsed on the 20th, pressures at East Anglian stations falling about 15 mb. in the 24 hours before the arrival of cold front Q, which is clearly traced in the abrupt temperature falls between the ground and the 700-mb. level on the 21st in Fig. 9. The new air mass brought temperatures 10–20°F. lower than had previously been observed. A very interesting feature of the analysis is the cooling, at various levels aloft, starting 24 hours before cold front Q arrived. At the 700–750-mb. level three stages in the cooling were traced, and at 650 mb. there were two stages in the cooling from 29°F. on the 19th ultimately to 15°F. on the 21st. That this prefrontal cooling aloft was not just a gradual process is seen from the observed inversions and isothermal layers at successively higher levels on successive ascents, most obviously in the case of the subsidence surface A in the ascents of the 19th–20th. The lifting of the subsidence surfaces with cooling of several degrees Fahrenheit in each case explains the successive upper cold fronts often noticed ahead of major cold fronts at the ground, and is attributed to the setting in of renewed horizontal convergence accompanied by vertical expansion (spreading upward) of the lower air layers ahead of the active cold front.

The increase in depth or re-gathering of a preliminary cold air mass ahead of cold front Q, actually considered as the surface air mass which had become shallow in the central regions of the anticyclone during its lifetime, may imply of course considerable horizontal advection. In the case of the English anticyclone analysed in the vertical diagram, Fig. 9, Mr. Douglas finds that the air concerned was drawn north from a cold pool over the Azores in which a deep reservoir of the cold air mass had accumulated, presumably after the passage of cold front P. Similar effects were revealed by an analysis of the anticyclones of the end of March 1946 over the British Isles and indeed appears to be very usual.

The same deduction of sudden stages of cooling in the upper levels ahead of cold front Q on Fig. 9 follows from the appearance of altocumulus castellatus and cirrostratus bands in the previously clear sky ahead of the front on the 20th. These bands of medium and high cloud were orientated parallel to the surface cold front which they preceded, indicating the controlling influence of this front, ahead of which scattered thunderstorms occurred in the Midlands during the evening of the 20th. There was a thunderstorm at Downham Market at midnight, also an hour or two in advance of the front Q. The prefrontal cooling aloft was of course responsible for introducing the latent instability, indicated by the crowding of the isotherms on Fig. 9 on the 20th. The same developing instability in the uplifted layers of air between former subsidence surfaces always favours turbulence in these layers, and this may produce turbulence cloud, whilst upgliding motions at the former subsidence surfaces themselves may lead to the appearance of stratus layers or thin veils of stratiform cloud. This is clearly one way in which the frequently observed multilayered cloud at major cold fronts can develop. Observers on the ground report varying types of altocumulus (C_M types 7, 8 or 9*) according to the number of different layers and the degree of instability apparent in the most unstable of them.

Similar circulation patterns and development of frontogenetic deformation fields in the vertical plane are considered to explain the re-forming of the tropopause, sometimes at a different level from before, after the previously existing tropopause has become diffuse.

Cloud structure at warm and cold fronts.—Bergeron[10,11] has given models of the cloud structure at simple warm and cold fronts and in occluded depressions viewed in vertical cross-section. These models have won general acceptance and have been widely quoted in meteorological literature. Nevertheless observation does not always confirm the standard sequence of cirrus clouds joining with, and giving place to, the medium and then the lower cloud sheets of the lowering frontal surface as one approaches the front, but rather suggests that in very many cases, outside the regions of moderate and heavy rainfall, the cirrus and medium cloud sheets constitute separate systems one above the other and both more or less separate from the lower cloud masses. So far, only one text-book, "Aeronautical meteorology" by G. F. Taylor[12], seems to have drawn attention to this variation. Yet most aviation forecasters nowadays refer in their forecasts to "solid" (i.e. unbroken) cloud masses extending from low to high levels at a frontal surface in particular cases only. It is the practice to search for clear "lanes" or interstices between the upper and lower cloud masses, indicated by stable layers in the upper air soundings, whenever these may be found.

It is clear that refinement of the accepted model of frontal cloud structure is needed in some situations, and that the charting of these clear "lanes" between the upper and lower cloud masses at a front may be of great importance to aviation. We have already made an approach to the problem

*C_M; type 7: double-layered altocumulus usually opaque in parts, a thick layer of altocumulus, or altostratus and altocumulus both present at the same or different levels; type 8: altocumulus castellatus or altocumulus floccus; type 9: altocumulus of a chaotic sky, generally at different levels.

in relation to the cold front Q in the vertical analysis of Fig. 9, which may be taken as an example; and this enabled us to suggest an explanation of the development of multilayered cloud ahead of some cold fronts. The vertical cross-section offers the most promising technique for following the trend of any one stable layer aloft from one sounding to the next, and therefore of correctly diagnosing the course of the clear " lanes " when these exist between cloud layers. This, and the *a priori* likelihood of common occurrence of incomplete stages of frontogenesis and frontolysis, seems to imply that there are in reality few simple warm and cold fronts, and that most pronounced fronts move in association with the decadent remains of older systems.

Douglas[13] has given descriptions from early flying experience of some of the more complex cloud structures which occur, perhaps often merely as a result of complicated vertical interchanges of humidity.

Conditions, which however favour deep cloud development at a front and therefore tend to make the upper and lower cloud decks merge into a typical simple system, are:—

(*a*) frontogenetic effects, leading (i) to the supply of fresh warm and humid air for uplift at the frontal surface, and (ii) to increased potential energy available for release as kinetic energy in the upgliding motion;

(*b*) instability in the uplifted air mass, which, in extreme cases, produces altocumulus castellatus as the frontal cloud and causes such turbulence as to destroy minor discontinuities surviving in the higher levels (partial destruction is liable to result in C_M type 9* as the frontal cloud, these chaotic skies being specially common in fronts approaching the British Isles from Spain);

(*c*) high moisture content in the uplifted air mass;

(*d*) moderate or heavy rainfall raising the humidity of the layers it falls through.

In addition, deep cold air masses (or cold pools) bounding the warm sector, resulting in rather steep frontal surfaces proceeding to high levels, also favour the realization of Bergeron's models of frontal cloud structure; although the existence of vestiges of an inner warm sector with additional surfaces of upgliding and duplicate cloud systems is not precluded even here. All such cases involve some unavoidable blind flying for aircraft flying across the fronts, except possibly near ground level. The reverse state of affairs, where frontolytic influences or subsidence are at work, where upgliding is replaced by downward motion, instability replaced by stability and high humidity by low humidity, causes the cloud layers to thin and break and may lead to complete clearance. The nearest cloud layer to the ground and its humidity sources is naturally the one most likely to persist (except in arid regions) and is widely separated by deep layers of clear air from whatever vestiges of thin altocumulus or cirrus may survive at higher discontinuity surfaces above the subsidence zone.

Observers on the ground can corroborate the upper cloud sheets ahead of a cold front encroaching upon a decaying anticyclone in which there has been no low cloud. Banded cirrostratus, ranged parallel with the advancing cold front, sometimes occurs 250 miles ahead. Later, multilayered cloud and rain may appear. On some occasions all the cloud, and more often all the higher

*See footnote, p. 68.

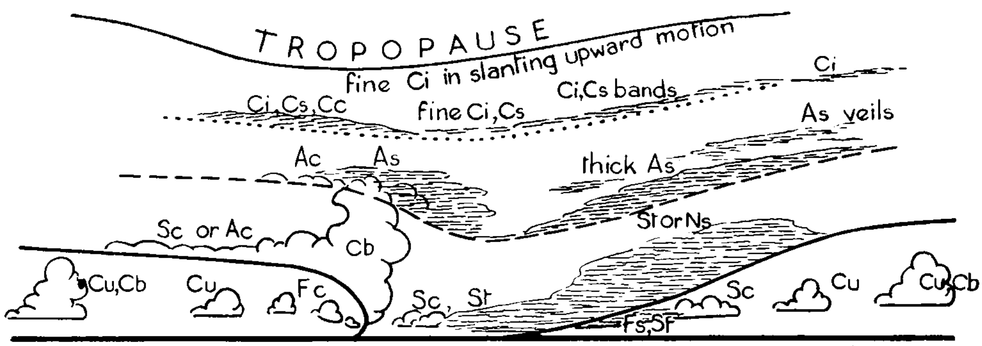

FIG. 10—SECTION SHOWING CLOUD STRUCTURE OF COMMON TYPE THROUGH A WARM SECTOR

cloud, clears as the front passes, implying that the cloud systems are on these occasions entirely ahead of the front. Fig. 10 gives a common model of frontal cloud structure which fits these observations.

Apart from the main frontal surfaces and the tropopause (both indicated by full lines) two residual discontinuity surfaces (marked by dotted and dashed lines) appear in the model. In origin these residual surfaces, which may be only weakly stable layers when upward motions are general (i.e. under conditions which reduce the main frontal surface to a deep transition layer), belong to older systems which have been imperfectly frontolysed. Inner warm sectors are fairly commonly noticed on the surface maps, and, with careful scrutiny, some traces of such earlier frontal discontinuities might often be discerned.

Such discontinuities are most readily preserved in stable air masses, and are therefore most commonly found as complicating factors in warm air masses and lifted warm sectors.

Upgliding at weak discontinuity surfaces in the free air produces stratiform cloud, either in thin veils or thicker sheets. Turbulence cloud types may form in the intervening layers, given suitable depth of the layer and lapse-rate and humidity conditions. Inasmuch as the depth of the layers is controlled by the main fronts and associated convergence at the ground, all these cloud systems are liable to show a banded structure parallel to the controlling front. Very fine cirrus or cirrostratus, sometimes only revealed by optical phenomena, may also form just below the tropopause.

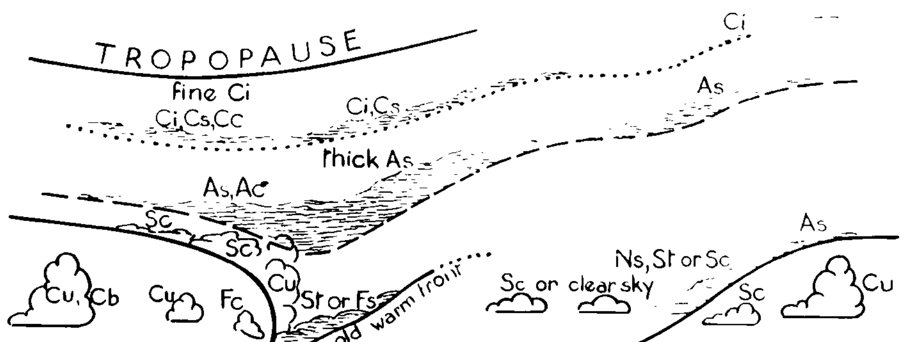

FIG. 11—SECTION SHOWING CLOUD STRUCTURE THROUGH A WARM SECTOR OF MORE COMPLEX ORIGIN

The narrower, inner warm sectors or residual warm tongues aloft are able to give cloud sheets associated with upgliding and turbulence ahead of the cold front, and in the narrowest ones the cloud system may become continuous across the entire warm sector. It is not surprising therefore that cirrostratus and sometimes altostratus are often continuous across narrow warm sectors, and probably across most warm sectors near the tip. The rather loose association of the minor discontinuities at high levels with the main fronts means that a wide range of different positions relative to the latter is possible in different instances; variations occur for instance when a slow-moving cold front is accelerated and the upper cloud sheets shift gradually forward ahead of the front or with changes in the vertical distribution of wind velocities. The number of such separate upper cloud systems also varies.

A slightly different picture is presented by Fig. 11, in which the cold front may be described as a complex front. This arises where the cold front has formerly been an occlusion or is preceded by relics of the warm front of a nearly occluded warm sector having practically the same orientation as the cold front. Surviving traces of occlusion character are reported to be particularly common with cold fronts in Australia; similar cases are however easily noticed at home and elsewhere. In these cases there is a tendency for the warmest and most humid air, occasionally with the only traces of really low cloud in the whole warm sector, to be experienced just before the cold front passes; whereas the simpler case represented by Fig. 10 is liable to show some slight cooling in advance of the cold front.

[*To be continued*

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RELAXATION METHODS AND THEIR APPLICATION TO METEOROLOGICAL PROBLEMS

By F. H. BUSHBY, B.Sc.

Introduction.—During the past fifteen years, R. V. Southwell[1,2] and his associates have developed the " relaxation technique " for obtaining numerical solutions to algebraic and differential equations. The method was originally devised to solve the simultaneous linear algebraic equations which occur in framework problems, but it has now been extended to non-linear partial differential equations of two and three dimensions. The method is a purely numerical one, and the aim is to obtain the answer to a specific problem as quickly as possible. The accuracy which it is worth trying to attain is dependent upon the degree of reliability of the physical data used.

The present article gives a brief indication of the principles involved in relaxation methods, and discusses the type of meteorological problem for which they may be used. The basic principles of relaxation used in the solution of differential equations are similar to those used in solving simultaneous algebraic equations, but the latter can be illustrated more easily and are therefore discussed first.

Algebraic equations.—The solution of three simultaneous linear equations will be considered first

$$P(x,y,z) \equiv a_1x+b_1y+c_1z+d_1 = 0 \qquad \ldots (1)$$

$$Q(x,y,z) \equiv a_2x+b_2y+c_2z+d_2 = 0 \qquad \ldots (2)$$

$$R(x,y,z) \equiv a_3x+b_3y+c_3z+d_3 = 0 \qquad \ldots (3)$$

F_x, F_y and F_z are defined as identically equal to P, Q and R respectively, and are referred to as residuals.

An operations table, Fig. 1, is first constructed in which are placed the increments in F_x, F_y and F_z corresponding to a unit increment in one independent variable when the other two variables are kept constant.

Equations for solution:—

$$F_x \equiv \quad 7x - 2y + 3z - 503 = 0$$

$$F_y \equiv - \ x + 8y - 6z - 412 = 0$$

$$F_z \equiv - 4x - 4y + 9z + 239 = 0$$

Operations Table

Δx	Δy	Δz	ΔF_x	ΔF_y	ΔF_z
1			7	−1	−4
	1		−2	8	−4
		1	3	−6	9
1	1	1	8	1	1

Relaxation Table

Assume solution: $x=0, y=0, z=0$

Δx	Δy	Δz	F_x	F_y	F_z
0	0	0	−503	−412	239
67	67	67	33	−345	306
	43		−53	−1	134
		−15	−98	89	−1
14			0	75	−57
	−9		18	3	−21
		2	24	−9	−3
−3			3	−6	9
		−1	0	0	0
78	101	53			

Solution: $x = 78, y = 101, z = 53$

FIG. 1—SOLUTION OF THREE SIMULTANEOUS LINEAR ALGEBRAIC EQUATIONS

As the equations are linear, if the increment $\Delta F_x = a$ when the increment $\Delta x = 1$, then

$$\Delta F_x = na \text{ when } \Delta x = n \qquad \ldots (4)$$

Other similar relationships are also true.

Some initial guess is made at the solution of (1), (2) and (3), say $x = 0$, $y = 0$, $z = 0$. The residuals F_x, F_y and F_z are then calculated, and they are placed in a relaxation table as shown in Fig. 1. The largest residual, say F_x, is then reduced as nearly as possible to zero by making a suitable increment in x. This is known as the basic operation of relaxation. It will, of course, change the values of F_y and F_z. The larger of F_y and F_z is next relaxed in a similar manner, making a suitable increment in y or z. The process is continued until $F_x = F_y = F_z = 0$ when the problem is solved.

The solution should be checked by substitution in the original equation. If a mistake has been made in the relaxation, some of the residuals will not be zero. However, the incorrect solution can now be used as a guess at the correct solution, and relaxation can be recommenced from this stage in the work. It is not necessary to check all the previous working, and this is a great advantage of the relaxation technique.

In problems in which the solution involves decimals, it will not generally be possible to reduce the residuals exactly to zero, but they should be reduced as nearly as possible to zero consistent with the degree of accuracy to which the solution is obtained.

The residuals may only converge slowly to zero, but various processes are available to speed up the relaxation. Block relaxation and over-relaxation are the two most commonly used. Block relaxation consists of making simultaneous equal increments in more than one variable, e.g. $\Delta x = \Delta y = \Delta z = 1$. The effect on the residuals is also indicated in the operations table in Fig. 1. This operation should be used to bring the sum of the residuals to zero, after which normal relaxation will usually give a quick solution. If the reduction of one residual to zero increases the value of the other residuals, over-relaxation will often facilitate the solution. Instead of reducing the largest residual to zero, it is reduced still further to about half its original magnitude but of opposite sign, and this is known as over-relaxation. The degree of over-relaxation is of course arbitrary, but with experience a rough estimation can easily be made.

In a slowly converging problem, it may become obvious that a group of operations is slowly reducing the largest residual, whilst having only a negligible effect on the other residuals. This group of operations can be used together as a group relaxation to reduce one residual to zero and yet produce little change in the other residuals.

In some slowly converging or apparently diverging problems, it may be difficult to bring all the residuals to zero. However it will be possible to find some stage at which F_x, F_y and F_z are in approximately the same ratio, one to another, as they were initially. Using the increments in x, y and z which were necessary to reach this stage, the increments necessary to reduce the residuals approximately to zero can be calculated. This gives an approximate answer to the problem. These values of x, y and z are substituted in the original equations, and new residuals calculated. These will be quite small and can easily be relaxed.

It can be seen from this example how the method can be extended to solve simultaneous linear algebraic equations with any number of variables. Non-linear equations can also be solved, but the relationship (4) does not hold. In practice, the method would never be used for solving simple problems like that in Fig. 1, but it is a very useful method when there are more than 4 or 5 variables.

Differential equations.—A differential equation is said to be solved numerically when the value of the function specified in the differential equation has been obtained at a network of points. The relaxation method can be applied to problems of any order or degree in one, two, or three dimensions, provided that a corresponding approximate algebraic equation can be found relating the values of the function at a network of points separated by small but finite differences (a finite-difference approximation). In two-dimensional problems, a solution is found at nodal points of a regular polygonal net. The net may be triangular, square, or hexagonal, but in practice it is most convenient to use a square net unless the actual boundary is an equilateral triangle or a regular hexagon.

As in algebraic equations, linear equations can be solved most easily, and the relaxation method can be demonstrated by considering Poisson's equation

$$\frac{\partial^2 z}{\partial x^2} + \frac{\partial^2 z}{\partial y^2} + Z(x,y) = 0 \qquad \ldots (5)$$

In the example a square relaxation net will be used, with nodal points a distance h apart. If the four adjacent nodal points to nodal point O are denoted by A, B, C and D, the finite-difference approximation to equation (5) is as follows:—

$$z_A + z_B + z_C + z_D - 4z_O + h^2 Z_O = 0 \qquad \ldots (6)$$

The error term is of the order of h^4.

The left-hand side of the equation (6) is defined as the residual F_0 at the point O. Similar equations to (6) can be written down for all nodal points inside the boundary which are surrounded by 4 other nodal points. With the boundary conditions, equations similar to (6) give a number of simultaneous linear algebraic equations which can be solved by relaxation methods.

The operations table can therefore be replaced by a diagram such as Fig. 2 showing the relaxation pattern; this being the same for all internal points. The changes in the residuals at O, A, B, C, and D, due to a unit increment in z_O when (5) is the governing equation, are shown in Fig. 2. Some initial guess at the solution is made, and the residuals at nodal points are calculated.

The residuals are then reduced step by step by adding increments to selected points and making corresponding changes at adjacent points in conformity with the relaxation pattern. A convention is adopted whereby the residuals are written on the right of the nodal point, and increments are written on the left. The working is done in an upwards direction, as is shown in the example in Fig. 4. When the residuals have been completely reduced to zero, the problem has been solved.

Over-relaxation and block relaxation are both very useful in obtaining the solution. Block relaxation consists of imposing equal increments on adjacent nodal points simultaneously. If in a block relaxation a boundary is drawn just outside all points at which a positive unit increment is made, then there is a positive unit increment in the residual at a point immediately outside the boundary for each point inside which is adjacent to it, and there is a negative unit increment in the residual at a point immediately inside the boundary for each point outside which is adjacent to it. Block relaxation should be applied to make the total residual inside the block zero. A simple block relaxation pattern is shown in Fig. 3.

A solution to Laplace's equation

$$\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} = 0 \qquad \ldots (7)$$

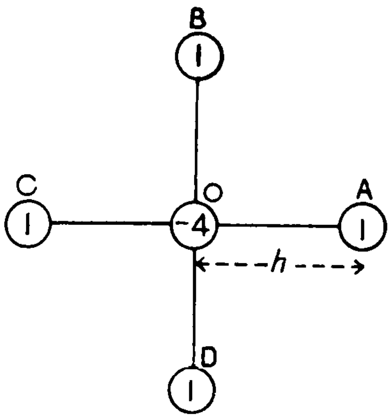

FIG. 2—CHANGES IN RESIDUALS FOR A UNIT INCREMENT IN z_0

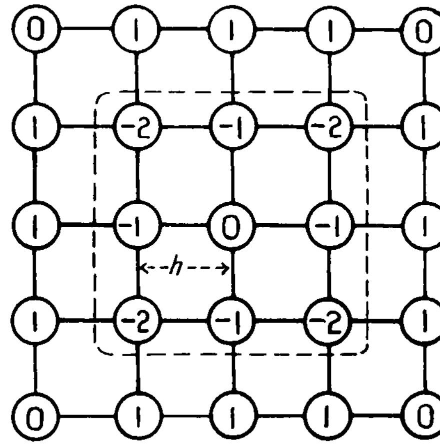

FIG. 3—CHANGES IN RESIDUALS FOR UNIT INCREMENTS AT ALL POINTS INSIDE DOTTED BOUNDARY LINE

is given in Fig. 4. The boundary conditions are given values of w along a square boundary of unit length. A square net of mesh length $\frac{1}{4}$ is used. One block relaxation is made initially to all internal points, and then the problem is completed by the ordinary basic operation of reducing the largest residual to zero.

The boundary may not, of course, always be rectangular; neither may the boundary conditions always be given as boundary values. In these cases, the problem can still be solved by modifications of the method. These are dealt with by Southwell[2].

Appropriate relaxation patterns can be obtained for other two-dimensional partial differential equations. The method can be extended to three dimensions, but care has to be taken over the method of representation. The volume for which the problem is being solved is divided by three systems of parallel planes at right angles. These have to be represented diagrammatically so that

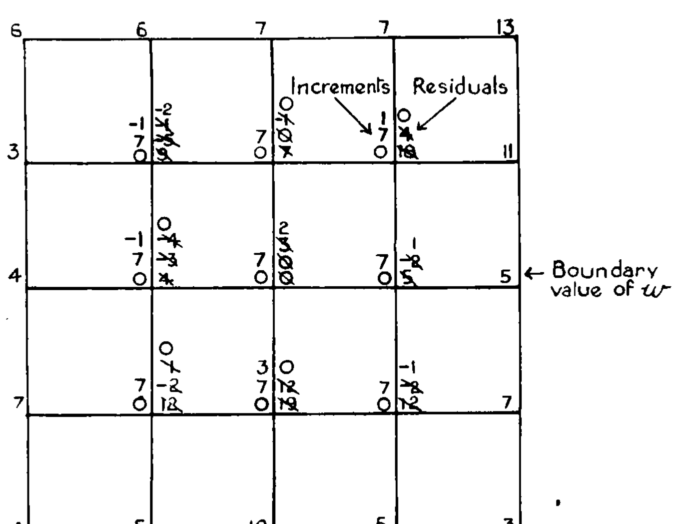

FIG. 4—SOLUTION OF $\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} = 0$

w given along the boundary

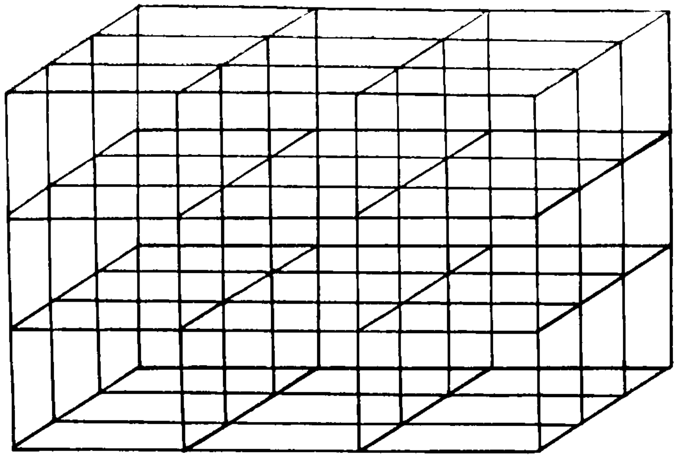

FIG. 5—DIAGRAMMATIC REPRESENTATION OF A CUBIC GRID

the intersections are clearly marked (see Fig.5), and there must also be space to write down the residuals and increments. This can usually be done by extending one dimension.

While the relaxation technique can deal directly with problems in which the boundary conditions are specified equally along all boundaries (sometimes known as "jury" problems[3]) it cannot deal directly with problems in which the boundary conditions are sufficient to determine a unique solution, but are not specified equally along all the boundary (sometimes known as "marching" problems). These latter often occur when one of the variables is a time variable, and this frequently occurs in meteorological problems. Such problems are dealt with by converting the "marching" problem to a "jury" problem. This is done by making a change of dependent variable which will increase the order of the differential equation sufficiently so that the equation could be uniquely solved if the number of boundary conditions on all parts of the boundary was equal to the largest number of boundary conditions given on any part of the boundary. Simple arbitrary boundary conditions involving the new dependent variable can now be added to those parts of the boundary where there are insufficient conditions, without in any way affecting the solution which will be obtained for the original dependent variable. The "marching" problem is thus transferred into a "jury" problem, which can be solved directly by the relaxation technique.

Non-linear equations can also be solved, but these are again more difficult as relations similar to (4) are not true.

Application to meteorological problems.—Charney[4], treating the 500-mb. level as an "equivalent barotropic level" has obtained equation (8) for the instantaneous tendency of the 500-mb. surface when the spherical earth is conformally mapped on a plane by a stereographic projection from the south pole.

$$\nabla^2 \frac{\partial z}{\partial t} = J\,(m^2 l^{-1} g \nabla^2 z + l,\, z) \qquad \ldots (8)$$

where z = height of 500-mb. contour surface

m = magnification factor $\sec^2\left(\frac{\pi}{4} - \frac{\phi}{2}\right)$

ϕ = latitude

$$J = \text{plane Jacobian}$$
$$\nabla^2 = \text{plane Laplacian}$$
$$l = \text{Coriolis parameter, } 2\omega \sin \phi.$$

The right-hand side of equation (8) can be computed numerically for a network of points, and, at a particular time, is a function of position only. Equation (8) is therefore a Poisson equation with the instantaneous tendency as the dependent variable. In equatorial regions there is little change in the 500-mb. contour height, and for boundary conditions $\partial z/\partial t$ can be taken as zero near the equator. The equation can be solved simply by the relaxation technique. Two cases have been investigated in the Forecast Research Division of the Meteorological Office at Dunstable. In each case the solution by the relaxation technique was quite straightforward and simple. The calculated height tendency did not show any close agreement with the change observed over 24 hours, and it is deduced that the fundamental assumptions on which equation (8) is based needs reconsideration.

At Dunstable, relaxation methods have not yet been applied to any further meteorological problems, but further applications are envisaged.

Conclusion.—In this article it has only been possible to deal very briefly with the fundamental principles of relaxation. Convergence of the method is not considered, and indeed no general classical proof of convergence is available. In certain particular cases, however, the method can be shown to converge[1,2]. However, Southwell and his associates have not yet come across a physical or engineering problem in which the solution by the relaxation technique could not be made to converge.

The degree of accuracy of the final solution has not been mentioned, but that again is discussed by Southwell. It is, of course, dependent upon the reliability of the physical data used in the problem.

So far, relaxation methods have only been used in a very limited way in meteorology. In dynamical meteorology the equations of motion of the atmosphere have been formulated in many ways, but, in the past, attempts to demonstrate their validity have been restricted to the consideration of hypothetical ideal depressions for which the distribution of wind and temperature, etc. could be expressed by analytical functions and the solution obtained by analytical methods. However, with the increased information from the free atmosphere there is a great need to work out the consequences of the theoretical equations when applied to the atmosphere as it actually is. This can only be done by numerical methods, and the potential applications of relaxation methods are many. In the immediate future the need is to discover whether the dynamical equations already derived from theory do in fact describe the behaviour of the atmosphere, and if not, to modify them. Ultimately, the application of numerical methods to forecasting may be possible.

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DEVELOPMENT OF MODERN TECHNIQUE IN MARINE METEOROLOGY

By A. H. GORDON, M.S.

The basis of techniques which have been employed during recent years for research in marine meteorology lies in the mechanical sorting and tabulating of marine observations which have been punched on Hollerith cards. Before 1921 all marine data in the Marine Branch of the Meteorological Office had to be extracted by hand from the original ship's logbooks before analysis. The introduction of Hollerith sorting and tabulating machines resulted in an enormous saving of time in the undertaking of any work carried out, and enabled projects such as the preparation and publication of climatological atlases of the oceans to be completed on schedule during the 1939–45 war as required by the Royal Navy.

Hollerith system.—Briefly the Hollerith system may be described as one in which given figures can be represented on a card by holes punched in corresponding positions on the card. The punched cards are inserted in machines in which electrical contact is made through the holes, enabling the cards to be sorted into groups and counted; in addition the columns of figures on the cards can be tabulated and their sum obtained. Three machines play a part in this process, each representing a step in the extraction and computation of marine meteorological data. They are:—

(i) the key punch by means of which the observations are punched on cards

(ii) the sorting machine by means of which the punched cards are sorted into appropriate groupings

(iii) the tabulating machine by means of which the figures on the punched cards are tabulated in columns together with the numerical sum of these figures and the total number of figures in the column.

After the various meteorological elements included in the observations have been punched in appropriate codes on cards, the latter are sorted and filed in packs according to the month and the 10° Marsden Square to which they belong. A total of approximately three and a half million British and six and a half million German cards are held in the Marine Branch at the present time.

The analysis of this vast mass of marine data in a way designed to provide the maximum contribution to meteorological knowledge is a problem which requires the evolution of special techniques. Such techniques have been developed and have been applied to the following three fields of meteorological research: statistical climatology, physical meteorology, and dynamic climatology.

Statistical climatology.—In the past the function of marine meteorology has been limited largely to the preparation of charts and atlases which have contributed to our knowledge of the climatology of the oceans. If a sufficient number of observations can be collected from one place, or from one sufficiently limited area, they will show what is the most frequent type of weather to be expected, or within what limits any meteorological factor may be expected to vary from year to year. Such statistical information may be of considerable value in areas where observations are lacking and for which forecasts cannot be made available with any reasonable degree of confidence; for example, if one requires to know at what time of the year the most favourable weather for a given operation is likely to occur.

There is one important difference between land and marine climatology. On land, except in sparsely inhabited polar or desert regions, a picture of the climatology of the region may be built up from a usually regular series of observations, extending over a period of years, for definite locations. At sea the situation is different. The sources of observation are the ships, and, even on the main shipping routes, the chance of getting many observations from a comparatively small area, say one square mile, is slight. It is therefore necessary to divide up the ocean into appropriate squares of latitude and longitude, usually either 2° or 5°, and to consider that all the observations within any square refer to a point at its centre. In general this method of grouping the observations is not such a disadvantage over the open sea as it would be over land for climate does not change so rapidly with position over the sea. Unlike meteorological observations over land there is little regularity about observations at sea. A series of observations at successive intervals of 3, 4, 6 or even 12 hours may be obtained in a given square, and there may be no further observations in that square for days, weeks or even years. The observations tend to be made mainly along the main shipping routes; elsewhere, over large parts of the ocean, only a few observations are available; these may not give a sample even approximately representing weather conditions for a given square.

One of the most effective methods of displaying climatological information is by means of isopleths of mean values, upper and lower percentile values, and percentage or actual frequencies. The climatological atlases*, which were prepared in the Marine Branch during the 1939–45 war, contained separate charts showing isopleths of the following meteorological elements over the oceans:—

- Mean pressure
- Percentage frequency of observations of winds of Beaufort force 0–4
- Percentage frequency of observations of winds of Beaufort force 7 or more
- Percentage frequencies of observations of visibility less than ½ mile
- Percentage frequencies of observations of visibility less than 5 miles
- Percentage frequencies of observations of snow
- Percentage frequencies of observations of precipitation
- Percentage frequencies of observations of lightning
- Mean cloud amount
- Percentage frequencies of observations of cloud amount between nil and 2 tenths inclusive
- Percentage frequencies of observations of cloud amount between 3 and 6 tenths inclusive
- Percentage frequencies of observations of cloud amount between 7 and 10 tenths inclusive
- Mean air temperature
- Range of air temperature—difference between upper and lower 5 percentiles

*Monthly meteorological charts of the western Pacific Ocean. London, 1942, revised 1945, reprinted 1947.
Monthly meteorological charts of the eastern Pacific Ocean. London, 1943, reprinted 1950.
Monthly meteorological charts of the Atlantic Ocean. London, 1944, reprinted 1948.
Monthly meteorological charts of the Indian Ocean. London, 1944, reprinted 1949.

Upper 5 percentile of air temperature
Lower 5 percentile of air temperature
Mean sea temperature
Range of sea temperature—difference between upper and lower 5 percentiles
Upper 5 percentile of sea temperature
Lower 5 percentile of sea temperature
Difference between mean sea and mean air temperature.

The drawing of the isopleths involves considerable smoothing before the pattern produced can be adopted as reasonably representative of actual conditions because of the irregular numerical distribution of the observations and consequent scatter of mean values.

In addition to the isopleths listed above, the climatological charts displayed vector quantities as follows:—

Direction of the vector mean wind by arrows
Isopleths of the force of the vector mean wind
Direction and constancy of predominant winds by arrows
Wind and swell roses.

The climatological charts illustrate very well how the patterns of the various meteorological elements change from month to month throughout the year. They are constructed under the assumption that any long-period variations extending over the whole period covered by the observations are too small to affect the main pattern appreciably.

It may be desired to investigate secular changes of the various meteorological elements as, for example, by decades. Marine data extend back for nearly a hundred years so that the sorting of data into decades can be accomplished. The major difficulty lies in the fact that such sorting frequently reduces the number of observations in a given square to such an extent that the mean values or percentage frequencies calculated become meaningless. Statistical significance tests may be applied to the variations of each element, throughout each time interval considered, to test their reality.

However, the application of statistical tests to marine data does not give such reliable results as for other scientific data. Difficulties arise because of the fact that successive ships' observations are not independent of one another.

Physical meteorology.—Climatological charts of the oceans may serve research in certain problems of physical meteorology. For example, the charts showing isopleths of the difference between mean sea and mean air values give one of the variables in the energy equations which describe the heat exchange between the oceans and the atmosphere.

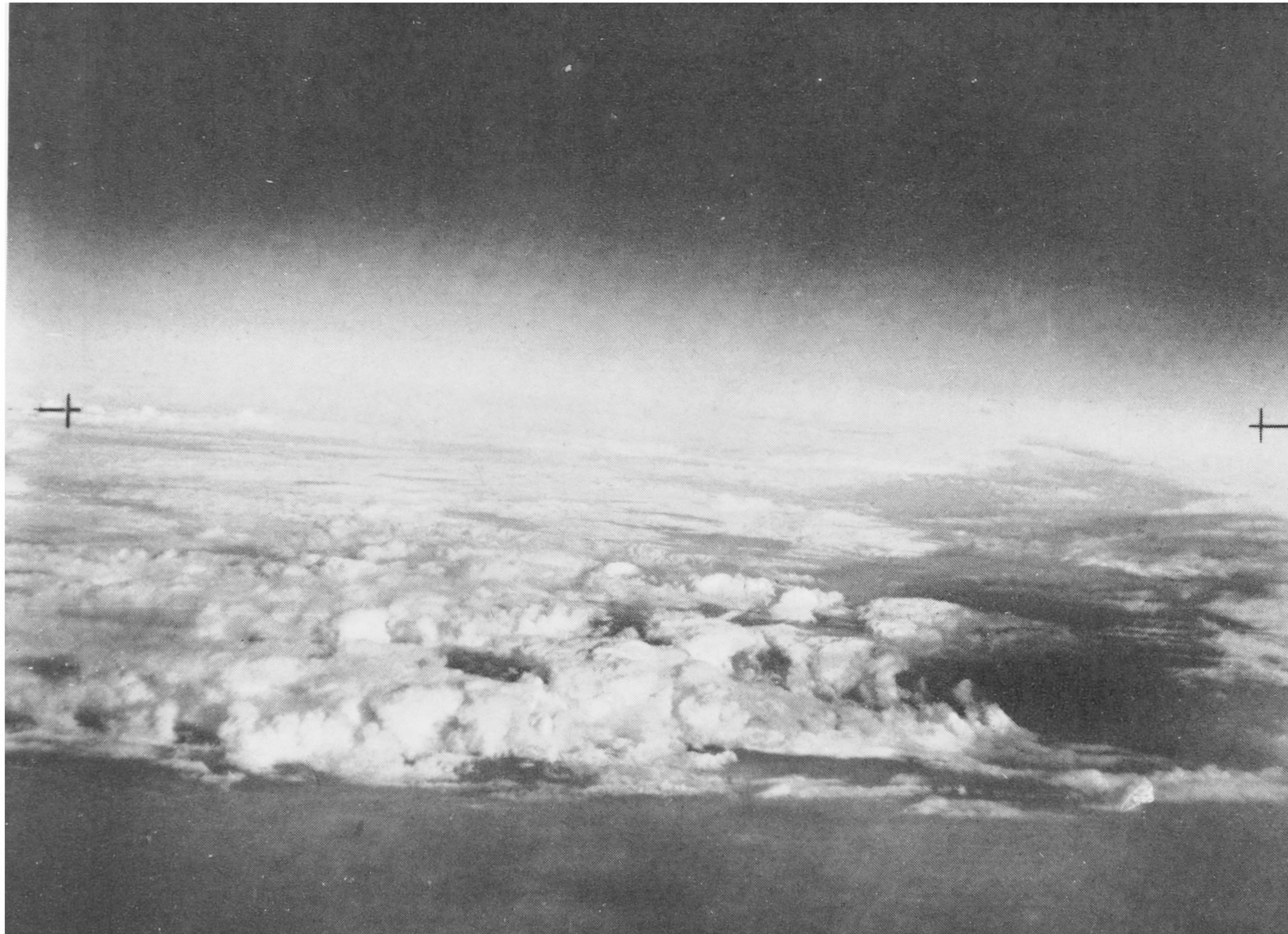
Marine data in selected squares may be sorted into times of day to isolate diurnal variations of the various meteorological elements. Curves may be drawn showing how the mean values vary from hour to hour throughout the day for each month or season as required. Isopleths of the amplitude of the diurnal variation may be drawn on charts to show spatial variations over the oceans.

The isolation of diurnal variation effects can be accomplished best from the analysis of ocean-weather-ship observations. The ocean weather ships are comparable with land stations of the first order in the regularity of their

Photograph by R.A.F.

FIG. 1—VERTICAL VIEW OF CUMULUS FROM 32,000 FT. OVER THE BRISTOL CHANNEL IN THE AFTERNOON, FEBRUARY 28, 1950

(see p. 89)



Photograph by R.A.F.

FIG. 2—GENERAL VIEW FROM 40,000 FT. OVER AN UNSTABLE AIR MASS, LOOKING FROM NORTH OXFORDSHIRE IN A NORTH-NORTH-EASTERLY DIRECTION, ABOUT MIDDAY, DECEMBER 8, 1949

Photograph by R.A.F.

FIG. 3—STRATOCUMULUS AND CIRRUS, FROM 35,000 FT., LOOKING SOUTH OF WEST FROM JUST SOUTH-EAST OF LONDON, MID AFTERNOON, OCTOBER 27, 1950

Photograph by R.A.F.

FIG. 4—ALTOCUMULUS LAYER, FROM 25,000 FT., LOOKING APPROXIMATELY WEST-SOUTH-WEST FROM THE WEST OF LONDON JUST BEFORE NOON, DECEMBER 1, 1949

Photograph by R.A.F.

FIG. 5—CIRRUS FROM 32,000 FT., LOOKING ALMOST DUE SOUTH OVER SALISBURY PLAIN, SOON AFTER NOON, FEBRUARY 28, 1950

observations. They refer to a position which is more or less fixed, and within the past three years sufficient observations have accumulated at these positions for investigations into diurnal variation effects to yield significant results.

In the Marine Branch work has been carried out on the diurnal variation of sea and air temperature, wind velocity and low cloud amount at ocean weather stations. An investigation into the diurnal variation of pressure in the Mediterranean Sea has been completed. The discussion and suggested explanations of these variations are mainly physical in nature.

Work has also been completed on the harmonic analysis of monthly means of sea temperature in the North Atlantic Ocean. The main feature of this work consists of monthly charts of isopleths of the harmonic constants and a discussion of their distribution.

Dynamical climatology.—It may appear difficult to define the line which divides the field of statistical climatology from that of the dynamical climatology. Here, dynamical climatology refers to the study of the application of climatological data to large-scale dynamical problems involving the general circulation of the atmosphere. One of the ways by which the general circulation may be studied is to analyse the seasonal variations of various dynamical properties of the atmosphere, such as pressure, momentum, convergence and vertical velocity, and show how the seasonal variations of these properties change with latitude. The variations may be represented on charts by isopleths of mean values for each month or by isopleths of differences in mean values between succeeding months as, for example, by isallobars in the case of pressure variations. A more concise method of representing seasonal variations of the dynamical properties is to ignore any variations along the parallels of latitude and to consider variations along meridians only. This may be done by the calculation of latitudinal profiles, which are either based on observations extending along one meridian or on the mean of all observations extending along each parallel of latitude between given meridians. Mean variations of the latter kind may also be represented by isopleths on a space-time chart whose axes represents units of months and degrees of latitude respectively.

Current meteorological opinion is tending to break away from the short-term synoptic outlook in an endeavour to solve many of the problems associated with the general circulation of the atmosphere. Instead, techniques are developed based on statistical data extending over periods ranging from several days to many years. Small-scale irregularities in the circulation are thereby ironed out while the dominant features remain.

Marine meteorology has much to offer towards the development of these techniques, and provides unique opportunities for the application of methods of dynamic climatology. Marine data are well suited for the investigation of mean variations of the different meteorological elements and the dynamical properties of the atmosphere, particularly seasonal variations, since weather conditions are less disturbed over the ocean than over land by erratic fluctuations caused by chance topographical and thermodynamical influences.

Several meteorologists have recently used marine data to investigate major problems of the general circulation. C. S. Durst[1] has mapped the seasonal convergence and divergence of mean vector winds over the oceans of the globe in terms of the rate of ascent and descent of air, using the relation between divergence and vertical motion. The isopleths he has drawn, representing the distribution of convergence and subsidence in the surface layers of air, give important information regarding the amount of cloudiness and precipitation which may be expected to occur in regions lacking in regular synoptic observations.

H. Riehl and T. C. Yeh[2] have calculated net meridional wind profiles and net latitudinal divergence and vertical motion profiles in January and July in a study of the intensity of the net meridional circulation. The net latitudinal divergence profiles have been compared with the mean latitudinal sea-level pressure profiles and a mean circulation inferred from the computations. Riehl and Yeh[3] have cast doubt on the validity of the explanation that the descent of air in the trade-wind belt is caused by radiational cooling in the upper troposphere. Instead, they attribute the descent to conditions near the surface and to the removal of vorticity by lateral divergence at the same rate at which it is imported.

C. L. Jordan[4] has calculated latitudinal profiles of mean zonal wind and compared them with profiles of mean geostrophic wind calculated from mean-sea-level pressure observations.

In the Marine Branch calculations have been made of the seasonal fluctuations in the mean latitude of the belts of maximum convergence and divergence and of the axes of the doldrums and semi-permanent subtropical anticyclone in the North Atlantic.

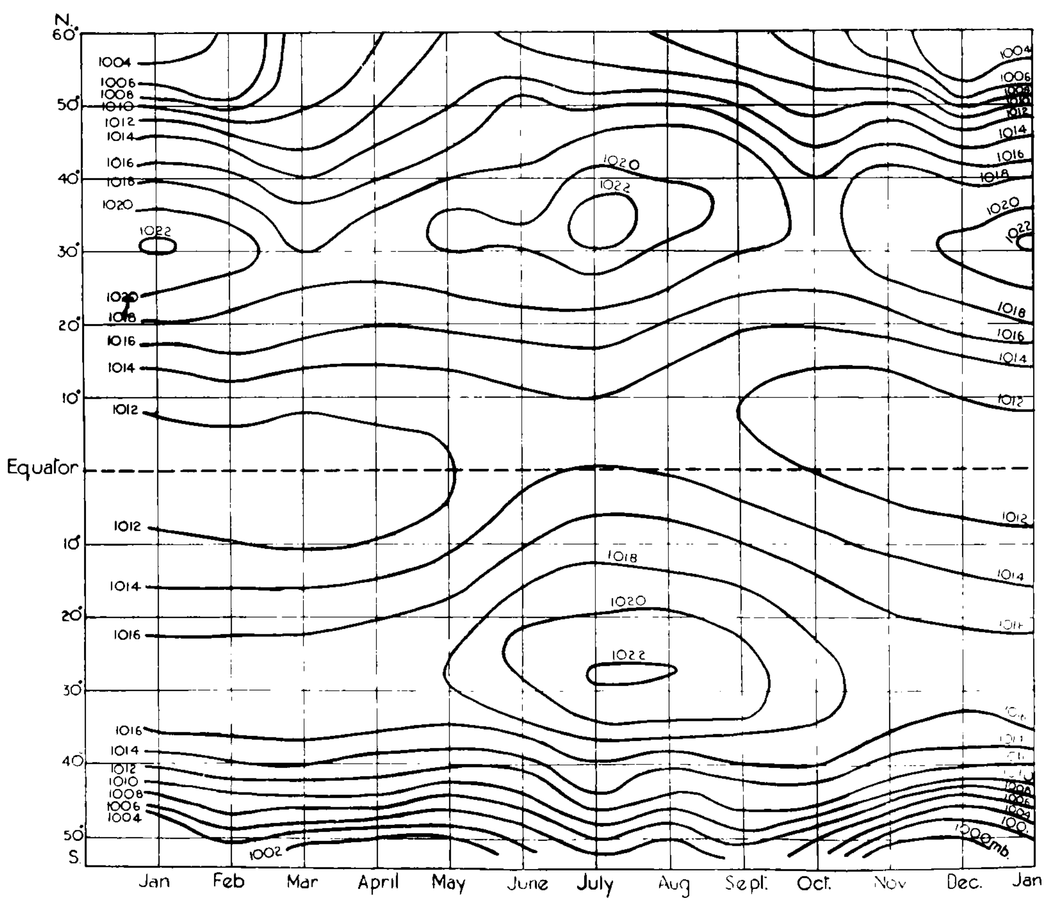


FIG. 1—LATITUDINAL MONTHLY MEAN SURFACE PRESSURE PATTERN OVER THE ATLANTIC OCEAN

Fig. 1 is an example of the kind of information that can be extracted from an analysis of marine data. It shows how the regular seasonal changes in the mean monthly pressure distribution over the Atlantic can be illustrated by a pattern as a function of latitude. Isobars are drawn through pressure values which have been averaged along each two-degree belt of latitude and plotted for each month. Fig. 1 will not be discussed here, but it does provide interesting information about the seasonal behaviour of the atmosphere over the ocean.

The development and application of modern techniques in marine meteorology can lead to a material increase in our knowledge and understanding of the seasonal variations in the intensity and character of the general circulation. The variable which is the primary cause of seasonal variations is known; it is the changing distribution of heat received on the earth's surface as determined by the apparent latitudinal movement of the sun across the sky. Conclusions may then be formulated from a study of seasonal variations regarding the nature of the general circulation itself.

Although purely statistical climatological functions will remain an important feature of marine meteorological work, the time has passed when the sole purpose of marine data is to provide a reference work of mean conditions over the oceans. Modern techniques are now enlisting the vast resources of marine data to assist in the solution of major problems of practical contemporary meteorology in the physical and dynamic fields of the science. It is in this direction that the greatest progress in marine meteorology will be made in the future.

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METEOROLOGICAL OFFICE DISCUSSION

Measurement of upper winds

The discussion held at 11 Carlton House Terrace on January 8, 1951, on the measurement of upper wind was opened by Dr. D. N. Harrison.

Dr. Harrison began by reviewing the assumptions underlying the present methods.

The first assumption is that there exists a " mean " wind at a given level, and that this is the value required for routine synoptic use. Superposed on this mean wind are fluctuations due to turbulence and also those due to errors of observation. A balloon moving with the mean wind velocity would follow a smooth track and the spacing of its positions at equal intervals of time would vary smoothly. The vector displacement of the actual positions from these hypothetical mean positions is random, the distribution depending on the type and degree of turbulence. Displacements of the same type, but differently distributed and of different magnitude, are produced by errors of observation. The plotter cannot distinguish between these two sources of scatter in his trace, and does not need to since he wants to remove both by smoothing.

(Smoothing is a sort of averaging by taking running means over unspecified intervals of time.) It is assumed that if the smoothing could be done correctly we should arrive at the true mean balloon track and mean wind vectors.

The wind vector is measured over a whole number of minutes, usually three. The speed and direction obtained are the actual values at some point which is generally near the centre of the interval, though it may not always be so. These are credited to the standard level occurring somewhere in the middle minute of the three. There is thus the possibility of an error of $\pm 0{\cdot}5$ min. or more in the timing, or ± 600 ft. in the height at which the wind is measured.

It is important for the plotter to know over what interval he should aim at taking a mean wind. This involves, in addition to some knowledge of the instrumental errors, a decision as to the thickness of the layer, or the duration of time, over which fluctuations of wind are significant.

Two further points must be remembered:—

(*a*) When the balloon follows a curved track, the straight-line distance between two given positions is shorter than the distance along the track, and therefore the mean speed measured by the vector displacement is too small.

(*b*) As is generally recognized, the wind measurements are not simultaneous values for points vertically above the observing station. The end of the ascent may be an hour after the beginning and fifty miles away.

The errors of radar wind observations can be calculated if the errors of the radar readings are known. The actual magnitudes of the radar errors are not so important as the change between successive readings. In other words, a random error which introduces scatter into the trace is worse than a systematic error which shifts the trace as a whole but has little effect on its shape. In addition to errors in the horizontal plane, height or pressure errors contribute to the wind error, as they lead us to attribute the measured wind to the wrong level. In this case it is the systematic errors which are the more important.

The errors in the angular readings of a radar set on land can be measured by comparison with pilot-balloon theodolite observations. On the ocean weather ships sextant readings provide a standard of comparison for the radar elevation. Alternatively, we can follow the same balloon with two radar sets near together, and from the differences between their readings assess the errors of observation and also the wind errors.

For GL III sets at radio-sonde stations the root-mean-square vector error of a wind measurement over a 3-min. interval is less than 1 kt. at the beginning of an ascent and about 2 kt. at the end. For the ocean weather ships the wind errors are roughly six times as large. In this connexion it is worth noting that on the ocean weather ships appreciable differences have been found between the winds obtained by two computers from the same radar readings. This is due to differences in smoothing the plotted traces.

The normal practice is to take one reading per minute, but it is of interest to consider how much benefit can be obtained from an increase in the frequency. Provided that the displacement of the plotted point from its true position is perfectly random, an increase in the number of readings will lead to an improvement. But if there is a correlation between the displacements—that is, if they are to some degree systematic—then there is correspondingly less improvement to be obtained by an increase in the number of readings. In the extreme case, when the error is constant, a large number of readings is no better than one.

Now if there are fluctuating errors having a certain period, and we take readings at intervals comparable with, or longer than, this period, we shall in general get errors which appear random. But if we take readings at intervals much shorter than the period of the variations, there will be some correlation between the errors of successive readings. This means that an increase in the frequency of reading reduces those errors which are of shorter period than the interval between the readings, but not those of longer period.

The radar-sonde theodolite, which is under development, will include automatic following devices, and electronic computers which will compute the wind components continuously and present mean values over pre-determined intervals. An important question will be the accuracy with which the automatic following mechanism performs its function. There will be errors, and these may be partly periodic. Their effect will depend not only on their magnitude but also on their period. The amount of benefit gained from continuous observation of wind velocity will depend on the nature of the instrumental errors in comparison with the effects of atmospheric turbulence.

Dr. F. E. Jones (Telecommunications Research Establishment), in the subsequent discussion, outlined the new radar-sonde theodolite system. The principal advantages which it is hoped to obtain over existing methods are:—

(i) greater range through the use of an airborne transponder, which gives a signal-to-noise ratio of 5:1 at 100 miles,

(ii) greater detail and accuracy by continuous automatic following and computing.

In the component across the line of sight the high accuracy specified by the Meteorological Office will be difficult to attain at extreme ranges, on account of the low rate of change of azimuth. The characteristics of the automatic-following system will be adjusted to give the best results. A further problem is to reconcile accuracy in the low angular rates at the end of an ascent with ability to follow the high rates which occur at the beginning. The position of the launching point will have to be arranged to minimize this difficulty and to ensure that wind measurement begins as quickly as possible after the release of the balloon.

Dr. F. J. Scrase stressed the importance of being able to distinguish the effects of atmospheric turbulence from those of observational error, and showed a graph of observed rates of ascent up to 100,000 ft. compared with the calculated probable error; this strongly suggested that the observed short-period changes were real. There was a marked decrease both in the mean rate of ascent and in the minute-to-minute fluctuations at the tropopause.

Mr. E. Gold pointed out that the balloon does not follow changes of wind instantaneously, and suggested that the lag might be appreciable.

Mr. D. G. Harley asked whether there were not, in the existing method of measurement, a danger of smoothing out real changes of wind of sufficient magnitude to be significant.

Dr. Harrison replied that plotters ought to be alert to this, and that provision was made for reporting discontinuities. The instructions depended upon the requirements of those who use the observations, and it was hoped that in the present discussion the users would express their views as to what these requirements were.

Dr. R. C. Sutcliffe said that the reason for the lack of a clear reply from the users was that they do not know what is significant. He considered the present standard of accuracy at British stations satisfactory for synoptic purposes. Dr. Sutcliffe also pointed out that with a 100-ft. suspension the swinging of the transponder might introduce an appreciable periodic variation into the measured wind velocity.

Mr. A. G. Matthewman discussed the connexion between the changes of temperature gradient and of wind on a sounding which passed through a front. The changes are related, but do not necessarily coincide. He said that there was a need for more detail in reports.

Mr. H. W. L. Absalom agreed with this.

Mr. J. K. Bannon said he had analysed ascents using measurements over 1-min. intervals, and found that large changes occur, and he made a plea for higher accuracy in wind reports.

Mr. A. L. Maidens said that the practice in regard to smoothing was not systematic, but that, for the 1500 G.M.T. ascents, winds were re-measured over 1-min. intervals without smoothing and the results were available for research purposes.

Several speakers pointed out that the accuracy needed depends on the distance between stations, and that in some regions of the world comparatively inaccurate observations are better than none.

Cdr. J. Hennessy, referring to Dr. Harrison's statement about the errors of the ocean weather ships' observations, said that improvements had recently been made in the type 277 P radar sets on the ships, and further improvements were being planned.

Mr. O. M. Ashford suggested that wind measurements were wanted from a wider area, and that there was a need for a cheap radar-wind set which would be simple to maintain and operate even at the cost of a reduction in range and accuracy.

The Director replied that the peace-time network in the United Kingdom had been planned for research, and the spacing of about 200 miles between stations was roughly equivalent to the interval of 6 hours between ascents. From the research point of view the network was still too coarse. We could not afford to sacrifice range or accuracy, and with the limited amount of effort available it was impossible to develop more than one type of equipment.

ROYAL METEOROLOGICAL SOCIETY

At the meeting of the Society held on December 20, 1950, Dr. R. C. Sutcliffe, Vice-President, in the Chair, the following papers were read:—

*Batchelor, G. K.—The application of the similarity theory of turbulence to atmospheric diffusion.**

Dr. Batchelor gave a very lucid account of the similarity theory of turbulence. He pointed out that G. I. Taylor had provided, in 1921, a statistical theory of turbulence leading to differential equations which could not be solved. Kolmogorov's similarity theory published in 1941 gave a way out of the

Quart. J. R. met. Soc., London,* **76, 1950, p. 133.

difficulty. The similarity theory concerns turbulent motion at high Reynolds numbers. In terms of the older " eddy " conceptions, we may imagine that the original generating mechanism, say a cylinder in a stream or an unstable layer of fluid, gives rise to a set of large eddies of size and directional arrangement dependent on the size and orientation of the generating system. These large eddies produce smaller eddies and so on indefintely. The basic hypothesis is then that the smaller the eddies the more isotropic they become. It is the smallest eddies which finally dissipate the energy as heat. The scheme may also be thought of in terms of the Fourier expression for the velocity in which the non-linear parts of the equations of motion produce, by cross-multiplication, higher and higher order components. From this it follows that the average properties of the small-scale components of any turbulent motion with large Reynolds number are determined solely by the kinematic viscosity and the rate of dissipation of energy. The rest of the theory is dimensional analysis. Dr. Batchelor showed how the theory led to formulæ for the rate of change of the mean square separation of the two particles in turbulent flow. This rate of change is proportional to the time when the particles are so close together that the relative motion is determined by the smallest eddies, and to the square of the time as the particles get further apart. In the discussion, considerable scepticism was shown as to whether the theory had any useful application to meteorological problems.

Mr. Charnock described his analysis of observations of the relative separation of two puffs of smoke which on some occasions supported the theory, but on others apparently did not; but Mr. Davis was not satisfied that Charnock's analysis could strictly be used to test the similarity hypothesis.

Craddock, J. M.—Advective temperature change in the 1000–700-mb. and 700–500-mb. layers.

Mr. Craddock said that his object was to find the extent to which the rate of change of thickness of the 1000–700-mb. and 700–500-mb. layers was determined by advective processes since the advective component of the rate of change could be estimated much more readily from the synoptic charts than the dynamical and non-adiabatic components. The work was done by measuring the advective components for the two layers over Downham Market at six-hourly intervals for the six consecutive winter months October 1945—March 1946, and comparing them with the actual changes in thickness. Statistical analysis gave correlation coefficients of about 0·6 between the thickness tendency and the advective component, and regression equations according to which about half the actual change of thickness is accounted for by advection in the case of the 1000–700-mb. layer and about four tenths for the 700–500-mb. layer. Mr. Craddock recommended that, in the absence of further evidence, the thickness tendency should be taken as half the advective component, and said that further statistical analysis showed that it would be useless to put the thickness tendency equal to the advective component. If the ageostrophic wind is constant with height the advective component is proportional to the area of the polar diagram of the hodograph of wind vectors. Mr. Craddock showed that this use of the hodograph, which has been proposed in the United States, gives poorer results than does the use of the full advective component. Mr. Craddock pointed out that the correlation coefficients showed the actual thickness tendency was the residual of two generally opposite factors, the advective component and the dynamical plus non-adiabatic components. In the course of the discussion. Dr. Eady said his work on instability showed that particles tended to move along a plane about half way between the isentropic surface and the nearly horizontal isobaric surface which might be related to Mr. Craddock's results; Dr. Stagg considered the correlations should be tackled on a basis of synoptic types since it was to some extent known when advection was or was not likely to be predominant; Dr. Sutcliffe said he favoured the investigation of special cases rather than overall statistical analysis, and thought that forecasters could make good estimates of the magnitudes of the components of the thickness tendency in spite of the statistical objections.

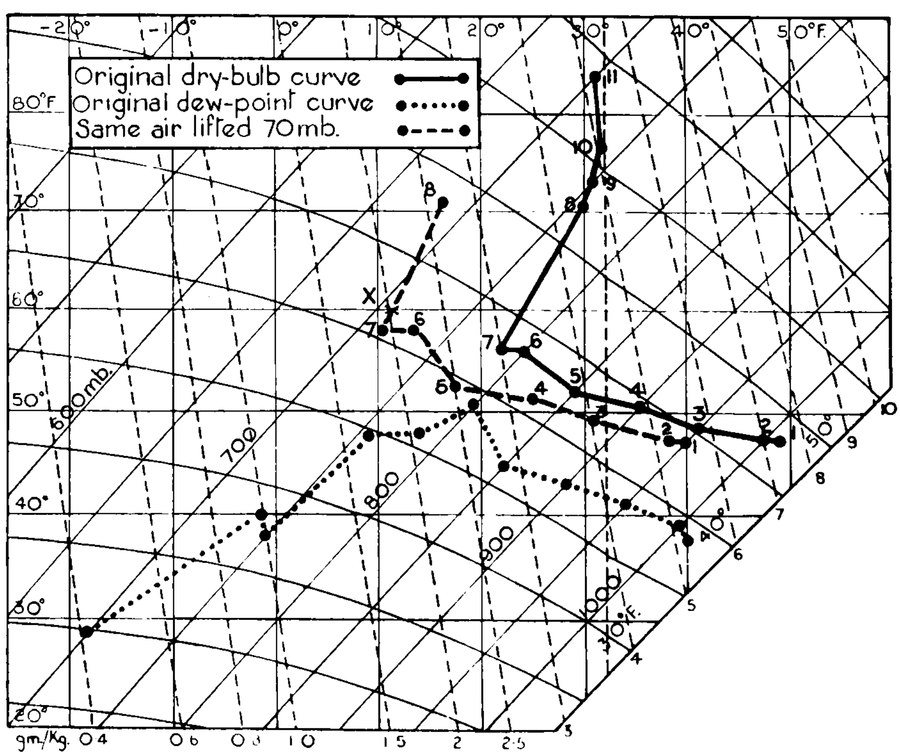
LETTER TO THE EDITOR

Conditional instability over the Highlands of Scotland

On Thursday, October 26, 1950, a southerly air stream covered the whole of Scotland. During the morning no fronts affected Great Britain, and even during the afternoon only the extreme west of Scotland was under the influence of an occlusion in the Atlantic.

The radio-sonde ascent for 1400 G.M.T. was typical of the ascents from Leuchars and Lerwick throughout the day and also from Stornoway as late as 1400 G.M.T.

At first sight these ascents would indicate cloud tops at 5,000–6,000 ft. But, in fact, the top of the cloud over central Scotland was very undulating, though much flatter over the North Sea; and aircraft flying over central Scotland during both the morning and afternoon were in cloud over large areas at 7,000 ft. with light ice and occasional bumps, while occasionally tops rose to 10,000 ft.



TEPHIGRAM OF RADIO-SONDE ASCENT AT LEUCHARS, 1400 G.M.T., OCTOBER 26, 1950

The reason for this increase in cloud tops may be seen from the broken-line curve in the tephigram, obtained by lifting the air represented by the Leuchars ascent by 70 mb., which corresponds to about 2,000 ft., the average height of the Scottish Highlands. The new curve represents air saturated up to the level marked X, and thus unstable to nearly 700 mb., or nearly 10,000 ft.

The choice of 70 mb. is arbitrary, and there is no evidence to show that the upper layers have been lifted to the same extent as the lower layers. If the upper layers were lifted less, the resultant curve would lie between the full curve and the broken-line curve, with the corresponding alteration in the height of the cloud tops.

The effect of ascent of air on the lapse rate is dealt with in text-books*: this is an example of the significance of this principle over the British Isles.

S. E. VIRGO

Pitreavie Castle, Dunfermline, Fife, October 27, 1950

NOTES AND NEWS

High-level cloud photographs

The cloud photographs reproduced in the centre of this number of the Magazine were taken by Royal Air Force aircraft flying over southern England.

The meteorological features revealed by the photographs are discussed in the notes which follow.

Fig. 1, a vertical view of cumulus from 32,000 ft., was taken over the waters of the Bristol Channel in the afternoon of February 28, 1950. The shadows of the cloud on the sea can be identified fairly readily, and it is, in fact, possible to assess the height of the cloud from the length of the shadows—in this case about 3,000 ft. above sea level. It will be noticed that the amount of cloud in the photograph is not large, but that shadows are visible at the top of the print of several clouds which are themselves out of the view of the camera.

Fig. 2 was taken from over 40,000 ft. and shows a general view over an unstable air mass. It was taken on December 8, 1949 at about midday, looking from north Oxfordshire in a north-north-easterly direction. The tops of the cumulus are at 10,000 ft. or rather more. The foreground cloud is some 20 miles from the camera, and, in the middle distance, the cumulus can be seen giving way to layer cloud (mainly altocumulus), though in the extreme distance to the north can be seen further big cumulus with tops to 10,000–15,000 ft. The nearer cloud is spreading out somewhat at the top, showing that convection was limited in height. The pilot stated that the photograph was taken near to a sheet of medium and high cloud (to the south) which was probably the trailing edge of frontal cloud, as an occlusion had just crossed the south-east coast of England that day. It probably accounts for the clear gap in the foreground of the photograph, as convection was not effective until some distance into the cold air. The polar maritime air mass was not unduly unstable, and only about a third of the stations in the Midlands area reported showers during the day. The hazy nature of the horizon will be noted; this is probably due to the haze extending to the tropopause, several thousand feet below the aircraft.

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*BRUNT, D.; Physical and dynamical meteorology. Cambridge 2nd edn., 1941, p. 44.

Fig. 3 was taken on October 27, 1950 from 35,000 ft. from just south-east of London, looking south of west. It was taken in mid afternoon, and the glare of the sun into the camera will be seen on the left-hand side of the photograph. The cloud in the foreground is stratocumulus with tops to about 4,000 ft. together with an isolated line of very thin cirrus. The stratocumulus sheet is seen stretching away in the distance until it is obscured by the main body of the cirrus, visible in the upper part of the print. This cirrus, which is about 20 miles distant, is fibrous in character, but with a clear shadow on the low cloud below; the broken nature of the nearer parts of this cirrus will be realized from the sunlit stratocumulus cloud beyond the shadow. The cirrus becomes more stratified as it disappears into the distance, though there are isolated clouds seen in the middle distance which, the pilot stated, still retained their brightness and character when he flew nearer to them. He did not descend through the cirrus layer, which he reported at about 22,000 ft., but at least in the vicinity of the brighter patches of cloud (nearly 50 miles away) the sheet was thin enough for the lower cloud to be seen through it at times. There was an occluded front from south Wales to the Channel Islands which was almost stationary (it hardly changed position during 24 hours) and sporadic rain was falling from the front well to the west of the area of photography—probably under the most distant cloud. Slight snow was reported from isolated, higher-level stations on Salisbury Plain. The wind at cirrus level was from NW. along the leading edge of the cirrus cloud.

Fig. 4 shows an altocumulus layer taken from a height of approximately 25,000 ft. just before noon on December 1, 1949, looking approximately west-south-west, so that the sun is shining from left to right across the picture. The main interest in the photograph lies in the fault running from the foreground away from the aircraft. The pilot of the aircraft stated afterwards that the cloud top was at a height of about 12,000 ft. above sea level and that the fault between the two sheets appeared to be about 500 ft. deep. Unfortunately, no information is available regarding the possibility of a wind shear at the discontinuity. A somewhat similar fault with a marked shear was described by Frith in *Nature**; on this occasion wind shear was undoubted, as an ice-seeded hole in the cloud across the fault was sheared by the movement of the air at different speeds on the two sides. The only evidence of discontinuity between the two sides of the fault line in the photograph lies in the smoother surface of the cloud to the south compared with that to the north. Above the aircraft, at a height of approximately 30,000 ft. a cirrostratus layer will be seen; there is some evidence of wispy cirrus in the right foreground. It will be seen that this layer is by no means continuous, as the rays of the sun are playing on many parts of the altocumulus layer. The synoptic situation at 1200 G.M.T. on December 1, 1949, was, briefly, a deep depression north-west of the Faeroes moving slowly north-east, and an associated feeble warm front along the English Channel drifting slowly southwards. The photograph was taken from just west of London.

Fig. 5 was taken from an aircraft flying at 32,000 ft. on February 28, 1950, looking almost due south over Salisbury Plain. The cloud seen is cirrus and the long rollers across the photograph were along the line of the upper winds

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*FRITH, R.; Details of wind structure revealed by artificial nucleation of supercooled clouds. *Nature, London*, **165**, 1950, p. 899.

which were from north-west. Close inspection shows that the cloud running diagonally across the photograph is indeed rolling, as upward movement is apparent on its further side and downward, evidenced by the darker line of clearance, on the nearer side. In fact, there was little or no cloud below the cirrus, and the bright spot visible in the centre foreground is probably reflection of the sun from some lake or river surface. The right-hand side of the cloud in the left foreground is showing signs of rising, as the feather of wispy cirrus in the middle distance shows. These clouds were about 20,000 ft. above sea level. The synoptic situation was that of a double occlusion, almost stationary, over west England and Wales, associated with a secondary depression which had moved from the south of Ireland to just south of Cornwall by midday. The fronts were degenerating, but considerable rainfall was still being experienced in Devon and Cornwall (well to the west of the cloud surface shown here). The photograph was taken soon after noon, as the reflection from the water surface and the illumination at the top of the print shows.

G. W. HURST

REVIEW

Handwörterbuch der Meteorologie. Edited by Karl Keil. 8¼ in.×5¼ in., pp. viii + 604, *Illus.* Verlag Fritz Knapp, Frankfurt am Main, 1950. *D.M.* 28.00.

Dr. Keil, of the Meteorological Service of the United States Zone of Germany, has produced a very useful addition to the small number of " encyclopædias " of meteorology and its applications.

Like the " Meteorological Glossary ", Dr. Keil's book provides a substantial descriptive account for the majority of the words included. The article on " clouds " runs to about 1,200 words but the great majority have between 50 and 100.

The book is very up-to-date as is shown by the entries for " ageostrophic ", " okta ", " sublimation nucleus ", Dr. Curry's bioclimatic factor " aran ", the methods of construction and application of charts of the topography of isobaric surfaces, and the synoptic code introduced in 1949. "Jet stream " (called *Strahlstrom* in German as a rule) is, however, neither mentioned as a name on its own account nor, so far as could be seen, is it referred to in any of the articles.

According to the preface the book contains explanations of 3,500 words. No branch of meteorology fails to receive reasonably sufficient description, though it will always be possible with this class of book to think of some words omitted and apparently as worthy of inclusion as some included. The only words noted as omitted as a class are those for the post-glacial climatic periods, Boreal, Atlantic, etc. The book follows the United States " Weather Glossary " in giving explanations of the synoptic-code abreviations, T_gT_g, etc.

An unusual feature is the inclusion of brief biographical details of some meteorologists, though one must wonder at a method of compilation which provides for the omission of Sir David Brunt when Sir Edward Appleton is included.

The only serious errors noted are the definition of the knot as one English mile per hour with English mile clearly stated elsewhere as 5,280 ft., and the incompleteness of the formula (under " Earth ") for the variation of gravity with latitude and height. The " English (London) mile ", equivalent to 1·524 Km., which is almost exactly 5,000 ft., included in the list of " miles ", is new to the reviewer.

A large number of local wind names are included but helm wind is not among them.

The reviewer has little complaint on the whole regarding omissions or errors, and his main criticism of the book is that many unnecessary words are included and that there is some duplication of information between the entries under main subjects and those under parts of them. On the first point, we find many astronomical and physical words such as " aberration " and " neutrino " of no particular meteorological interest; and is it necessary in this glossary to define " Christmas " and explain how the date of Easter is determined? As examples of the second point, the entry for " decrease of temperature with height " is largely repeated under " temperature " and " temperature gradient "; the same comment applies to the entries for " weather service " and " organization of the weather service ". Further, is the entry " London fog " justifiable on the basis of its use as a phrase for dense fog in general? Space saved by judicious pruning could have been used to avoid the rather ugly practice of using in the descriptions only the initial letter of the word described and possibly to reduce the very high cost.

There are no photographs and the only illustrations are small line blocks. The book is well bound. The price of 28 *D.M.*, equivalent to some £2. 3*s.* 0*d.*, is very high, especially when compared with 8*s.* 6*d.*, the price of the " Meteorological Glossary ".

G. A. BULL

METEOROLOGICAL OFFICE NEWS

Festival of Britain 1951.—Meteorology will have a prominent place among the Festival of Britain exhibits in the Dome of Discovery where British achievements in science will be displayed. The meteorological exhibit will include the making of observations both at the surface and in the upper air, the instrumental equipment which is used, the organization for the collection and dissemination of basic data, the processing of this raw material and the supply of meteorological information to the community generally and in particular to the many and varied interests served by the state meteorological service.

The central feature of the exhibit will be a " live " forecast unit. This unit will be connected to the Central Forecasting Office on the first and second teleprinter channels and by telephone, and will prepare daily, in view of the public, a sequence of synoptic charts. A forecaster will be on duty to answer inquiries, and, by arrangement with His Majesty's Stationery Office, a souvenir *Daily Weather Report* will be prepared for sale at a moderate charge. There will be a meteorological enclosure in the Festival grounds and observations will be made and exhibited daily.

R.A.F.V.R. Meteorological Section.—Meteorologists, whose full time service with the Meteorological Office ended with the war but who have since joined the Royal Air Force Volunteer Reserve, have had to begin by bringing their meteorological knowledge up to date. Most of the reservists have now done this, and in 1951 will be expected to help the work of the Office by attachment to R.A.F. summer camps and to operational squadrons during exercises. A special course at the Meteorological Office Training School is being arranged this year for a small number of reservists.

Hydrology.—The ever increasing demands by industry, agriculture and domestic users for adequate supplies of water have focussed attention upon hydrology, and this science is being fostered in the Meteorological Office by wider study of what happens to precipitation after it has reached the ground. This wider interst was reflected in a paper on rainfall run-off and evaporation which was read by Dr. J. Glasspoole under the auspices of the British Water Works Association at the Public Works and Municipal Services Congress at Olympia, London, in November 1950.

Potato-blight warnings.—The weather of 1950 resulted in outbreaks of potato blight which reached epidemic proportions in many areas, but the warnings supplied by the Meteorological Office greatly assisted the planning of preventive spraying and much valuable food was saved. A recent Conference of Advisory Plant Pathologists, which discussed the system of potato-blight forecasting, expressed its appreciation of the information supplied, extended its thanks to all observers who had taken part and looked forward to co-operation along the same lines in 1951.

Inquiries from the Press and General Public.—The increasing use of meteorological information by the London Press and the General Public is shown by the number of inquiries received by the forecast section in Kingsway since the war. The number of inquiries dealt with there, mostly by telephone, were:—

Year	1946	1947	1948	1949	1950
No. of inquiries	14,503	23,815	23,145	32,307	43,612

In general, summer week-ends were the busiest periods, but 542 inquiries on the prospects of fog clearance were logged on November 25, 1950, and 495 on the likelihood of rain ceasing for the Test Match at Lords on June 23, 1950. The largest number of inquiries received in any one month was 5,044 in July 1950.

Falkland Islands.—The August 1950 *Meteorological Magazine* included a paragraph about meteorological work in the Falkland Islands and mentioned that assistants for the Falkland Islands Dependencies Survey were being recruited from amongst the Meteorological Office staff. As a result the following assistants were selected and left in the *John Biscoe* early in November: J. R. Cowling, J. Ford, B. D. Hunt, P. H. Hoare, A. F. Lewis, A. I. MacArthur, P. W. Mander, N. H. Thyer, R. A. Todd-White, and A. J. Vernum. A. F. Lewis, well known to his friends at home as the holder of the Air Ministry swimming championships for several years, has made an excellent start in his new sphere. On the trip from Port Stanley to his base, in the *John Biscoe*, he retrieved an indispensable roll of cable which had fallen overboard. The temperature of the water was 31°F.

Ocean weather ships.—The *Weather Recorder*, owing to a defect in her steering gear, was unable to manœuvre in the normal way when being relieved by *Weather Observer* at station JIG on January 11, 1951. As a result of this in a very heavy squall a sea was shipped over the stern of the *Weather Recorder* which damaged the doors leading into the balloon shelter and injured some of the crew. Fortunately the damage was superficial and the injuries not serious.

Thanks to the kind interest of Captain Fanshaw, R.N., the members of the Carlton Club have arranged to send magazines to the weather ships. The first gift has been received and sent to Greenock.

Awards to Staff by the Royal Humane Society.—We are pleased to be able to record that, in recognition of their attempts to rescue a man from drowning at Benbecula in August last, letters have been received by Messrs. D. M. Sadler and J. Meadows from the Chief County Constable of Inverness notifying them of the undermentioned awards from the Royal Humane Society:—

D. M. Sadler, the Society's bronze medal and bronze medal certificate.

J. Meadows, the Society's testimonial on vellum.

Examination successes.—We offer our congratulations to Messrs. A. A. Harrison and W. J. T. Norris on having passed the Intermediate B.Sc. Examination, London, in July last, and to Messrs. M. T. Batstone, A. D. Krill and A. C. Roberts on passing the same examination in November.

WEATHER OF JANUARY 1951

Mean pressure was above 1020 mb. over an area extending from Morocco and southern Portugal across the Azores, Bermuda and the south-east of the United States to northern California, with an extension north-westwards across Saskatchewan to the Arctic Ocean. It was below 1000 mb. between the Hebrides and southern Greenland and slightly below 990 mb. over a small area south-west of Iceland.

The mean pressure was slightly above normal over most of the North Atlantic between Portugal and the south-east of the United States, but was below normal over the greater part of North America and considerably below normal over most of the Mediterranean and Europe and from the Bay of Biscay and the western coasts of the British Isles north-westwards to southern Greenland. The deficit was 8 or 9 mb. over the British Isles and much of central Europe, and about 10 mb. over the Atlantic in about 60°N. from 10°W. to nearly 40°W.

In the British Isles the weather was rather cold except in the south-east, though not nearly as cold as the previous month. It was unsettled and wet on the whole, with considerable snowfall at times, but sunshine appreciably exceeded the average in Northern Ireland and locally in the north and east of Scotland and north-east England.

In the early hours of the 1st a secondary depression over north Wales moved slowly north and was associated with rather heavy snowfall in Northern Ireland, north Wales, the Midlands and north-west England; at 0900 on the 1st snow lay to a depth of 12 in. at Buxton, 10 in. at Malham Tarn and 8 in. at Lake Vyrnwy. During the 1st another centre of low pressure moved along the English Channel, and on the 2nd yet another moved east over the south of England to Holland and then turned north-east. Snow occurred in southern England and the Midlands, and lay $10\frac{1}{2}$ in. deep at Whipsnade and 8 in. at Birmingham on the morning of the 2nd, and $11\frac{1}{2}$ in. and 9 in. respectively on the morning of the 3rd. This period was very cold generally, temperature in the screen falling to 8°F. at Houghall, County Durham on the 2nd. A gale occurred at the mouth of the English Channel on the 1st. On the 4th and 5th a trough to a depression south-westward of the British Isles moved north over southern England causing heavy rain, and on the 6th the main depression, now centred south of Ireland, moved quickly north-east giving further rain. Gales were recorded locally on the south-west coasts and temperature rose in southern districts but remained low in the north. Thereafter a trough of low pressure moved east across the country giving more rain. On the 10th a depression, which had developed over the south of Ireland, moved north-east across Scotland, while an associated trough crossed England. Heavy precipitation occurred in the west and north on the 9th (2·04 in. at Kilsyth, Stirlingshire) and more generally on the 10th; in Scotland snow fell up to a foot deep in places on the 10th. On the 11th a deep depression south-west of Iceland moved a little south-east and a trough crossed England; more precipitation occurred and rainfall was moderately heavy locally; gales were registered at times at exposed places from the 10th to the 12th. Subsequently a depression south of Iceland moved east and a spell of showery weather ensued, snow showers occurring in the north. A ridge of high pressure moving east on the 15th was associated with a mainly fair day. The ridge was quickly followed by a trough which caused heavy rain in the west and north on the 16th and 17th (3·85 in. at Kinlochquoich, Inverness-shire, and 2·50 in. at Sloy Power Station, Dumbartonshire on the 16th and 2·87 in. at Kinlochquoich on the 17th), while temperature rose considerably throughout the country. The mild weather persisted during the ensuing days with pressure high off Spain and depressions moving east off the north of Scotland. Rainfall was generally slight over most of England, Wales and Ireland but heavier in parts of Scotland. Gales were registered locally at times on the 17th and 18th. On the 22nd and 23rd a depression moved from north-westward of Ireland to the Bay of Biscay; some rain fell in Ireland and southern England. Subsequently pressure became high in a belt across Great Britain; temperature fell and there was fog in the Midlands and the north on the 24th. On the 25th and 26th a trough moved slowly across the country giving precipitation in most areas, heavy locally in the west. On the 27th a depression off our south-west coasts moved away south-east giving some precipitation in the west and another ridge built up over the British Isles; temperature fell decidedly and there was considerable fog and severe frost. In the closing days a trough moved over western districts but weather continued mainly cold except in the west.

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

	Air Temperature			Rainfall		Sunshine
	Highest	Lowest	Difference from average daily mean	Percentage of average	No. of days difference from average	Percentage of average
	°F.	°F.	°F.	%		%
England and Wales ...	58	8	−0·5	127	+2	93
Scotland	54	11	−1·9	130	+1	104
Northern Ireland ...	54	16	−1·7	112	0	121

RAINFALL OF JANUARY 1951

Great Britain and Northern Ireland

County	Station	In.	Per cent. of Av.	County	Station	In.	Per cent. of Av.
London	Camden Square ...	2·84	153	*Glam.*	Cardiff, Penylan ...	5·33	144
Kent	Folkestone, Cherry Gdn.	3·52	156	*Pemb.*	Tenby	6·00	160
,,	Edenbridge, Falconhurst	3·52	144	*Card.*	Aberystwyth	4·05	126
Sussex	Compton, Compton Ho.	5·01	158	*Radnor*	Tyrmynydd	7·03	112
,,	Worthing, Beach Ho. Pk.	3·37	145	*Mont.*	Lake Vyrnwy	6·86	119
Hants.	Ventnor, Roy. Nat. Hos.	4·43	172	*Mer.*	Blaenau Festiniog ...	12·06	118
,,	Bournemouth	3.22	119	*Carn.*	Llandudno	2·70	112
,,	Sherborne St. John ...	2.95	127	*Angl.*	Llanerchymedd ...	3·88	123
Herts.	Royston, Therfield Rec.	2·49	144	*I. Man*	Douglas, Borough Cem.	5·30	158
Bucks.	Slough, Upton	2·82	152	*Wigtown*	Port William, Monreith	4·59	140
Oxford	Oxford, Radcliffe ...	3·07	170	*Dumf.*	Dumfries, Crichton R.I.	5·62	175
N'hants.	Wellingboro' Swanspool	2·38	129	,,	Eskdalemuir Obsy. ...	7·87	146
Essex	Shoeburyness	1·40	104	*Roxb.*	Kelso, Floors	3·09	177
,,	Dovercourt	1·83	114	*Peebles*	Stobo Castle	4·01	133
Suffolk	Lowestoft Sec. School ...	2·04	122	*Berwick*	Marchmont House ...	3·73	166
,,	Bury St. Ed., Westley H.	2·26	126	*E. Loth.*	North Berwick Res. ...	2·82	164
Norfolk	Sandringham Ho. Gdns.	2·85	147	*Midl'n.*	Edinburgh, Blackf'd. H.	2·59	147
Wilts.	Bishops Cannings ...	2·95	127	*Lanark*	Hamilton W. W., T'nhill	3·72	113
Dorset	Creech Grange... ...	4·41	135	*Ayr*	Colmonell, Knockdolian	4·49	104
,,	Beaminster, East St. ...	4·40	126	,,	Glen Afton, Ayr San. ...	6·02	118
Devon	Teignmouth, Den Gdns.	3·26	112	*Bute*	Rothesay, Ardencraig ...	5·93	132
,,	Cullompton	3·62	112	*Argyll*	Morvern (Drimnin) ...	9·39	148
,,	Ilfracombe	4·80	146	,,	Poltalloch	6·72	133
,,	Okehampton Uplands	7·29	143	,,	Inveraray Castle ...	8·44	103
Cornwall	Bude, School House ...	4·92	162	,,	Islay, Eallabus	5·53	118
,,	Penzance, Morrab Gdns.	6·10	161	,,	Tiree	8·65	204
,,	St. Austell	5·32	124	*Kinross*	Loch Leven Sluice ...	4·80	152
,,	Scilly, Tresco Abbey ...	5·31	169	*Fife*	Leuchars Airfield ...	3·12	171
Glos.	Cirencester	4·12	164	*Perth*	Loch Dhu	8·87	97
Salop.	Church Stretton ...	2·54	97	,,	Crieff, Strathearn Hyd.	4·71	117
,,	Shrewsbury	1·89	97	,,	Pitlochry, Fincastle ...	2·75	79
Worcs.	Malvern, Free Library	2·43	110	*Angus*	Montrose, Sunnyside ...	3·76	189
Warwick	Birmingham, Edgbaston	3·01	149	*Aberd.*	Braemar	3·31	104
Leics.	Thornton Reservoir ...	2·44	123	,,	Dyce, Craibstone ...	4·01	170
Lincs.	Boston, Skirbeck ...	3·28	202	,,	Fyvie Castle	3·35	141
,,	Skegness, Marine Gdns.	2·83	164	*Moray*	Gordon Castle	2·77	137
Notts.	Mansfield, Carr Bank ...	1·85	86	*Nairn*	Nairn, Achareidh ...	2·26	125
Derby	Buxton, Terrace Slopes	5·22	117	*Inverness*	Loch Ness, Garthbeg ...	4·73	107
Ches.	Bidston Observatory ...	1·80	85	,,	Glenquoich	12·46	91
Lancs.	Manchester, Whit. Park	3.23	129	,,	Fort William, Teviot ...	9·73	100
,,	Stonyhurst College ...	5·09	119	,,	Skye, Duntuilm ...	7·65	144
,,	Squires Gate	3·93	151	*R. & C.*	Tain, Tarlogie House ...	3·13	128
Yorks.	Wakefield, Clarence Pk.	1·81	94	,,	Inverbroom, Glackour...	5·89	110
,,	Hull, Pearson Park ...	1·72	95	,,	Applecross Gardens ...	8·45	154
,,	Felixkirk, Mt. St. John...	1·83	91	,,	Achnashellach	9·25	102
,,	York Museum	1·91	108	,,	Stornoway Airfield ...	4·95	101
,,	Scarborough	1·97	98	*Suth.*	Loch More, Achfary ...	7·69	106
,,	Middlesbrough... ...	1·69	106	*Caith.*	Wick Airfield	2·62	107
,,	Baldersdale, Hury Res.	3·15	97	*Shetland*	Lerwick Observatory ...	5·19	122
Norl'd.	Newcastle, Leazes Pk....	1·03	52	*Ferm.*	Crom Castle	3·93	118
,,	Bellingham, High Green	3·11	109	*Armagh*	Armagh Observatory ...	2·65	105
,,	Lilburn Tower Gdns. ...	2·46	119	*Down*	Seaforde	4·50	143
Cumb.	Geltsdale	3·78	135	*Antrim*	Aldergrove Airfield ...	2·47	90
,,	Keswick, High Hill ...	4·67	92	,,	Ballymena, Harryville...	3·57	96
,,	Ravenglass, The Grove	4·16	124	*L'derry*	Garvagh, Moneydig ...	4·52	131
Mon.	Abergavenny, Larchfield	4·34	128	,,	Londonderry, Creggan	4·15	115
Glam.	Ystalyfera, Wern House	8·74	138	*Tyrone*	Omagh, Edenfel ...	3·52	99