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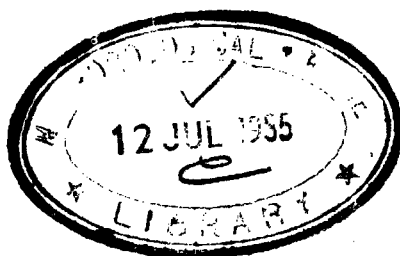
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# DEPRESSIONS CROSSING LABRADOR AND THE ST. LAWRENCE BASIN

By A. G. FORSDYKE, Ph.D.



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# DEPRESSIONS CROSSING LABRADOR AND THE ST. LAWRENCE BASIN

By A. G. FORSDYKE, Ph.D.

**Summary.**—Depressions which traverse the eastern part of North America may be divided into two main classes according to their subsequent behaviour; they may either move out into the Atlantic or become slow moving somewhere to the west of Greenland. The relation between the behaviour of these depressions and the synoptic situation over western Europe is examined, with a view to its possible use in extended forecasting for the British Isles. The corresponding hemispherical 500-mb. contour patterns are studied but they appear to afford little indication of the subsequent surface developments.

The development and movement of individual depressions is examined in relation to the 1000–500-mb. thickness pattern, but no simple connexion, which would be useful in forecasting, is found.

**Introduction.**—One of the outstanding problems in extended forecasting for the British Isles is concerned with the behaviour of depressions over the north-eastern regions of the American continent and the adjacent sea areas. It is well known that these systems have two broad modes of behaviour: they may either move out into the Atlantic or swing northwards and perhaps north-westwards to become slow moving somewhere to the west of Greenland. In the former case they may be expected sooner or later to bring cyclonic weather to the British Isles. The latter movement is frequently accompanied by at least the temporary building up of a ridge of high pressure on the Atlantic with the threat of a cold northerly type of weather over the British Isles. The present study was undertaken primarily to search for some criterion which would enable the broad mode of behaviour of particular depressions to be forecast long enough in advance to make it useful for medium-range forecasting. The associated large-scale thickness and upper-flow patterns were the main basis of the study to begin with.

It was found that the period studied could be divided into spells each characterized by the similar behaviour of a few successive members of the sequence of depressions, and that each spell could be associated with some characteristic features of the hemispherical upper-flow patterns. Little success was however achieved in the search for the medium-range forecasting criterion. It seems that the behaviour of these systems depends to a large extent on their detailed structure as well as on the details, in their own locality, of the associated upper air patterns. There is considerable evidence for the thermal steering of these systems, and, broadly in relation to the thickness patterns, the systems may be said to behave in accordance with the developmental ideas put forward by Sutcliffe\*, but in most cases the surface and thermal patterns evolve together and give little advance indication for forecasting the behaviour of one on the basis of the other. But although its main object has not been achieved, this study has led to some interesting statistical results regarding the evolution of depressions of the type considered. The report is divided into two parts. Part I deals with the general behaviour of the systems studied, and Part II consists of a statistical treatment, for selected groups of systems, of the relation between movement and deepening and certain features of the thickness pattern. Throughout this paper the term "contour" or "upper flow" refers to the 500-mb. contour pattern, and "thickness" to the 1000–500-mb. thickness pattern.

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\* The index numbers refer to the bibliography on p. 44.

**Data.**—All depressions which occurred in a specified area (denoted by "L"), comprising Labrador and the north-eastern part of the United States, during the year 1950 were selected for study. The boundaries of L are, to the north 60°N., to the east 50°W., to the south-east the line joining 50°N. 50°W. to 40°N. 60°W., to the south 40°N. and to the west 80°W. (see Figs. 2 and 3).

The data were extracted from the 1 : 30 million circumpolar charts prepared twice daily at the Meteorological Office, Dunstable. All depressions which, while located in L, had at least one closed isobar (isobars at 4-mb. intervals) were considered. Track charts were plotted showing the position and central pressure of each depression at 12-hourly intervals over the period from two days before its centre entered L to three days after it left. The depressions were divided into two classes called "major" and "minor" respectively, according to their central pressure, as follows :—

	Major mb. ≤1000	Minor mb. >1000
Summer (April–September) ..	≤992	>992
Winter (October–March) ..	≤992	>992

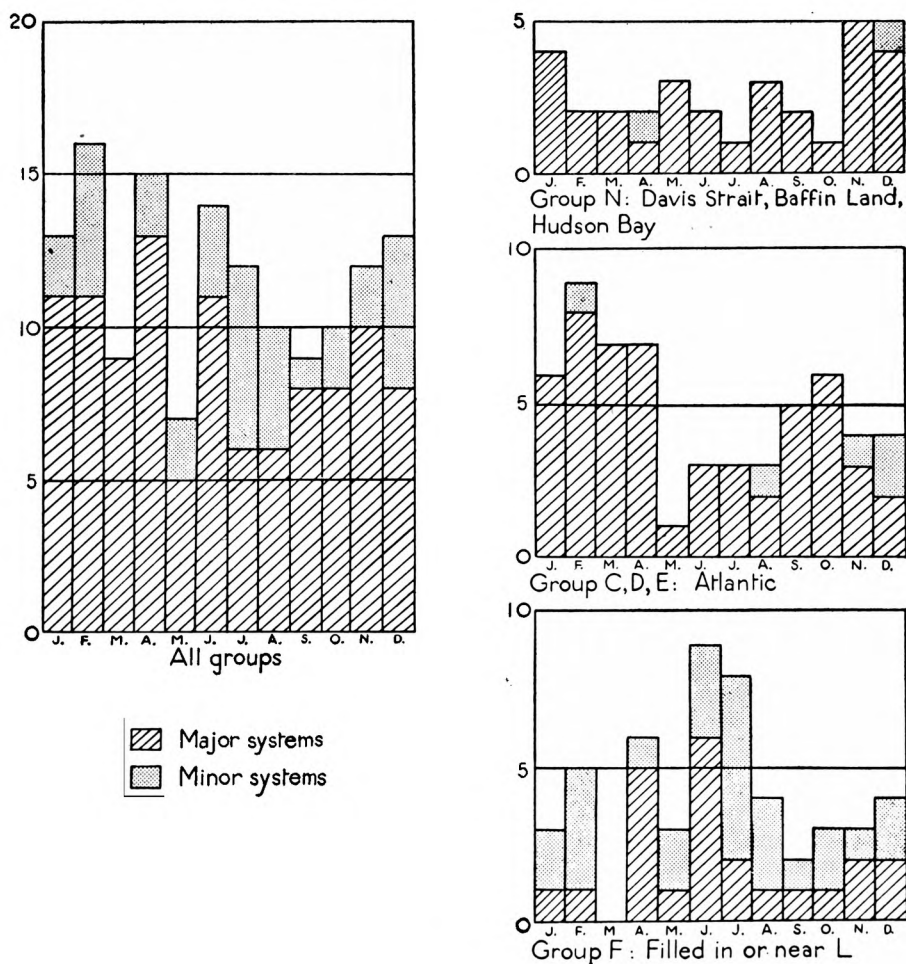


FIG. 1—MONTHLY FREQUENCY OF DEPRESSIONS TRAVERSING AREA L

A depression was classified as major if for at least one position on the track chart the central pressure reached the value specified.

#### PART I—GENERAL

**General survey.**—A general survey of the selected group of depressions is given here first, the purpose being to provide the factual background for this study and an ordered assembly of the data. It is not suggested that the numerical values quoted have any special significance for they are based on one year only, and there is no reason to think that they would necessarily correspond at all closely with the data for other years.

The total number of depressions studied was 140, of which 106 (approximately 75 per cent.) were major systems.

*Classification of depressions according to movement.*—The depressions were classified according to their movement into and out of L, the result being shown in Table I. For movement into the area the systems are classified as west if they entered across the western boundary, and so on; for movement out of the area the table is self explanatory. The plain entries refer to major systems, those in brackets to minor systems as defined above.

TABLE I—FREQUENCY OF DEPRESSIONS ACCORDING TO MOVEMENT INTO AND OUT OF AREA L

	Movement out of area L				Filled or absorbed by another low in or near L	Total
	towards west Greenland, Baffin Land, north Canada Class N	towards south-east Greenland, Iceland Class C	towards the south-east; Azores Class D	eastward into the Atlantic Class E		
Formed in L ..	1 (1)	3 (0)	1 (1)	6 (1)	4 (5)	15 (8)
Movement into L from {	west 25 (0)	13 (0)	1 (0)	12 (1)	14 (15)	65 (16)
	south 4 (1)	7 (0)	0 (0)	10 (2)	3 (7)	24 (10)
	east 0 (0)	0 (0)	0 (0)	0 (0)	1 (0)	1 (0)
	north 0 (0)	0 (0)	0 (0)	0 (0)	1 (0)	1 (0)
Total ..	30 (2)	23 (0)	2 (1)	28 (4)	23 (27)	106 (34)

In regard to major systems only, the main facts provided by Table I are as follows :—

(i) The majority of depressions originated outside L and moved into it from the west (61 per cent.) or south (23 per cent.). The remainder nearly all formed within L; movement into L from the north, east (or south-east) was rare.

(ii) One half of the total number of systems moved out into the Atlantic, 27 per cent. more or less eastwards and 22 per cent. on tracks towards south Greenland and Iceland. Only two systems moved definitely and consistently towards the Azores region.

(iii) Rather more than one quarter of the total number of systems remained west of Greenland after moving out of L. Of the 30 such systems only one had formed in L, four had moved into L from the south and the remainder had moved in from the west.



*Monthly frequency of depressions.*—For obvious reasons the chief interest centres in the behaviour of depressions after they leave the area L. Accordingly for the purpose of this study they were divided into the following groups based on the classes of Table I.

Group N	Depressions which after leaving L remained west of Greenland
Groups C, D, E	Depressions which moved out into the Atlantic
Group F	Depressions which filled or disappeared in L or near L (except Group N).

The monthly frequency of these groups is shown in Fig. 1. The distribution over the year is irregular and in no way remarkable. The occurrence of a large proportion (32 out of 67) of depressions of Group F during the summer months is in accordance with expectation. Groups N and C, D, E consist predominantly of major systems ; of the total of 34 minor systems 27 filled in or near L.

*Scatter of the depression centres.*—The position of the centres of major depressions at intervals of from one to four days after they entered area L are shown in two series of charts, Figs. 2 and 3. Fig. 2 is for systems which entered L from the south and Fig. 3 for those which entered from the west. For convenience these two classes are denoted respectively by "S" and "W". In Figs. 2 and 3 the main seasons (Winter, January to March and October to December, and Summer, April to September) are distinguished by the type of symbol marking the position of the centre. For ease of identification on successive days the catalogue numbers used in the original tabulation of data for this study have been entered beside the position symbols for some of the more interesting systems.

In a large number of cases the drawing of track charts for individual centres is not a simple straightforward procedure. With few exceptions depression centres undergo complex processes of splitting, development of secondaries and absorption of other systems, so that in the drawing of track charts it is often necessary to exercise judgment regarding the identification of centres in successive positions.

Though Figs. 2 and 3 do not bring to light any systematic behaviour of the systems studied they do indicate certain broad features which are of some interest.

(i) Of the 24 systems which entered L from the south 16 (67 per cent.) were still in existence on the fourth day. Of systems entering L from the west, 36 out of 65 (55 per cent.) were still in existence on the fourth day. The remainder had either filled, or been absorbed into other systems. Of those which filled, many had developed secondaries of one form or another, and the secondary may in such cases be regarded as having taken over the role of the original system though the identity of centres is not preserved.

(ii) The area to the west of Greenland appears to be a specially favoured region for the filling of depressions, generally those of class W. Only four systems of class S reached this area. It is well known that depressions moving from Labrador or Baffin Land often fill off west Greenland ; this filling is frequently accompanied by the formation of a secondary off south-east Greenland which moves away eastward.

(iii) The almost complete absence of centres from the mainland of Greenland is in accord with experience ; it is however partly explained by the lack of observations. Only one of the systems studied (No. 27, Fig. 3) actually crossed Greenland. It is well known that depressions do sometimes appear to "jump" across Greenland from west to east ; it is here suggested that these are systems which approach Greenland from west or north-west without traversing area L.

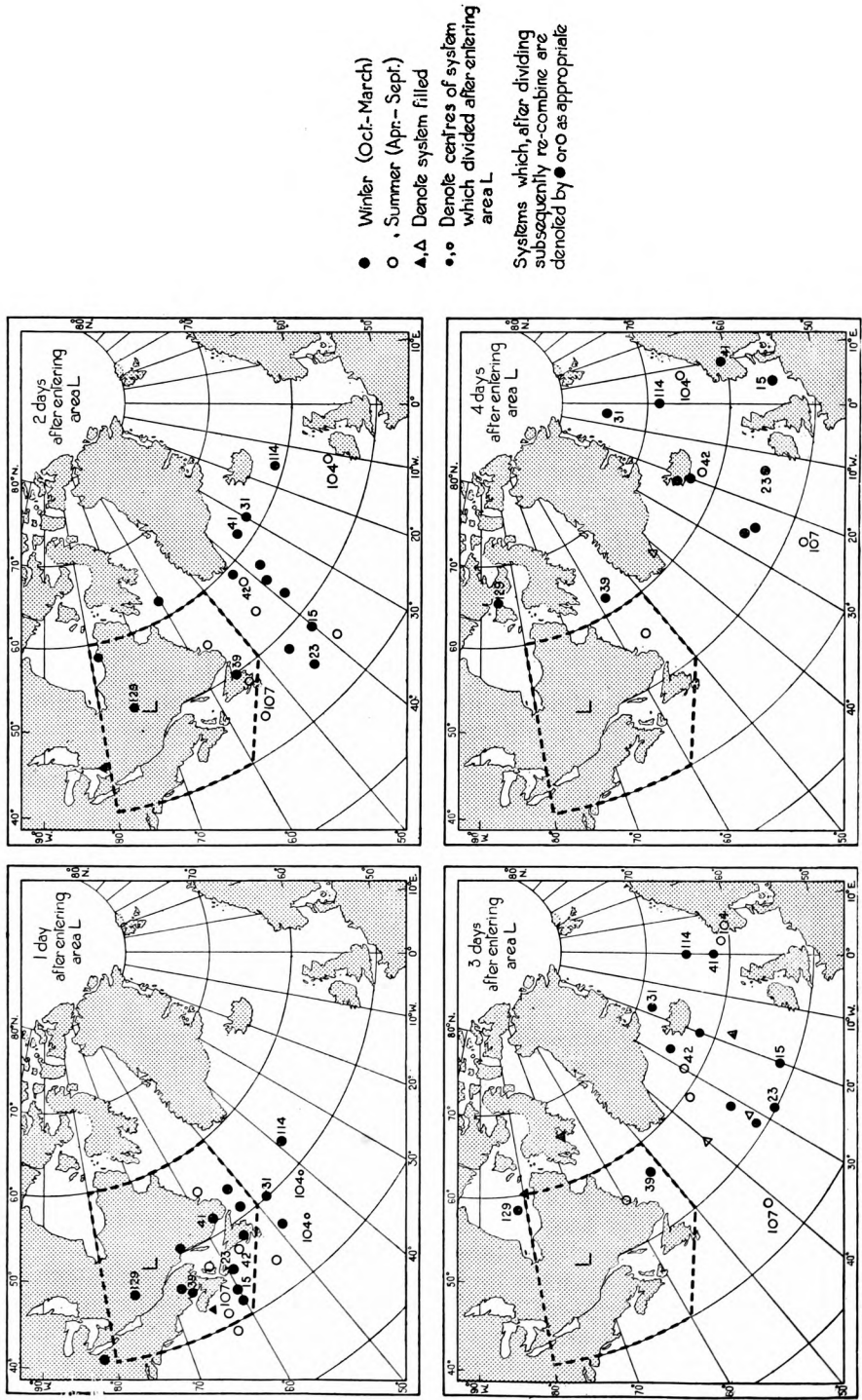


FIG. 2—POSITIONS OF CENTRES OF DEPRESSIONS WHICH ENTERED AREA L FROM THE SOUTH

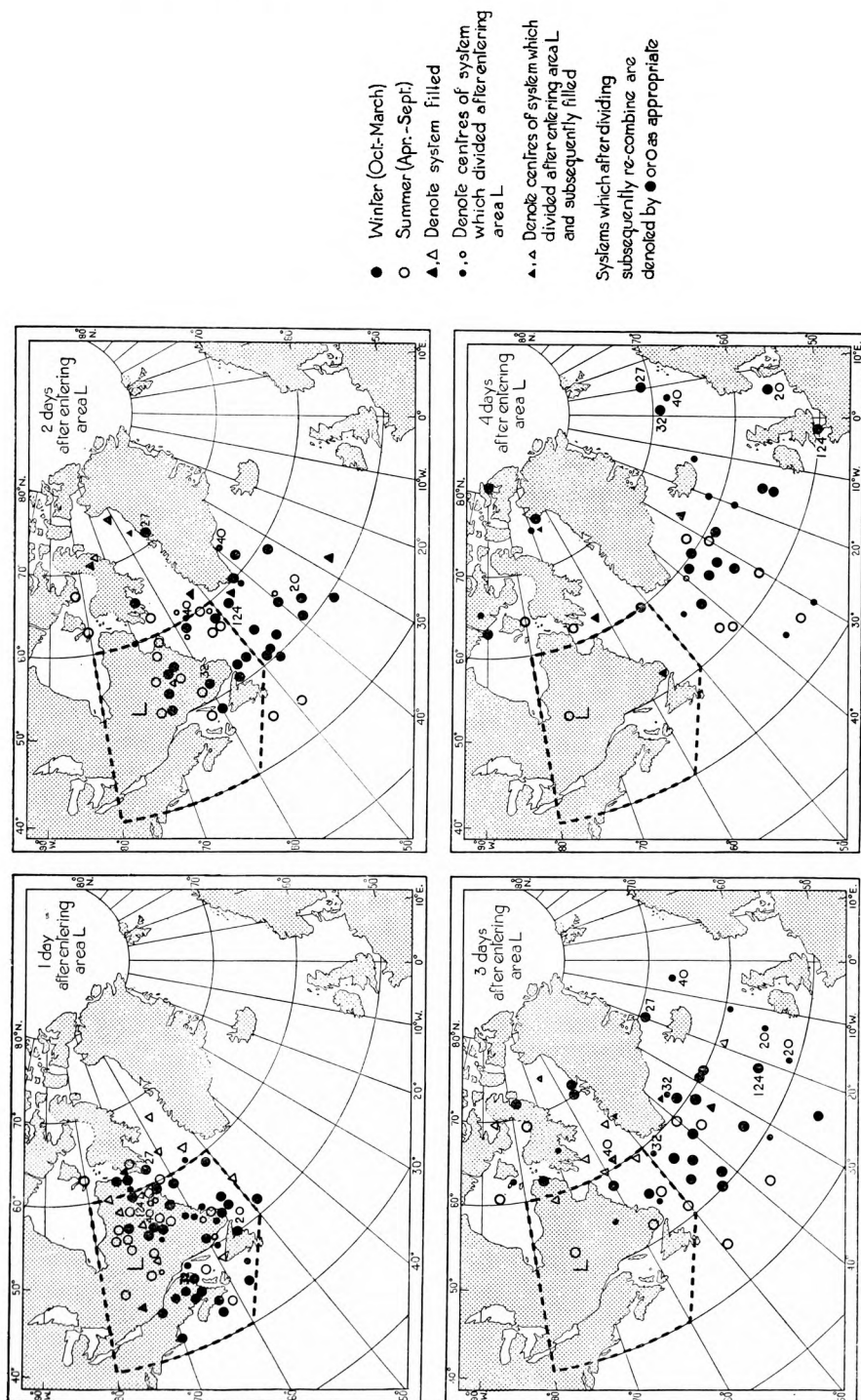


FIG. 3—POSITIONS OF CENTRES OF DEPRESSIONS WHICH ENTERED AREA L FROM THE WEST

(iv) It is also well known that the area immediately to the east of the southern tip of Greenland is a very favoured location for depressions. This is not brought out by Figs. 2 and 3 so that it may be concluded that depressions in this area are not, as a rule, those which have traversed L. It is believed that they frequently arise from the movements or developments referred to in (ii) and (iii), or are trough extensions from deep systems centred near Iceland.

(v) On the whole Figs. 2 and 3 confirm the well known fact that depressions in middle and high latitudes move faster in winter than in summer. There are, however, one or two examples of very fast moving (late) summer systems, Nos. 104 and 107, Fig. 2. These were both tropical storms, originating between Bermuda and Florida. The acceleration of tropical storms on passing into temperate latitudes has been referred to by Sawyer and Ilett<sup>2</sup>. No. 42 (Fig. 2), occurring in early April, only just qualifies as a summer system; its behaviour closely resembles that of the immediately preceding winter systems, Nos. 40 and 41.

(vi) Little distinction can be drawn between the classes S and W as regards mobility. Figs. 2 and 3 tend to give the impression that the S depressions move eastward the more quickly of the two, but it should be pointed out that their starting point, as far as these diagrams are concerned, is farther east in all cases. It is apparent however that the S-type depressions have little tendency to become slow moving on the western Atlantic, as the W-type depressions do as shown by the grouping south of Greenland in the lower part of Fig. 3. The S-type depressions also show a large scatter, while there is a distinct tendency for W systems to group themselves between 50°N. and 60°N. up to the fourth day.

**Types and spells associated with depressions in the Labrador-St. Lawrence region.**—A study of these depressions through the course of the year indicates that they tend to occur in groups or sequences consisting of about two to four members whose behaviour, particularly as regards movement, is similar. Such a pattern of behaviour may persist for a few days or a week, occasionally longer. Its importance lies in the associated large-scale pattern which may be affected over a sufficiently wide area to determine the broad pressure distribution over regions as distant as the British Isles. Table II lists the spells occurring during 1950 which lasted at least four days.

The dates given as the beginning and ending of a spell are respectively that on which the first members of the group of depressions comprising the spell entered L and that on which the last member of the group left L.

Seven types may be distinguished, based on the classes of Table I, with some subdivision. Table II gives the characteristics of each type, the length of each spell and the total occurrence in days, in summer and winter respectively.

Detailed studies were made of these spells primarily with the object of discovering any common features in the large-scale surface and upper air patterns which would enable the onset of a spell to be recognized beforehand. Such common features as there are, however, are recognizable only on a very broad basis, and differ so much among themselves in small- and medium-scale features that their value for forecasting cannot be very great.

The results of these studies are discussed in the following paragraphs. Lest it should seem that an undue amount of attention is given to type N1 it must be remembered that the broad distinction adopted lies between stagnating systems (N1) on the one hand and mobile systems (N2, C, E) on the other.

TABLE II—LIST OF TYPES AND SPELLS

Type	Description	Date	Duration of spell	Total number of days	
				Winter	Summer
N1	Systems move north or north-west bodily from area L to Greenland, Baffin Land or north Canada. Little or no tendency for subsidiary systems to break away into the Atlantic.	1950	days		
		Jan. 14-19	6		
		May 6-16	11		
		June 10-19	10		
		Aug. 17-28	12	26	33
		Nov. 20-Dec. 5	16		
N2	Systems move as in type N1, but subsidiary systems break away into the Atlantic. The subsidiary system often extends south-east from the main centre; it frequently deepens while the parent system fills.	Dec. 11-14	4		
		Feb. 18-23	6		
		Mar. 23-27	5		
		July 11-15	5	19	14
		Sept. 18-26	9		
		Dec. 24-31	8		
C	Systems move north-east from area L to east of Greenland, sometimes beyond Iceland.	Feb. 24-Mar. 5	10		
		Mar. 28-Apr. 12	16	25	12
		Oct. 12-22	11		
E	Systems move in a general easterly direction from area L to mid Atlantic, sometimes reaching the British Isles.	Feb. 4-17	14		
		Mar. 12-20	9		
		June 20-26	7	23	18
		July 23-Aug. 2	11		
CE	Combination of C and E. Either systems of types C and E alternate, or they move as type E to mid Atlantic, and then turn sharply north towards Iceland.	Jan. 2-12	11		
		Jan. 26-Feb. 3	9		
		Apr. 23-May 3	11		
		Aug. 9-17	9		
		Aug. 31-Sept. 18	19	49	40
		Sept. 30-Oct. 6	7		
		Nov. 5-18	14		
		Dec. 16-24	9		
F	Systems fill in area L, or within a short time after leaving L.	Apr. 12-23	12		
		June 3-8	6		
		June 27-July 8	12	0	34
		July 17-20	4		
A	No depressions in area L, which is often anticyclonic.	Jan. 20-25	6		
		May 20-June 2	14		
		Aug. 3-8	6	14	20
		Oct. 27-30	4		
		Dec. 6-9	4		

**Type N1. Systems remaining substantially to westward of Greenland.**—These systems though not associated with significant forward break-aways were, as a rule, complicated by secondaries moving from the south-west; these secondaries usually became absorbed into the main system and so are classified as F in Table I. In five out of the six spells the original depression was the first of a group of two or more independent systems moving from the south-west, each intensifying in turn near L and taking over the role of the main system, defining the type. Such renewal or replacement would seem to be necessary to the establishment of a spell, for in the five cases of a single depression of this class the centre did not survive as the main feature for the necessary four days, and no spell was recorded.

The northward or eastward movement of the centre was in all cases broadly consistent with the direction of the thermal steering, implying a thermal trough near the longitude of Hudson Bay. In most cases (14 out of the 18 studied in detail) this trough was already in existence in high latitudes before the beginning of the spell, with frequently a cold pool over Hudson Bay or the Canadian Archipelago. Sometimes a thermal ridge developed north-westwards from south Greenland across Baffin Land to the extreme north of Canada, separating the Hudson Bay cold pool from the polar basin. The southward extension of the cold trough, necessary for northward steering from area L, was, however, most often effected in conjunction with the low itself over area L, rapidly transforming an eastward or north-eastward steering pattern into a northward or north-westward one. It appears therefore that the pre-existing thermal pattern over L affords little guide to the onset of a spell of this type. This point is discussed in more detail on p. 40.

*Large-scale patterns associated with type N1.*—The definition of this type implies some degree of stagnation in the vicinity of Labrador; if there is any coherence at all in the large-scale surface patterns it would be reasonable to look for immobility in other parts of the hemisphere also. A study of the hemispherical 500-mb. flow patterns during the six spells listed in Table II does indicate that there is immobility of the large-scale troughs and ridges in a broad sense, though the patterns are disturbed from time to time by small mobile features. Characteristically also the troughs and ridges are features of large amplitude, and usually they persist through the whole of a spell. But though the six spells have these broad features in common, there are important differences between them, arising from the longitudinal locations of the ridges and troughs, apart from the trough over eastern North America, which, from the type definition, is to be expected as a constant feature. The sectors of the hemisphere which were occupied by slow-moving and persistent upper troughs and ridges in the six spells are shown in Fig. 4. Troughs are marked by full lines and ridges by broken lines drawn along arbitrarily selected parallels of latitude, one for each spell. Generally the extent of the sector marked indicates the range over which the axis of the trough or ridge varied during the spell, but for the spell, January 14–19, the line extending from 130°W. to 40°W. indicates that the whole of this sector was occupied by a broad trough. On the whole the axes of the troughs and ridges were inclined at only a small angle to the meridians so that little difficulty arises in placing a trough owing to the latitudinal variation of the position of its axis. The overlapping lines in the Pacific for the spell August 17–28 do however indicate a quasi-stationary “cyclonically” distorted pattern consisting of a ridge in high latitudes and a trough farther south with their axes lying from north-west to south-east.

Fig. 4 shows clearly that the locations of the persistent upper troughs and ridges differ between spells. In particular there is a marked shift to westward of the ridge-trough pattern over the Atlantic and Europe in the last three as compared with the first three spells. It is evident from the dates of these spells that this shift is not a seasonal effect, as might be expected having regard to the fact that the mean zonal flow and the associated spacing in the long-wave pattern are greater in winter than in summer. Other features which are common to most of the spells, though still somewhat variable in location, are the ridge near the east Pacific, the trough in the eastern central Pacific and the trough off the east Asiatic coast. No features are shown over the eastern half of Asia because of the scarcity and uncertainty of the observations there.

A further characteristic of the upper-flow patterns associated with this type is that in high latitudes the circumpolar vortex is usually split up into a number

of separate centres each covering a substantial area. One of the most prominent of these lies over Labrador or Baffin Land, separated from the polar basin by a ridge across the Canadian Archipelago from the north-west Atlantic to Alaska.

Associated with the persistent upper troughs and ridges are large-scale cyclonic and anticyclonic circulations at the surface—often with their longer axes orientated more or less meridionally. The individual cyclonic regions remain on the whole distinct and separate throughout a spell, with little or

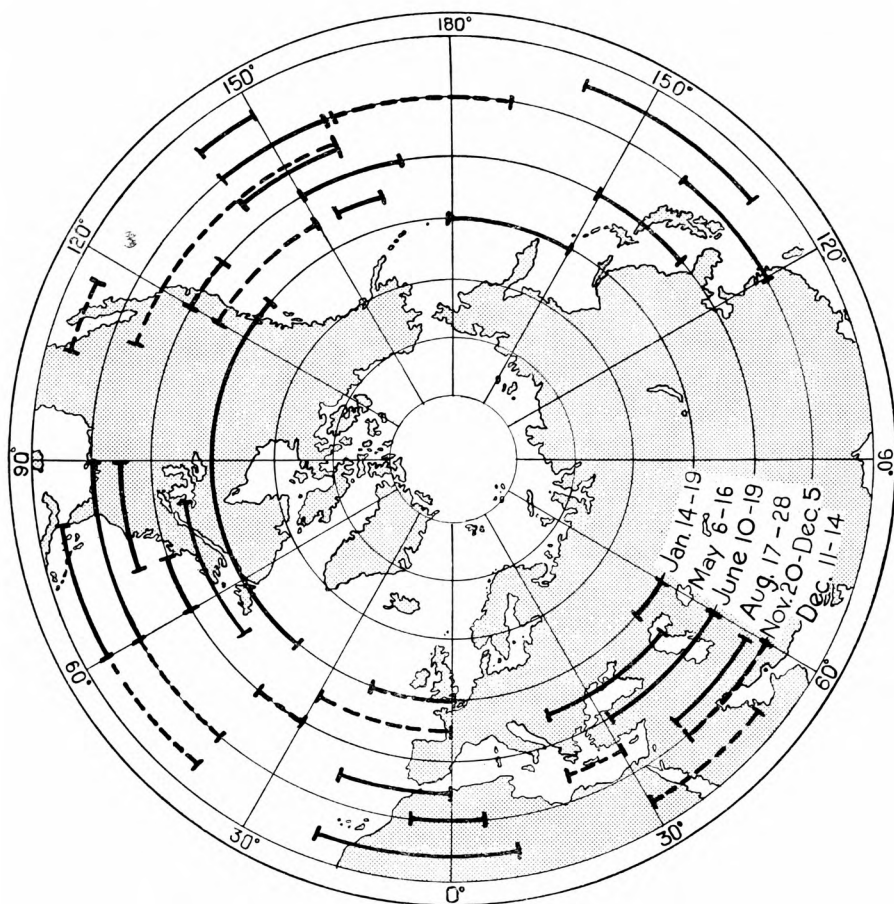


FIG. 4—SECTORS OCCUPIED BY PERSISTENT UPPER TROUGHS AND RIDGES IN TYPE N1 SPELLS

— Troughs      - - - Ridges

no tendency for depressions, except very weak ones, to pass from one to the other. But as in the case of the upper troughs and ridges there were no geographical regions (apart from Labrador) which preserved consistently cyclonic or anticyclonic régimes throughout all the spells. In one spell, June 10-19, the surface patterns were quite disorderly, consisting of numerous small and weak systems which showed little constancy from day to day. Of the remaining five spells, four were characterized by persistent cyclonic activity in the region Bering Strait-Gulf of Alaska-east Pacific, three in the region



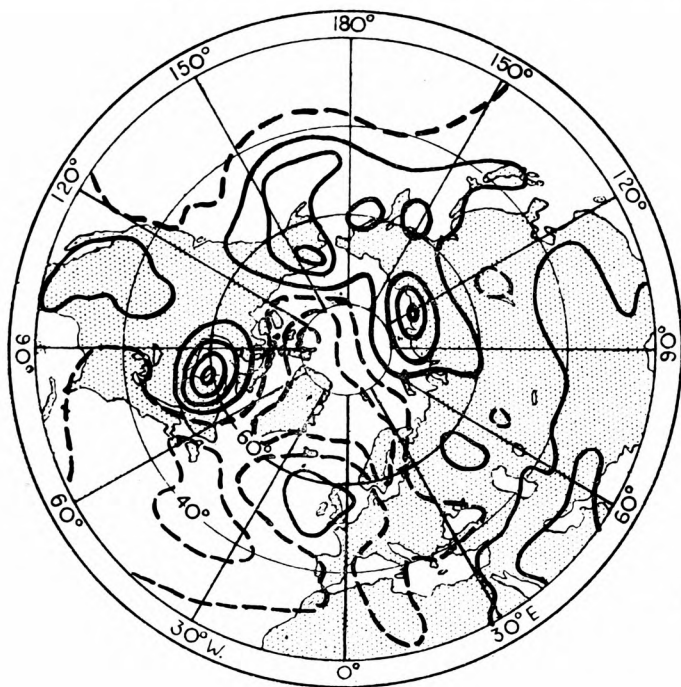
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FIG. 5—SURFACE CHARTS FOR TYPE N1 SPELL, AUGUST 17-28, 1950  
Isobars at 8-mb. intervals    ——— 1008 mb. and below    - - - - 1016 mb. and above



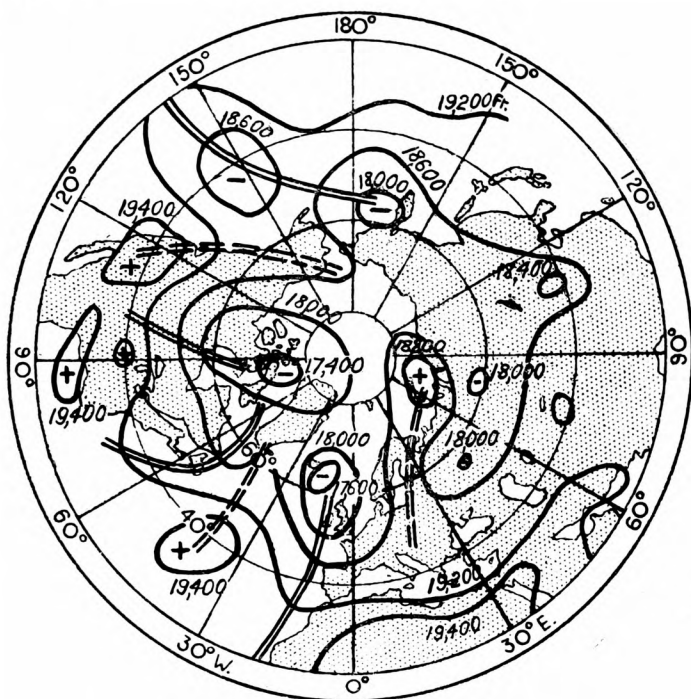


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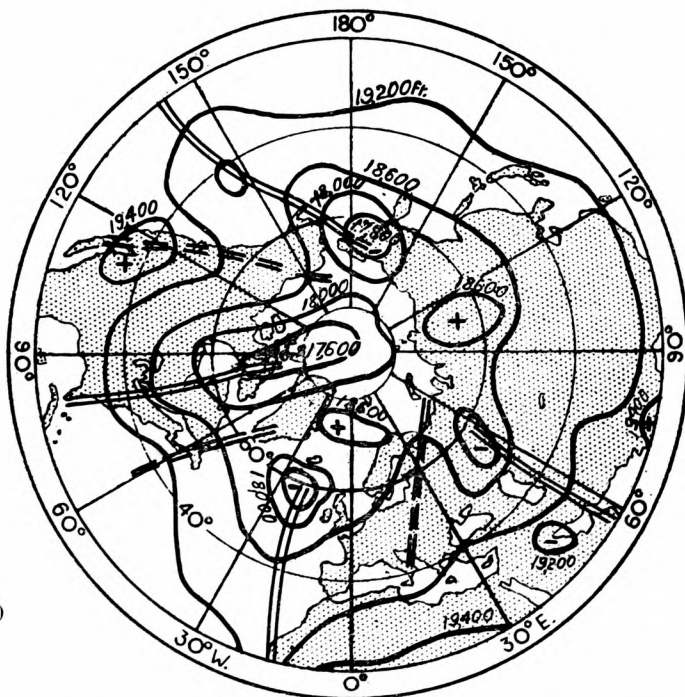


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FIG. 5—SURFACE CHARTS FOR TYPE N1 SPELL, AUGUST 17-28, 1950 (*continued*)  
 Isobars at 8-mb. intervals ——— 1008 mb. and below - - - - 1016 mb. and above



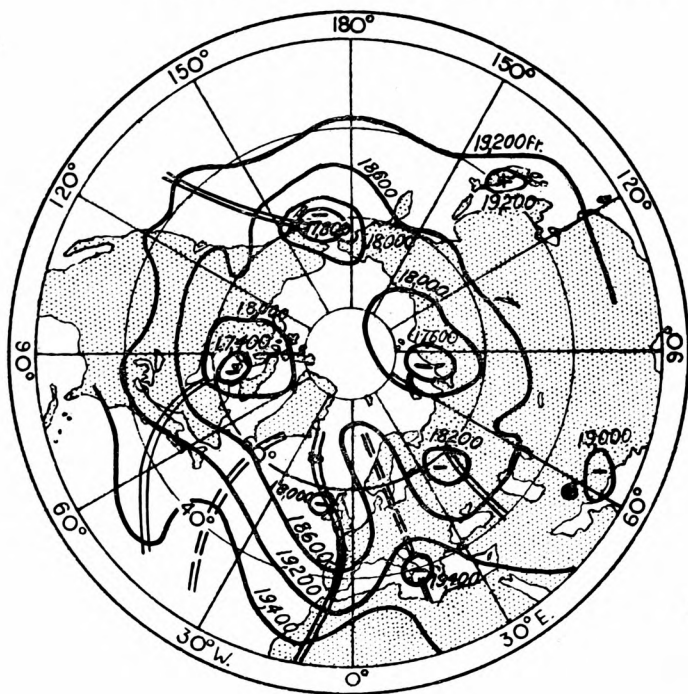
0300, August 17, 1950



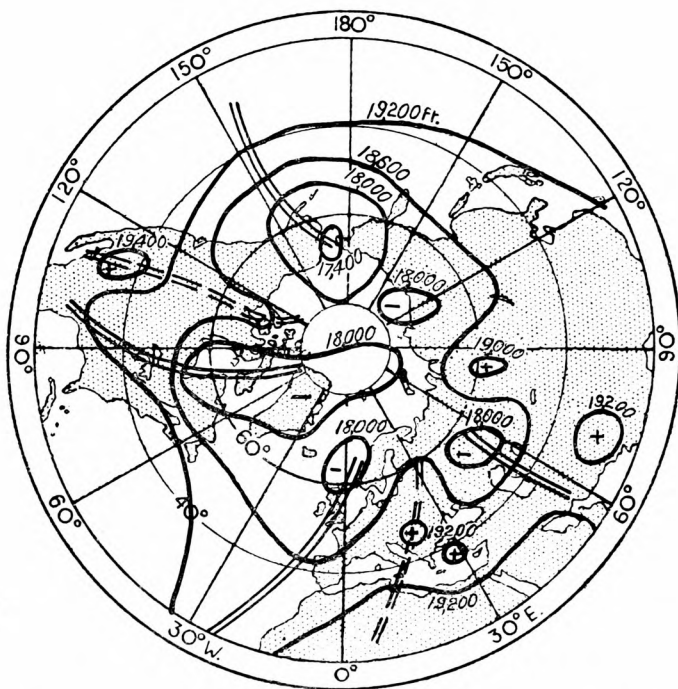
0300, August 20, 1950

FIG. 6—500-MB. CONTOUR CHARTS FOR TYPE N1 SPELL, AUGUST 17-28, 1950

===== Persistent trough lines      = = = = Persistent ridge lines



0300, August 24, 1950



0300, August 28, 1950

FIG. 6—500-MB. CONTOUR CHARTS FOR TYPE N1 SPELL, AUGUST 17-28, 1950 (continued)

===== Persistent trough lines      = = = = Persistent ridge lines

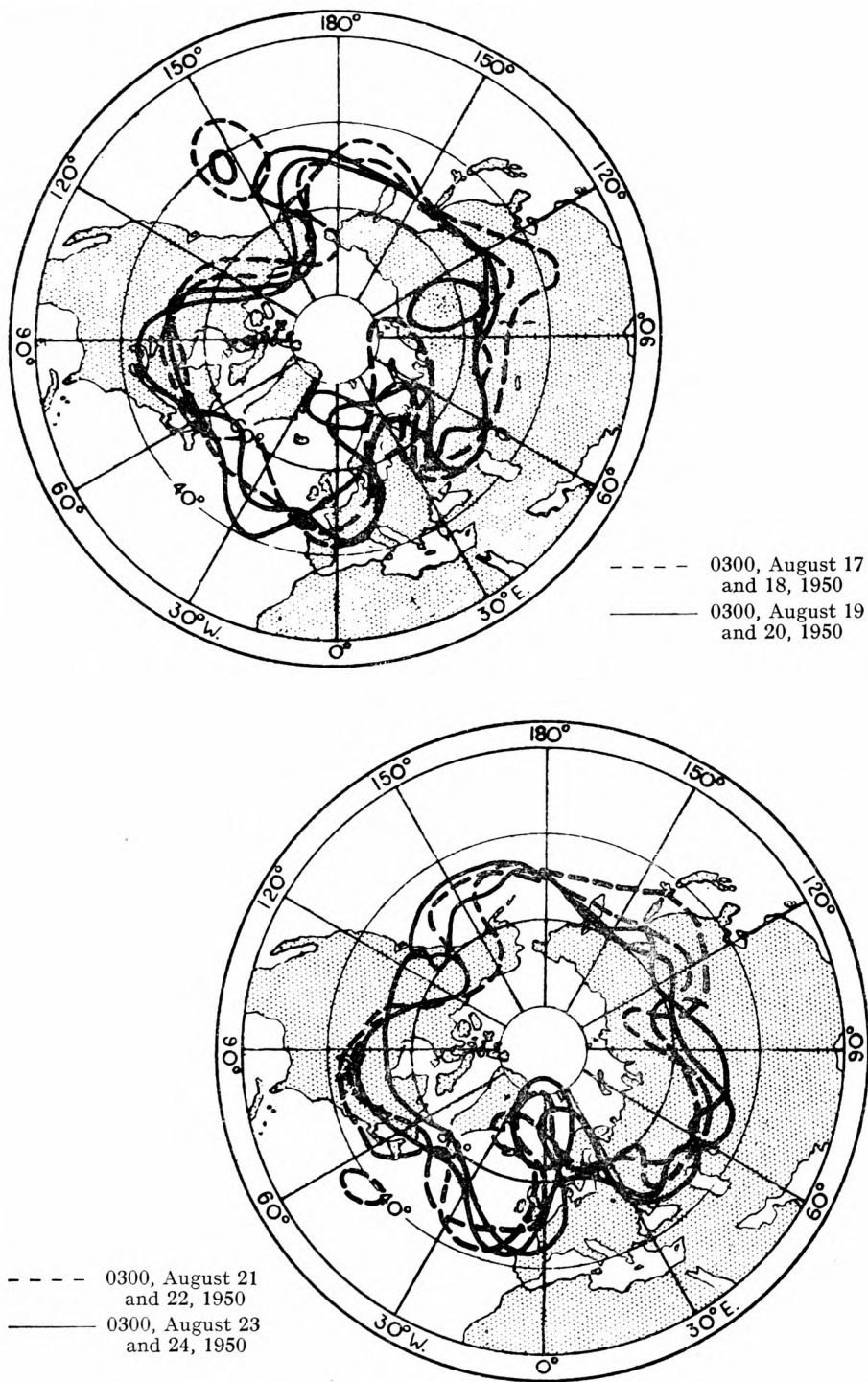


FIG. 7—COMPOSITE CHARTS OF 18,600-FT. LINE IN 500-MB. PATTERN FOR TYPE N1 SPELL, AUGUST 17-28, 1950

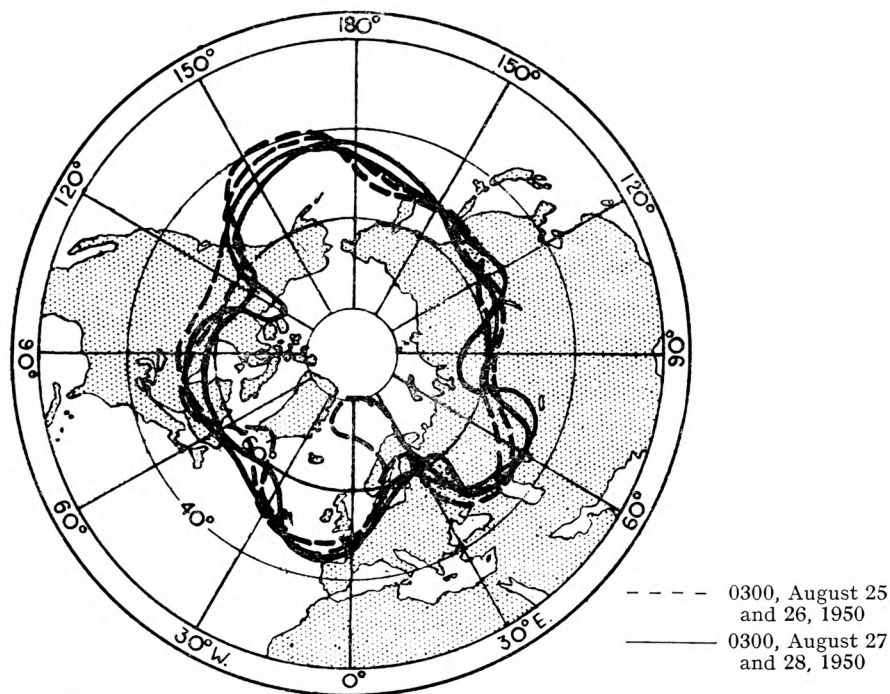


FIG. 7—COMPOSITE CHARTS OF 18,600-FT. LINE IN 500-MB. PATTERN FOR TYPE N1 SPELL, AUGUST 17-28, 1950 (*continued*)

British Isles–Faeroes–Scandinavia, and two in the region west Pacific–north-east Asia. Perhaps more characteristic of these five spells were the persistent meridional anticyclones extending from the subtropics to the polar basin, though these differed somewhat in orientation and location from spell to spell. The last three spells had persistent meridional anticyclones over Greenland and the mid Atlantic. In other spells and in other sectors, meridional highs, though not persisting throughout the whole period, were sufficiently prominent and lasting to set the general character of the surface circulation.

Near the British Isles the broad features of the surface patterns in the six spells were as follows :—

- |                   |  |
|-------------------|--|
| January 14–19 ..  | Straight isobars between high to north and low to south at first—later anticyclonic                            |
| May 6–16 .. ..    | Anticyclonic easterly or northerly throughout—high centre shifted from north of the British Isles to Greenland |
| June 10–19 ..     | Pattern complex with numerous small weak systems   |
| August 17–28 ..   | Cyclonic south-westerly  |
| November 20–      | } Cyclonic northerly.  |
| December 4        |  |
| December 11–14 .. |  |

By way of illustration a more detailed discussion of one of these spells is now given.

*Spell of August 17–28, 1950 (type N1).*—The surface charts for four days spaced as nearly as possible at equal intervals over the spell are reproduced

in Fig. 5. The regular time interval was the only consideration leading to this particular selection of charts; the intermediate charts do of course show some variation from these, but the broad features of the large-scale type are to be found on almost all the daily charts throughout the spell.

The surface charts show a persistent cyclonic region over Labrador, Hudson Bay and Baffin Land. Five separate depressions passed across the area L during the spell, four of them becoming slow moving in the way characteristic of type N1. The other depression originated as a tropical storm, moving into L from the south-west and passing away east into the Atlantic. This interruption, which lasted for two days only (August 22 and 23), was not regarded as important enough to break the spell.

There are examples of persistence also in some other parts of the hemisphere, apart from the low pressure over the southern half of Asia and the high pressure over the subtropical Atlantic and Pacific which are seasonal or semi-permanent features. Persistent cyclonic areas are (i) Bering Strait, Alaska and the Aleutians, (ii) the British Isles and north-east Atlantic, and (iii) the Urals. Anticyclonic situations persist over (i) Greenland and the western North Atlantic, (ii) north central and south-east Europe, and (iii) north-west Canada. There is probably sufficient persistence in these features to specify a large-scale circulation type, which, however, depends more upon the general lack of mobility than on the precise geographical location of synoptic systems. Furthermore, considerable changes are to be seen in some areas; for example the western half of North America is anticyclonic in the first part of the period and cyclonic in the second. On the whole the surface circulations have a meridional character, as is to be expected from the large amplitude features of the 500-mb. pattern, shown in Fig. 6. In these charts the axes of troughs and ridges have been marked for persistent features only. There are persistent troughs over (i) the east Pacific, (ii) eastern America and the western Atlantic, (iii) the eastern Atlantic and the western seaboard of Europe, and (iv) the Black Sea and Caspian area. Ridges persist over (i) western America and Alaska, (ii) the western central Atlantic, and (iii) central and northern Europe. The several centres of the circumpolar vortex are well shown on all four charts.

The day-to-day persistence of the 500-mb. troughs and ridges is illustrated by Fig. 7. These are composite charts each showing the configuration of a selected contour (18,600 ft.) on four successive days, the three charts together covering the whole spell. The persistent troughs and ridges of Fig. 6 will be easily recognized throughout the series, and it will be readily seen that the day-to-day changes are small. The major troughs are particularly constant over the last four days of the spell (Fig. 7, August 25–28); the fact that the greatest degree of steadiness in the upper-flow patterns is reached at this period suggests that the general pattern of the spell is set more by the circulation at the surface than by that at the upper levels.

**Type N2. Systems moving as in type N1, but subsidiary systems breaking away into the Atlantic.**—The subsidiary systems appear either as warm-front waves (Sawyer<sup>3</sup>) or develop at the point of occlusion of the main system. In the latter event they usually originate as small waves moving from the south-west on the main cold front. The most marked development seems to occur when the thermal trough from Davis Strait penetrates far south-east into the Atlantic; cyclonic development is then propagated south-eastwards in association with the tip of the thermal trough. The details of the development, however, appear to depend on the particular circumstances of each case. With cyclonic systems breaking out into the Atlantic from the west any meridional development of high pressure in the longitude of Greenland is likely to be short-lived. A



latitudinal belt of high pressure may, however, be a persistent feature, usually in the normal low-latitude position, but occasionally in middle and high latitudes with the cyclonic activity coming out on a track well to the south.

*Large-scale patterns associated with type N2.*—In so far as the depressions traversing the area L stagnate to westward of Greenland, this type might be expected to show the slow-moving features characteristic of type N1. On the other hand the breaking away of substantial systems to the east or south-east suggests some degree of mobility in the patterns. An examination of the 500-mb.

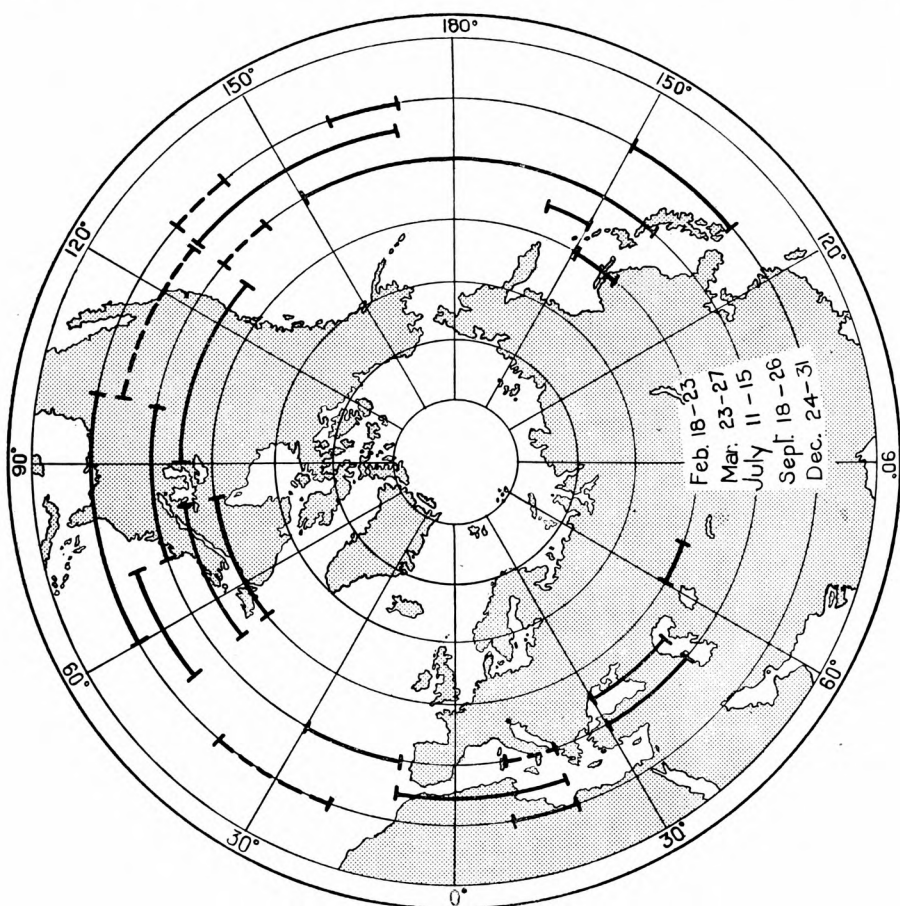


FIG. 8—SECTORS OCCUPIED BY PERSISTENT UPPER TROUGHS AND RIDGES IN TYPE N2 SPELLS

——— Troughs      ---- Ridges

contour charts confirms these expectations to a considerable degree. In all five spells there are present a number of slow-moving troughs of large amplitude. These troughs are on the whole less well defined than in type N1 while the intervening ridges are much less conspicuous. Between the troughs the patterns are often zonal in the middle and lower latitudes, clearly associated with the tendency for subsidiary depressions to break away eastward from the slow-moving primaries. In the higher latitudes the circumpolar vortex is usually broken up into a number of distinct centres, from which the lower-latitude



0000, September 20, 1950



0000, September 23, 1950

FIG. 9—SURFACE CHARTS FOR TYPE N2 SPELL, SEPTEMBER 18–26, 1950  
Isobars at 8-mb. intervals    ——— 1008 mb. and below    - - - - 1016 mb. and above



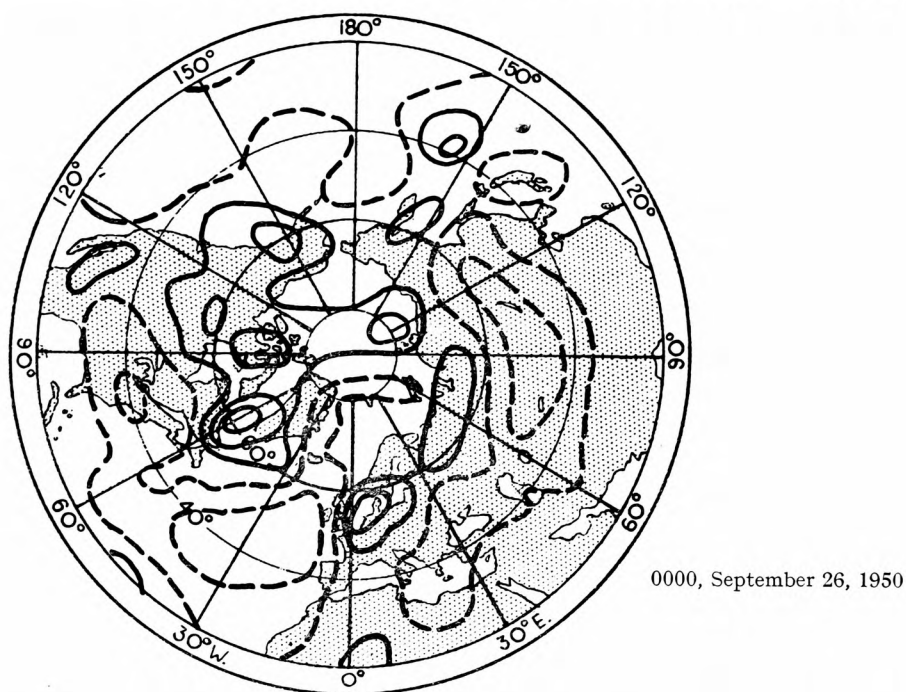
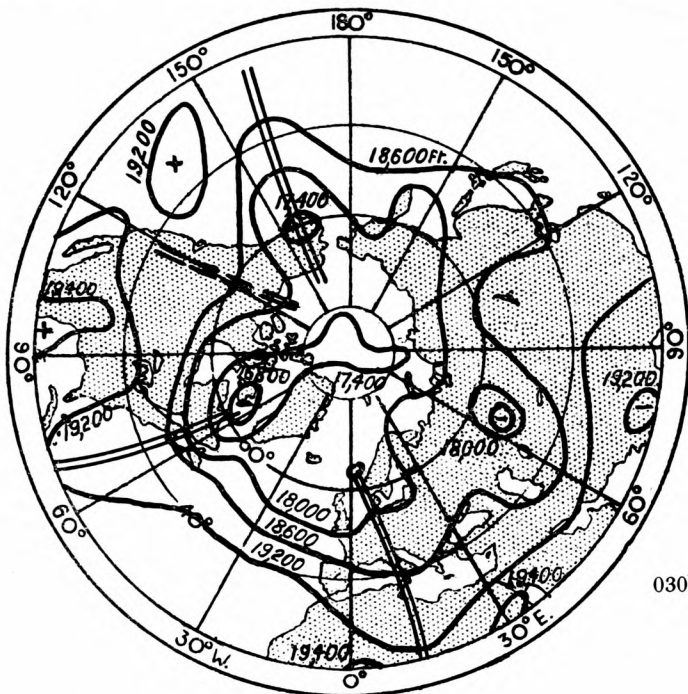


FIG. 9—SURFACE CHARTS FOR TYPE N2 SPELL, SEPTEMBER 18–26, 1950 (*continued*)  
 Isobars at 8-mb. intervals ——— 1008 mb. and below - - - 1016 mb. and above

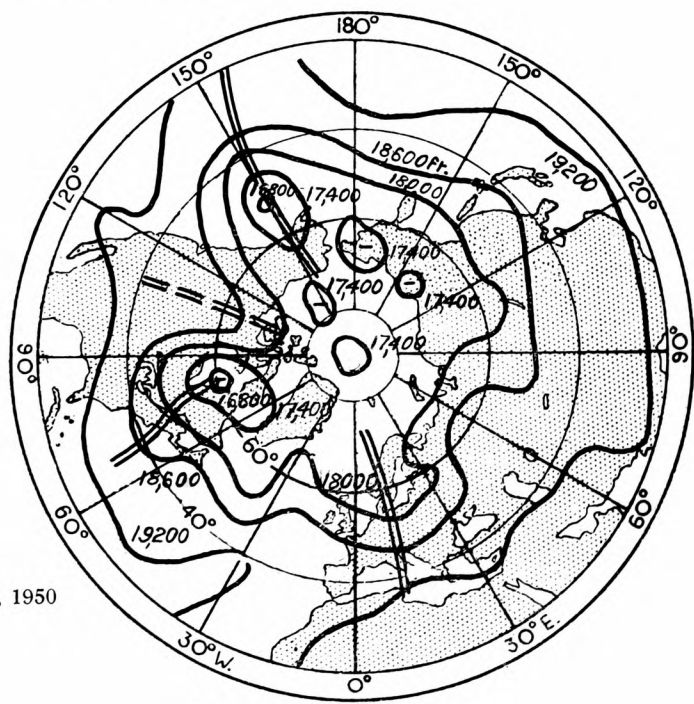
troughs extend more or less meridionally. Between these centres the flow patterns are weak and irregular with few well defined ridges.

The main troughs are often persistent though rather more mobile than in type N1. Fig. 8, corresponding to Fig. 4, shows the sectors occupied by persistent large-scale ridges and troughs in the five spells of type N2. Again differences between the spells can be seen, but as in Fig. 4 the troughs over the west Atlantic and the east and west Pacific are present on most occasions. The shift of the European trough from Russia in the earlier part of the year to western Europe in the latter part, noted in Fig. 4 is seen also in Fig. 8. An examination of the daily charts shows that as compared with type N1 the upper troughs in type N2 tend to be broader, with strong nearly straight currents on their southern peripheries. Small features run along these currents and often continue more or less eastwards in the low and middle latitude zonal flow between the troughs.

In regard to surface features, the only areas of the hemisphere in which conditions were persistently similar in all five spells were the subtropical oceans where the normal anticyclones were more than usually elongated in the west-to-east direction. The polar basin was on the whole anticyclonic, though not entirely so throughout any spell. In four of the five spells there was a persistent cyclonic situation in the Gulf of Alaska. Otherwise the surface situation showed gradual changes owing to both movement and development in each of the spells.



0300, September 20, 1950



0300, September 23, 1950

FIG. 10—500-MB. CONTOUR CHARTS FOR TYPE N2 SPELL, SEPTEMBER 18–26, 1950

===== Persistent trough lines      = = = = Persistent ridge lines

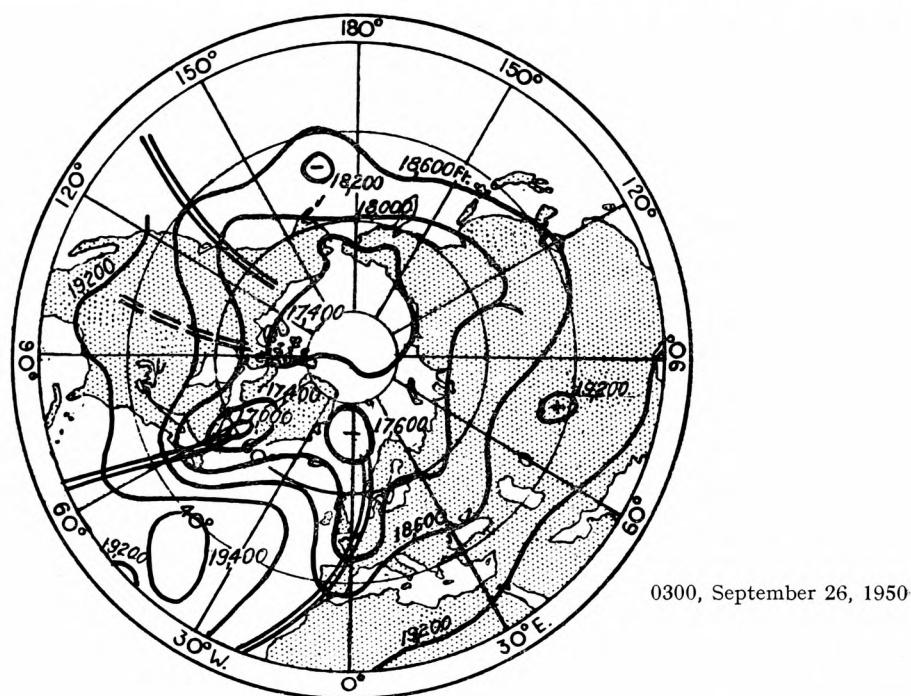


FIG. 10—500-MB. CONTOUR CHARTS FOR TYPE N2 SPELL, SEPTEMBER 18-26, 1950  
(continued)

===== Persistent trough lines      = = = = Persistent ridge lines

*Spell of September 18-26, 1950 (type N2).*—This spell is illustrated by the surface and 500-mb. charts for three equally spaced days (Figs. 9 and 10) and by composite charts of the 18,600-ft. contour (Fig. 11). During this period two major depressions entered area L from the region of Hudson Bay, and swung northward or north-westward; both had prominent subsidiary systems which broke away into the Atlantic. The chart for September 23 (Fig. 9) shows the first primary near Hudson Bay with its break-away system south of Greenland. On the chart for September 26, Fig. 9, the second primary is in Davis Strait and the incipient break-away appears as a trough to the south-east of Greenland. Apart from area L and its neighbourhood, other persistently cyclonic areas during this spell were (i) north-west Canada and Alaska and (ii) Scandinavia and northern Eurasia; the cyclonic activity in (ii) extended at times over the British Isles. The subtropical high-pressure belt persisted right round the hemisphere apart from a few small gaps. The contour patterns of Fig. 10 show persistent troughs over the east Pacific, the west Atlantic and Europe and the ridge over America. These features are less well defined than in type N1. The nearly straight flow in middle latitudes is well shown for the Atlantic on September 20 and the Pacific on September 23 (Fig. 10). The persistence or otherwise of these features of the flow pattern appears from the composite charts; the large-scale troughs are persistent on the whole but there are numerous small mobile features. In this example also the flow pattern does not reach its most steady state until the latter part of the spell.

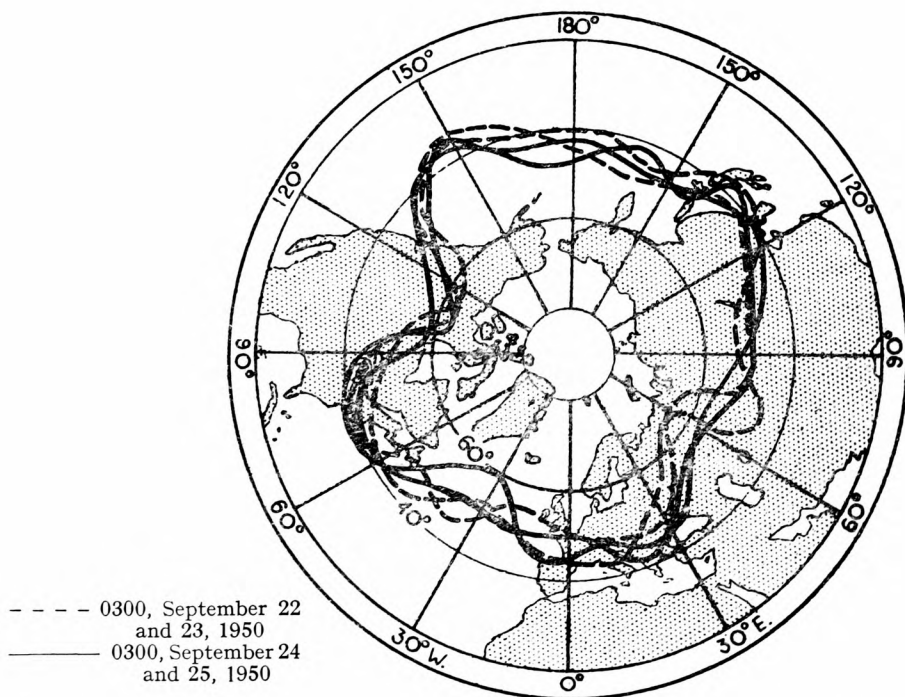
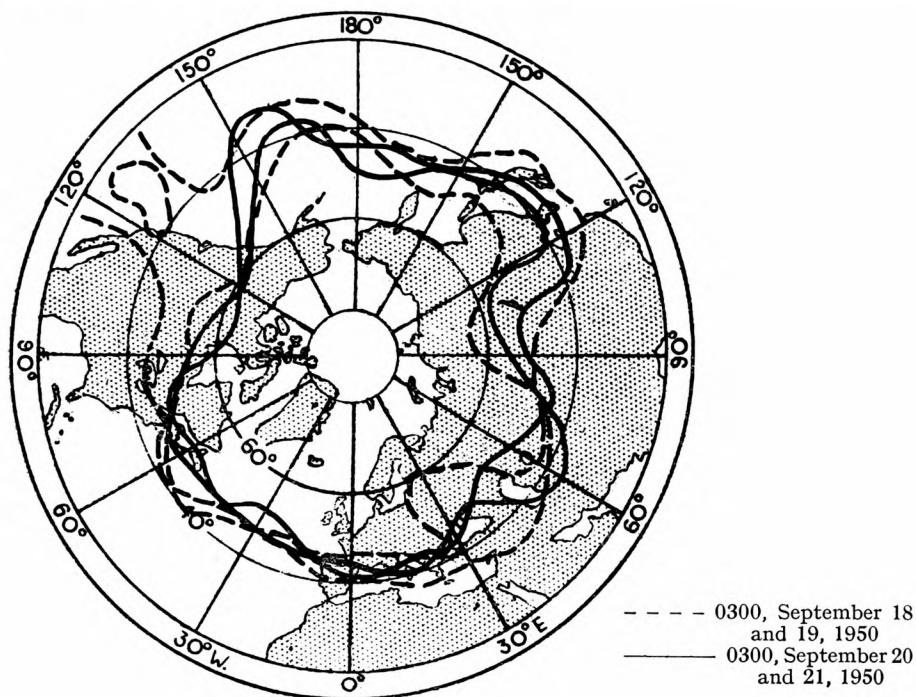


FIG. 11—COMPOSITE CHARTS OF 18,600-FT. LINE IN 500-MB. PATTERN FOR TYPE N2 SPELL, SEPTEMBER 18-26, 1950

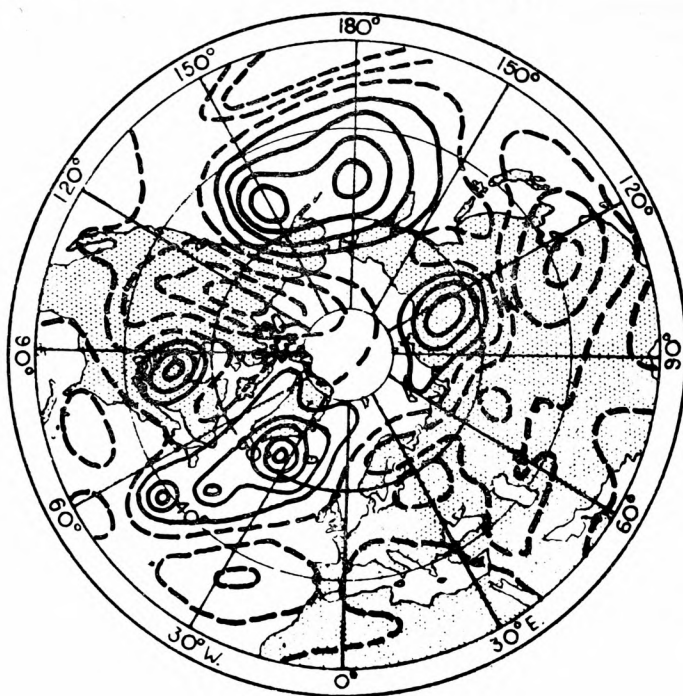
**Type C. Depressions moving north-east towards Iceland.**—In view of the widely recognized association of depressions with the Iceland-south-east Greenland area the small number of spells with depressions moving from area L into this area seems a little surprising; this has been remarked upon on p. 8. Also, some of the depressions which enter this area are interspersed with systems moving directly eastwards and are included in the combined type CE of Table II.

On the whole the movement of depressions of type C conforms to the direction of thermal steering. Generally there is a large-scale thermal trough over the Hudson Bay region; the trough is widely open to northwards and has a strong thermal gradient on its south-eastern flank. A common feature of the four spells recorded is the "cold pool" near north-west Greenland, i.e. farther east than in types N1 and N2, which is in conformity with north-eastward rather than northward steering. This location of the cold pole in association with depressions in the Iceland area appears to agree with a recent (unpublished) finding of Brezowsky that there is a relation between the position of the cold pole over Canada and the character of the European winter; if the cold pole is west of Hudson Bay winters in Europe tend to be cold and anticyclonic, but if to the east of Hudson Bay European winters are milder and more cyclonic.

*Large-scale patterns associated with type C.*—The 500-mb. flow patterns associated with this type are more complex and show a greater tendency to change from day to day than with types N1 and N2 already discussed. They are characterized by numerous troughs and ridges in the middle and lower latitudes. In the higher latitudes the patterns are somewhat simpler and usually show a large and compact polar vortex (i.e. one without narrow straggling troughs or numerous small centres) having a kind of two-fold symmetry with lobes in the diametrically opposite sectors west Atlantic and west Pacific. The troughs and ridges of the inner and outer parts of the pattern are often in antiphase, giving rise to well marked confluences and diffluences, and to localized bands of strong flow (jet streams). In the three spells studied there were two persistent troughs, one over east America and the west Atlantic and the other over Europe. Otherwise the upper troughs and ridges were temporary and mobile features though often moving rather slowly.

This is essentially a mobile type, and there are few persistent stationary features in the surface patterns. The depressions moving into the Iceland region from the south-west often deepen there, and contribute to the formation of a large cyclonic complex which extends at times over much of north-west and north Europe, Iceland and Spitsbergen. Intermittent weak cyclonic activity over south-east Europe and the Mediterranean is associated with the persistent upper trough over Europe mentioned above; there is often some steering of cyclonic activity from high latitudes south-eastward on the western flank of this trough. The Aleutian low is a common but not a persistent feature. The Siberian high is usually extensive, with its main centre rather towards the east of the land mass. The polar basin is often in a col between cyclonic regions over the north Pacific and extreme north-east Atlantic and anticyclones over Canada and east Siberia; the col may be cyclonic or anticyclonic, its character varying within a given spell.

*Spell of February 24–March 5, 1950 (type C).*—Charts for this spell are shown in Figs. 12, 13 and 14. These illustrate a type in which individual systems are mobile, and therefore three days at short intervals have been selected on which the movement of one and the same depression can be followed. This is the depression near the Great Lakes on March 1 (Fig. 12), over Labrador on the 3rd and off north-west Norway on the 5th; it is the same as No. 32 in Fig. 3. The variable nature of the large-scale surface patterns is illustrated by the changes over Canada, the central part of northern Asia and the polar basin.



0000, March 1, 1950



0000, March 3, 1950

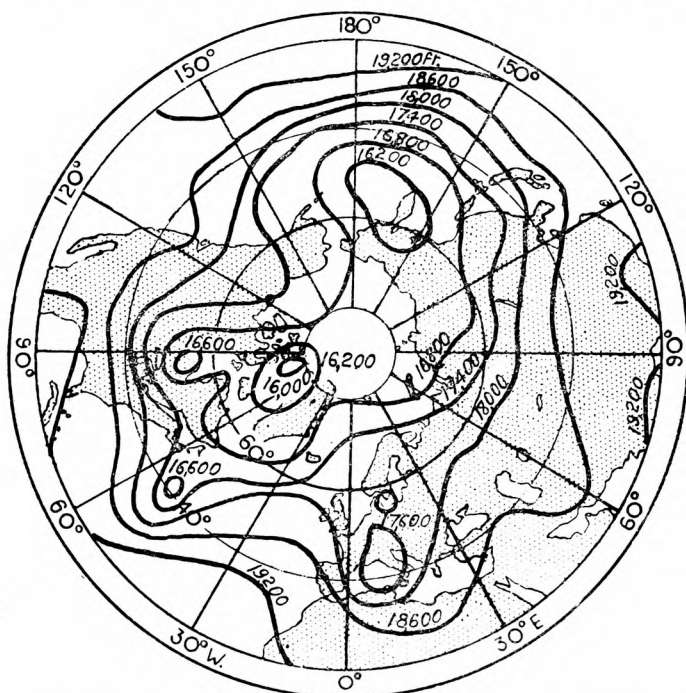
FIG. 12.—SURFACE CHARTS FOR TYPE C SPELL, FEBRUARY 24–MARCH 5, 1950  
 Isobars at 8-mb. intervals ——— 1008 mb. and below - - - - 1016 mb. and above





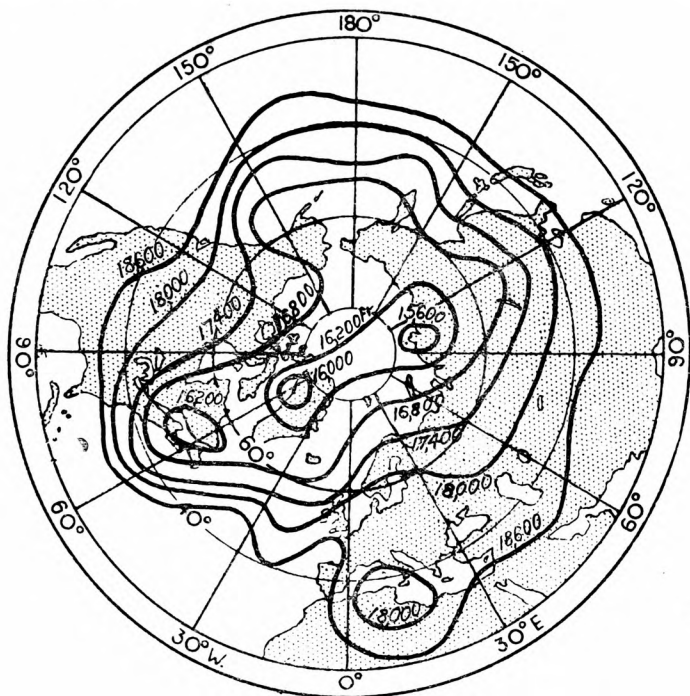
0000, March 5, 1950

FIG. 12—SURFACE CHARTS FOR TYPE C SPELL, FEBRUARY 24–MARCH 5, 1950  
(continued)  
Isobars at 8-mb. intervals ——— 1008 mb. and below - - - - 1016 mb. and above

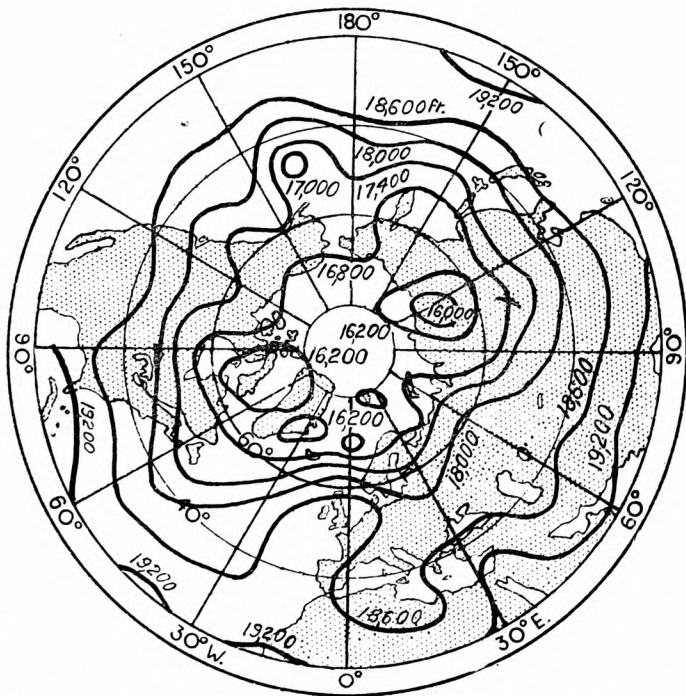


0300, March 1, 1950

FIG. 13—500-MB. CONTOUR CHARTS FOR TYPE C SPELL, FEBRUARY 24–MARCH 5, 1950



0300, March 3, 1950



0300, March 5, 1950

FIG. 13—500-MB. CONTOUR CHARTS FOR TYPE C SPELL, FEBRUARY 24—MARCH 5, 1950  
(continued)



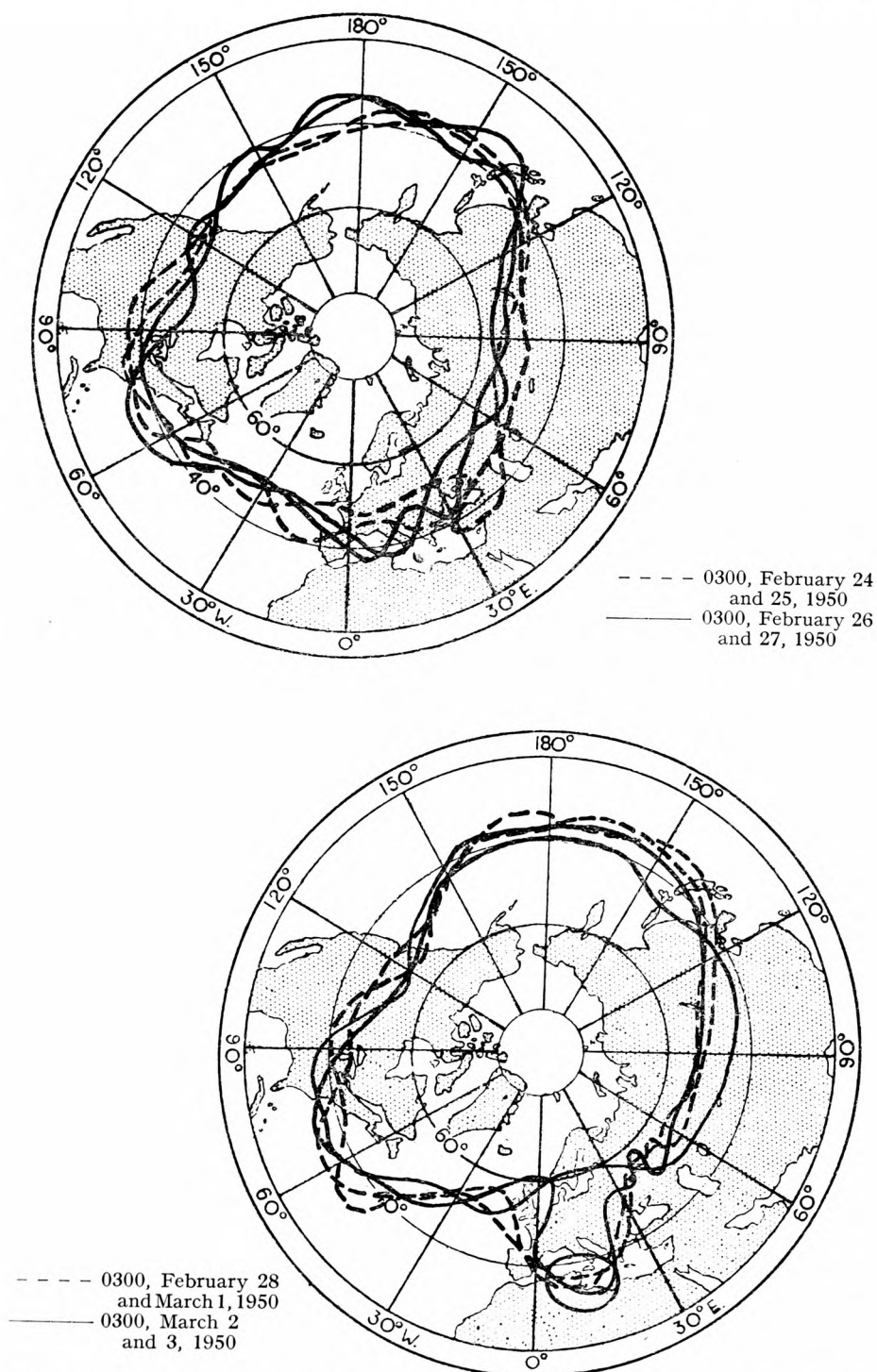


FIG. 14—COMPOSITE CHARTS OF 18,000-FT. LINE IN 500-MB. PATTERN FOR TYPE C SPELL, FEBRUARY 24–MARCH 5, 1950

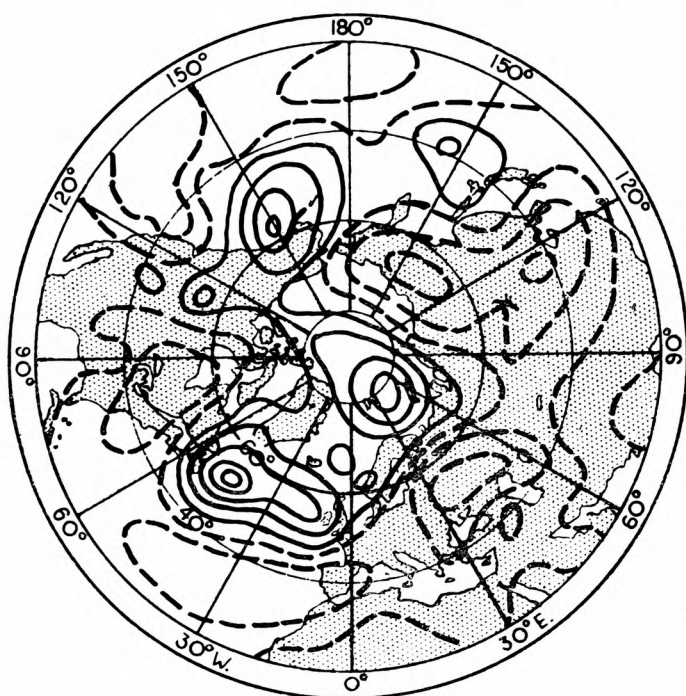


0000, March 12, 1950



0000, March 16, 1950

FIG. 15—SURFACE CHARTS FOR TYPE E SPELL, MARCH 12-20, 1950  
 Isobars at 8-mb. intervals ——— 1008 mb. and below - - - - 1016 mb. and above



0000, March 20, 1950

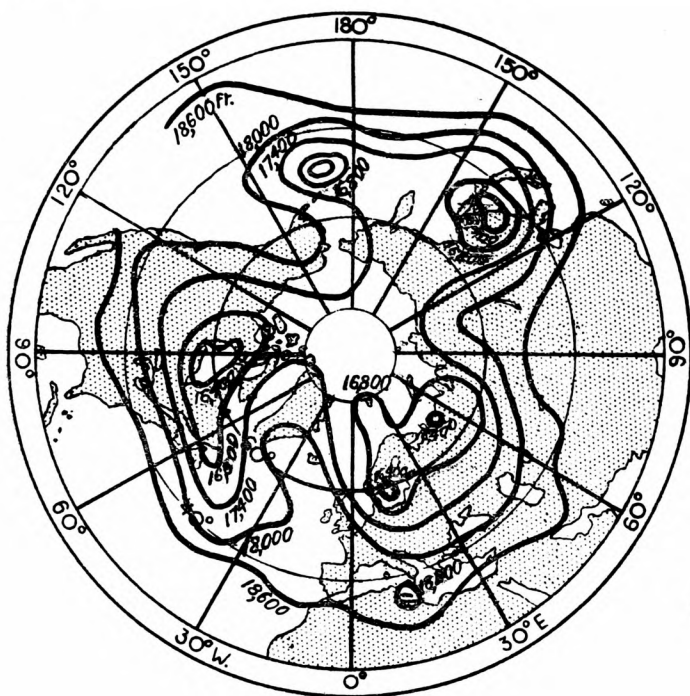
FIG. 15—SURFACE CHARTS FOR TYPE E SPELL, MARCH 12–20, 1950 (*continued*)  
Isobars at 8-mb. intervals ——— 1008 mb. and below - - - - 1016 mb. and above

The 500-mb. patterns are zonal in character, with the main flow well out from the pole in most sectors. There are several examples of high and low latitude ridges and troughs in antiphase. The composite charts for the first eight days of the spell (Fig. 14) show that the large-scale characteristics are preserved; on the whole the flow patterns are smooth, with small mobile ridges and troughs. The more permanent troughs on the west Atlantic and over Europe are common to all three spells of this type (Table II).

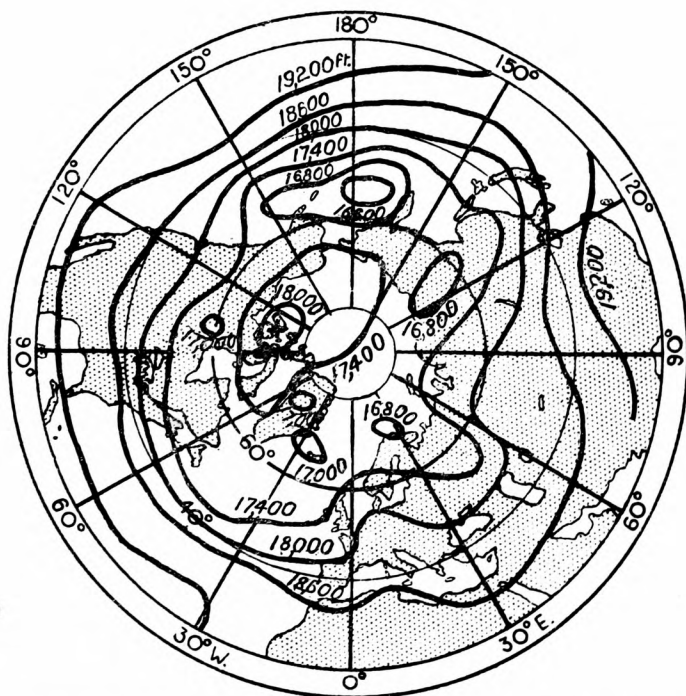
**Type E. Depressions moving in a generally easterly direction to mid Atlantic.**—In all four spells the general eastward movement is associated with a zone of thermal concentration running roughly eastwards through L and well out into the Atlantic; it is generally well marked in winter, but weaker and variable in summer. In the two winter spells the thermal concentration lay on the southern flank of a large cyclonic thermal eddy which had its root near Hudson Bay and protruded far into the Atlantic. Considerable cyclonic activity was associated with the exit to the thermal “jet” thus formed.

In two spells, March 13–20, and June 20–26, 1950 there was a persistent thermal ridge with an associated anticyclone over Greenland. This thermal pattern resembles that which occurs with type N1, but is more twisted. In type N1 the ridges are blocking features of large meridional extent; in type E they are high-latitude features undercut by the cyclonic features moving east in middle and lower latitudes. In the spell from February 4–17 there was also high pressure over Greenland for the most part, but it was associated with an overlying thermal trough.

*Large-scale patterns associated with type E.*—At the 500-mb. level the inner part of the circumpolar vortex is complex, with many small centres and weak

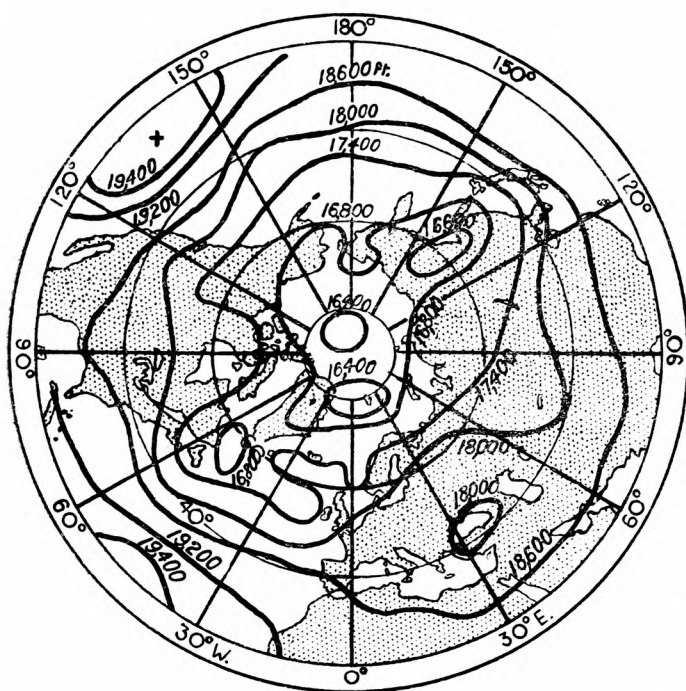


0300, March 12, 1950



0300, March 16, 1950

FIG. 16—500-MB. CONTOUR CHARTS FOR TYPE E SPELL, MARCH 12-20, 1950



0300, March 20, 1950

FIG. 16—500-MB. CONTOUR CHARTS FOR TYPE E SPELL, MARCH 12–20, 1950 (*continued*)

gradients. The main westerly flow is well out from the pole but is often much more distorted than with type C. The main upper troughs are broad features, flanked to the south by nearly straight belts of strong upper flow; depressions move quickly eastward in these belts and, swinging to the left, deepen and become slow moving in the weak upper flow to the north. Between the broad troughs there are rather narrow and often distorted ridges. The troughs are often persistent, but the ridges are transitory and subject to rapid changes of amplitude.

The large-scale surface patterns show marked seasonal differences. By definition, the type is associated with much cyclonic activity in the North Atlantic. In winter this fits naturally into the climatological mean picture, together with a similar large and active cyclonic area over the North Pacific and the continental anticyclones of Siberia and North America. This suggests that this type of winter circulation is a stationary mode, with the thermal effects of the undersurface and the dynamically balanced strong zonal flow, with long wave-spacing, mutually in phase. In summer the type requirement (by definition) of oceanic low pressure (at least over the North Atlantic) having presumably a dynamical cause, would appear to conflict with the thermally induced monsoonal low pressure of the continents. The resulting surface patterns are rather ill defined with many small and weak centres; only the subtropical anticyclones appear as well formed and lasting features.

*Spell of March 12–20, 1950 (type E).*—Surface and 500-mb. charts for this spell are given in Figs. 15 and 16 at 4-day intervals. The basis of classification for this period is the large cyclonic area over the Atlantic, which the daily charts show to have developed mainly from depressions moving eastward from area L.

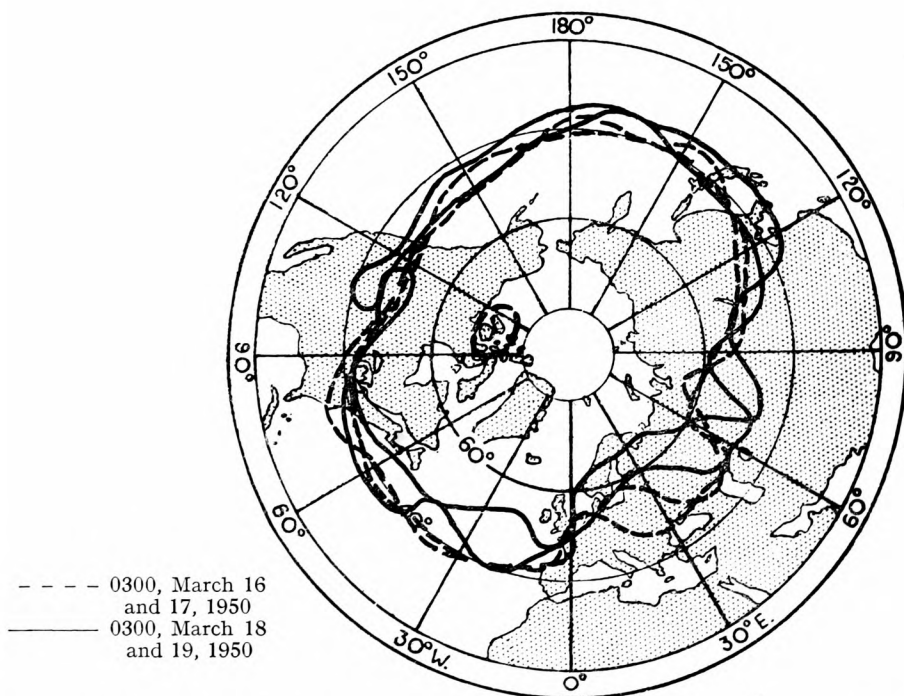
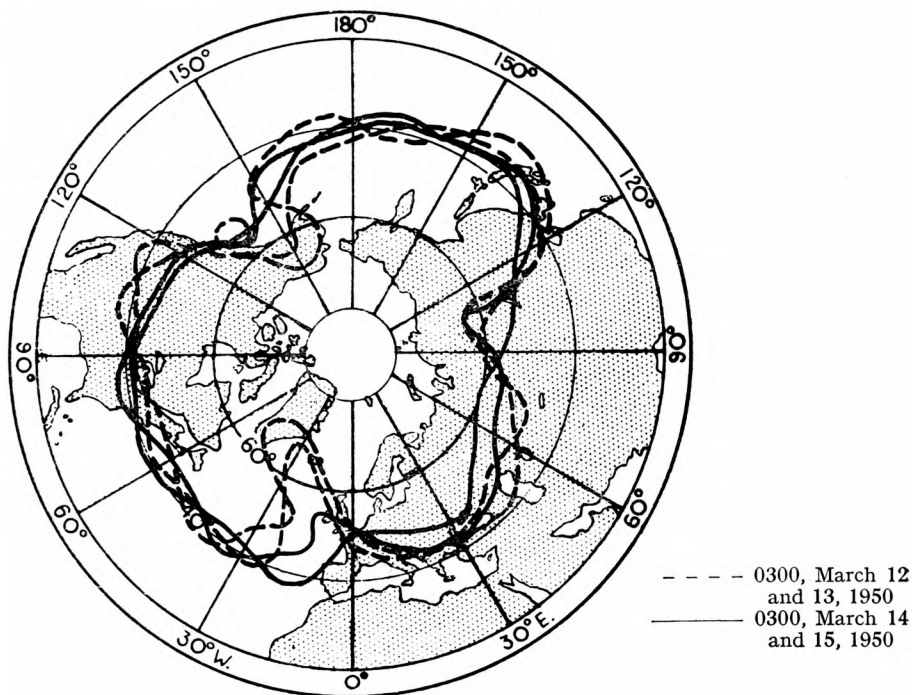


FIG. 17- -COMPOSITE CHARTS FOR 18,000-FT. LINE IN 500-MB. PATTERN FOR TYPE E SPELL, MARCH 12-20, 1950



The centre of this cyclonic complex is almost ten degrees south of the normal seasonal position for the Icelandic depression. There is a similar cyclonic complex in the Pacific. It is interesting to notice that the two systems have somewhat similar histories—an eastward movement and intensification followed by a splitting into two large components, the axis of the composite system lying south-west-north-east. A similarity appears also in the 500-mb. patterns which, to begin with, have marked cyclonic distortions in the Atlantic and Pacific. The subsequent degeneration of these features is seen in the charts for March 16 and March 20 in Fig. 16. The composite chart of Fig. 17 for March 12–15 shows that the Pacific and Atlantic ridges disappear simultaneously and in a similar way. Subsequently the flow pattern settles down to a steady smooth type in most sectors, apart from some mobile medium-amplitude features over Europe and Asia.

**Other types.**—The remaining types CE, F and H were also studied, but are only briefly discussed in this paper for the reasons given below.

*Type CE. Spells combining the characteristics of types C and E.*—This, a combination of two fairly common types, occurs the most frequently of all the types considered. Individual lows from area L move into the Atlantic but fall into no particular grouping; movements towards north-east, east and south-east appear to occur more or less at random. Some systems combine the characteristics of types C and E by moving more or less directly eastward to mid Atlantic and then turning sharply northwards towards Iceland. The large-scale patterns have some characteristics of both the preceding types, discussed on p. 25 and p. 31, so that they will not be dealt with in further detail here. The thermal trough over east America is usually broad in shape and extends out over the west Atlantic. There is also a broad trough at the 500-mb. level, which tends to be somewhat to the eastward of the thermal trough; this is associated with a semi-permanent surface depression near or somewhat to the eastward of Iceland. Systems moving out from North America feed into or renew this semi-permanent feature from time to time. The steering of these systems appears to conform more nearly to the contour than to the thickness pattern.

*Type F. Depressions filling in or near area L, soon after leaving it.*—Table II shows that spells of this type in 1950 occurred in the summer half year only. There are no common and easily recognizable characteristics of the thickness and contour patterns associated with type F. On the whole the thermal gradients are weak and irregular. The vicinity of area L, where depressions are filling, is an inactive region, and would hardly be expected to have appreciable influence on the circulation patterns of a wider area.

*Type A. No depressions in area L, which is often anticyclonic.*—These include all spells in which no actual low-pressure centres were situated in area L. In most cases the area lay in the region of straight isobars between high- and low-pressure regions. On a few occasions, however, the area was actually covered by an anticyclone. Four out of the five spells recorded lasted only six days or less; the remaining spell, from May 20 to June 2, lasted 14 days. An examination of the daily charts during this spell shows that conditions were by no means persistently anticyclonic in area L which was at times invaded by weak frontal troughs. The upper patterns showed a tendency for the presence of a ridge in the Hudson Bay region (where the mean thickness charts show a trough). This ridge however was a recurrent, rather than a persistent, feature, and it was interspersed with irregular upper patterns.

**Changes of type.**—Considered in relation to the problem of medium-range forecasting, the onset and break-down of these spells, being associated with

type changes, are equally as important as their persistence. The flow pattern in its broader aspects is naturally examined for any possible advance indication that the flow is about to settle down into a quasi-stationary state such as accompanies certain of these spells. Bearing in mind that from the large-scale point of view the most easily recognizable distinction lies between the stagnating type N1 and the remaining mobile types, a special study was made of the onset and break-down of this one type. The hemispherical upper-flow patterns were examined over at least the four-day periods preceding and following each spell as listed in Table II. The result of this study was not sufficiently encouraging to extend it to other types, and instead of the definite forecasting criteria which, it was hoped, would emerge only a few rather uncertain suggestions can be made.

*Onset of spells (type N1).*—It was stated on p. 10 that depressions of type N1 are associated with a thermal trough near Hudson Bay, but that before the beginning of the spell the thermal trough is in evidence only in the higher latitudes. It has also been seen that there is usually a large-amplitude trough at 500 mb. in the same longitude after the N1 character of the depression is established. It is obviously important to investigate the question as to whether the upper trough existed beforehand in which case the movement of the depression is brought about by simple steering in the upper current, or whether the depression itself is a necessary factor in establishing the upper trough, largely by thermal advection.

The surface and 500-mb. charts were examined over a period of four days covering the onset of each N1 spell. In each case there was an upper vortex in high latitudes over or to the westward of Baffin Land before the spell began. But in five out of the six spells the southward extension of the trough to form the usual large-amplitude feature was not effected until the depression had, so to speak, moved into position east of the growing trough. In the remaining case the upper pattern was in existence before the spell began; in this instance (December 11–14), however, the spell followed within six days of the end of a similar spell and the previously existing upper pattern was scarcely disturbed. The interval between the two spells was marked by an intense anticyclone in the vicinity of L, which maintained the large-amplitude upper patterns except for a slight shift of phase.

These changes accompanying the onset of a spell are illustrated in Fig. 18, which shows the 500-mb. patterns for the four days November 19–22, 1950 and the first and second members of the depression sequence. It is clear that the large-amplitude trough is not established until November 21 or even November 22, and that the circulation of the depression is a principal agency in its development.

It is sometimes argued that the formation of such a large-amplitude upper trough and depression complex is a purely dynamical effect, that is, a downstream wave in the upper-flow pattern resulting from barotropic flow in association with a large-amplitude up-stream feature. On this basis, the upper trough would be causal and the surface depression consequential. The characteristic large-amplitude quasi-stationary upper-flow patterns which have been found to be associated with the N1 type lend some support to this argument. On the other hand the upper trough over eastern America does not reach its characteristic full development until after the depression has moved into a suitable position. This would suggest that, though dynamical considerations would require a large-scale upper trough in a particular sector, it will not form unless there is a depression already in existence which can phase-in with the developing upper trough; that is the surface and upper patterns must be regarded as playing equally important roles in this development.



Having regard to the large-scale patterns it seems reasonable to look for signs of the development of the characteristic large-amplitude slow-moving ridges and troughs in other sectors of the hemisphere as well as in that with which this paper is primarily concerned, namely eastern America and the Atlantic. In particular the developments in the sector up stream of this one should be studied, with a view to judging whether the idea of down-stream propagation of large-scale features of the upper flow can be useful. The six N1 spells were considered in some detail from this point of view.

*Summary of conditions preceding the onset of spells (type N1).*—It was concluded that the conditions antecedent to the spells discussed have little in common that could be used as an aid to extended forecasting. There is no consistent evidence of either down-stream or up-stream propagation of the large-amplitude characteristics of the upper patterns. In this connexion the spells might be classified as follows :

Down-stream propagation, 2 periods, January 14–19, June 10–19  
Up-stream propagation, 1 period, November 20–December 5.

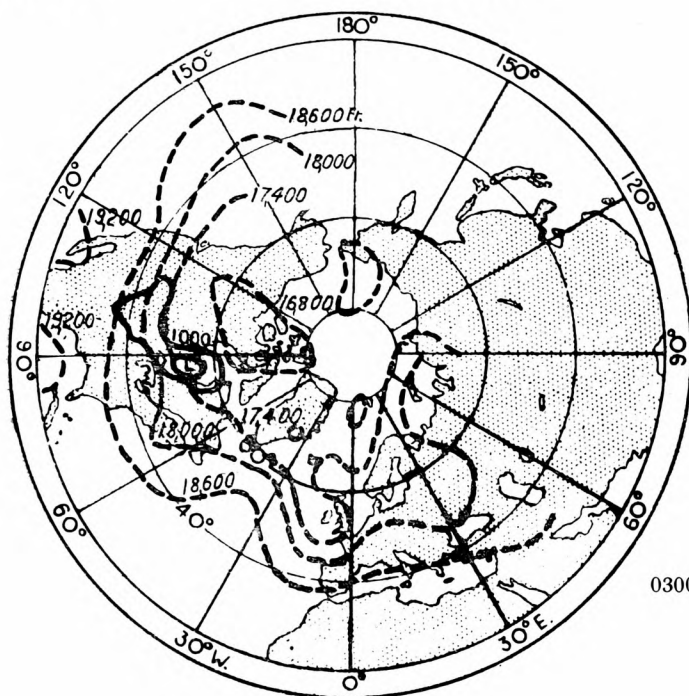
The remaining three cases were indefinite. In three of the spells there was development of important surface features which would not have been anticipated on thermal development ideas. These were blocking anticyclones in the Atlantic in two spells (January and August) and a deep depression over America (May). An “unexplained” upper oscillation occurred in the Pacific in the January spell. These suggest that the type changes are brought about by the setting in of instability in the upper or surface patterns, possibly both together. In any case no precursory signs of the change were detected. In two of the spells (May and August) there was westward movement of an important system from west Europe to the Atlantic (retrogression with blocking).

*Break-down of spells (type N1).*—Of the six spells, three were followed by type A (anticyclonic in area L) and three by type CE or E (depressions moving north-east or east from area L into the Atlantic).

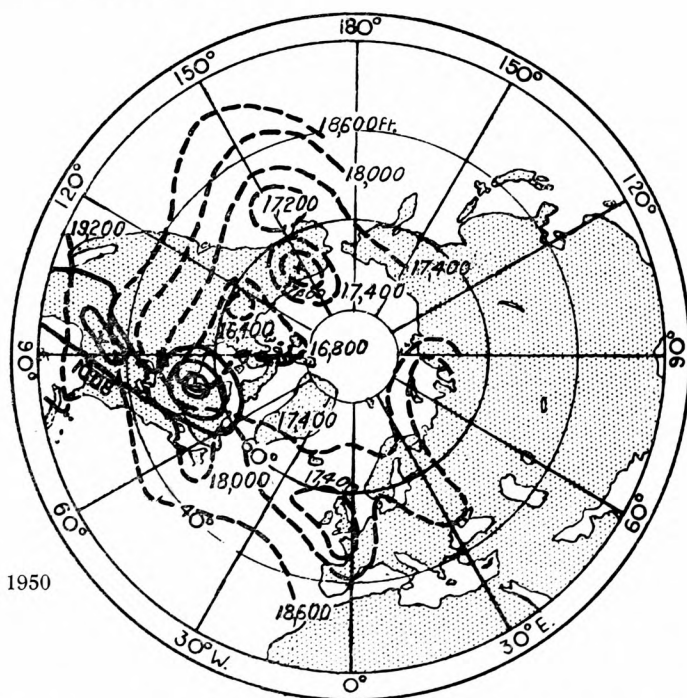
Of the spells followed by type A, two occurred in winter (January and November–December). The anticyclone in each case was very large and intense, its existence doubtless being helped by the cold land mass to westward of area L. Dynamically the upper patterns were not inconsistent with anticyclogenesis, though at the same time not appearing to demand it. The advection thrust cold air well southwards on the western Atlantic, and in effect displaced the upper trough eastwards from the Hudson Bay region, though this effect was to some extent masked by the seasonal trough over the continent. In both these cases the large-amplitude troughs and ridges were preserved beyond the end of the spell, but became mobile. The remaining spell followed by type A occurred in May; the anticyclone in area L was one of many small features in a very complex and distorted general pattern, and its occurrence in that particular locality seems (on the broad scale) to have been largely fortuitous.

The break-down of each of the remaining three spells was preceded by a degeneration of the large-scale ridge and troughs into cut-off pools and their replacement by smaller mobile features in a narrow “zonal” band threading its way between the pools. The accompanying surface changes were complex, but usually involved some increase of mobility.

To summarize, it may be said that the break-down of the stationary type was associated with a change to a more zonal type of flow, brought about either by cold air being thrust well southwards on the Atlantic or by a degeneration of the large-amplitude troughs and ridges.



0300, November 19, 1950



0300, November 20, 1950

**FIG. 18—EVOLUTION OF CHARACTERISTIC 500-MB. CONTOUR PATTERN DURING ONSET OF TYPE N1 SPELL, NOVEMBER 20–DECEMBER 5, 1950**

- - - 500-mb. contours at 0300      ——— Surface isobars at 8-mb. intervals at 0000  
(near area L)

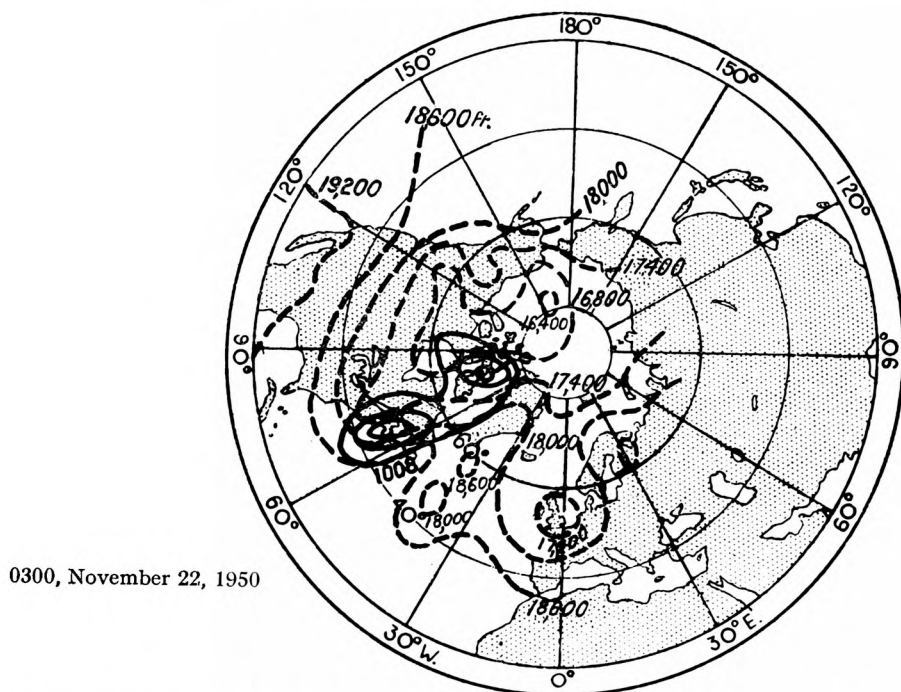
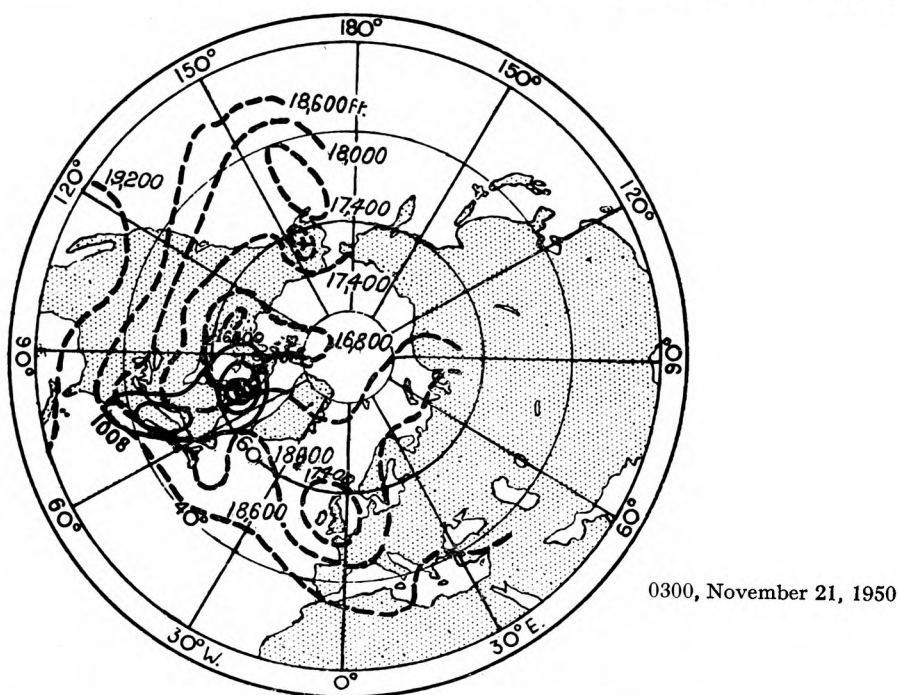


FIG. 18—EVOLUTION OF CHARACTERISTIC 500-MB. CONTOUR PATTERN DURING ONSET OF TYPE N1 SPELL, NOVEMBER 20–DECEMBER 5, 1950 (continued)  
 - - - - 500-mb. contours at 0300      ———— Surface isobars at 8-mb. intervals at 0000 (near area L)

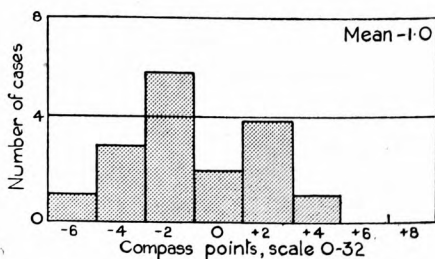
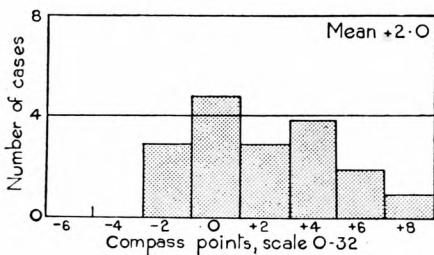
## PART II—STATISTICAL ASPECTS

**Thermal steering.**—It was remarked on p. 10 that, though the movement of depressions which swing northwards (type N) is broadly consistent with the existing steering pattern, the north-to-south orientation of the thickness lines near the centre is not usually in evidence beforehand, but is effected by the circulation of the depression itself. The track charts indicate that depressions of this type swing northwards rather abruptly. For 18 out of the 30 depressions of type N it was possible to specify definitely the time and position at which this abrupt change in direction occurred; for ease of reference they are denoted by  $H_0$  and X respectively. Other times are specified thus:  $H_{-24}$  denotes 24 hr. previous to  $H_0$ ,  $H_{+24}$  denotes 24 hr. after  $H_0$  and so on.

In 16 out of the 18 cases examined the direction of the thickness lines at X backed by  $45^\circ$  or more between  $H_{-24}$  and  $H_0$ ; the average backing for all cases was approximately  $60^\circ$ .

These cases were segregated into depressions which were on the one hand the first members of a group comprising a spell, and on the other, second or subsequent members. It was suggested that the first member should, as it were, set the thickness pattern for the spell by creating the large-scale trough-ridge pattern over east Canada, the remaining members of the group being simply steered round the trough. If this were so it would be expected that the backing of the thermal wind associated with the first member of the group would be greater than with the others. The figures show no significant distinction. A further examination of the charts shows that most spells arise from a series of more or less independent depressions, and as each system passes away to northward the eastward or south-eastward run of the thickness lines across L is restored, to be distorted again as the next member of the sequence comes on.

The detailed examination of these 18 cases suggests that the changes in the thermal pattern and in the track of the depression are not quite simultaneous, but that the former of these processes precedes the latter. This suggestion was tested, with the results shown in Fig. 19 which is a frequency table of values of the difference (called the "steering deviation") between the direction of the thickness lines over the centre and the direction of motion of the centre itself. Directions are specified to the nearest two points on the 32-point (compass) scale. Positive values indicate that the depression is moving across the thickness lines from the cold to the warm side, and *vice versa*. In Fig. 19 the mean direction of movement of the low in the interval  $H_{-24}$  to  $H_{+24}$  is compared with the direction of the thickness lines at (X,  $H_0$ ). This mean is regarded as the approximate instantaneous direction of movement of the low at (X,  $H_0$ ). There is evidently some tendency for this movement to be veered in relation to the direction of the thermal wind over the centre, suggesting that it has not



Steering deviation in interval  $H_{-24}$  to  $H_{+24}$

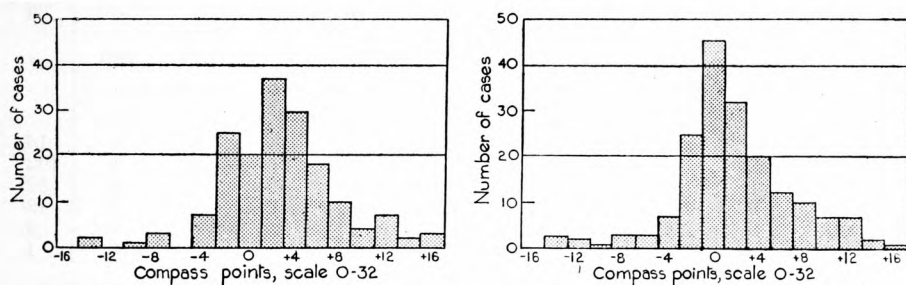
Steering deviation in interval  $H_0$  to  $H_{+24}$

FIG. 19—DEVIATION BETWEEN MOVEMENT OF CLASS N DEPRESSIONS AND DIRECTION OF THICKNESS LINES OVER THE CENTRE

"caught up" with the turning thermal wind. In Fig. 19 also the direction of movement of the low in the interval  $H_0$  to  $H_{+24}$  is compared with the thermal wind at  $(X, H_0)$ , i.e. over the centre at the beginning of the interval. There is here shown a distinct tendency for the movement of the low to be backed relative to the thermal wind. This confirms that for the depressions of type N the backing of the thermal wind tends to precede the turning of the low—a result which may have some value in short-range forecasting.

Of the four class N depressions which entered the area L from the south, three occurred on the east side of a thermal trough of large amplitude, and the northward steering of the centre took place in a straightforward way without appreciable distortion of the thickness lines. The fourth system distorted the thermal pattern in the manner discussed above; it was not, however, essentially different from a depression entering the area L from the west, for it moved up from the south-west and crossed the boundary of the area L very near its south-west corner.

Histograms of the steering deviation were also prepared for depressions of types C and E. The measurements were made on all possible occasions and not restricted to cases of a marked change of direction. The results are given in Fig. 20. These each show a distribution curve of approximately normal shape but slightly skew, indicating a tendency in the mean for depression centres to cross the (instantaneous) thickness lines from the cold to the warm side. For the mean movement in the interval  $H_{-24}$  to  $H_{+24}$  the mode is slightly positive,  $+2$ , but for the interval  $H_0$  to  $H_{+24}$  it is zero. The thermal pattern over the centre at  $H_0$  is a slightly better indicator of the movement of the low in the subsequent 24 hr. than of its mean movement in the 48 hr. centred on  $H_0$ .



Steering deviation in interval  $H_{-24}$  to  $H_{+24}$

Steering deviation in interval  $H_0$  to  $H_{+24}$

FIG. 20—DEVIATION BETWEEN MOVEMENT OF TYPES C AND E DEPRESSIONS AND DIRECTION OF THICKNESS LINES OVER THE CENTRE

As a test of the usefulness of the principle of thermal steering the percentages have been evaluated of steering deviations having the value zero and lying within the range  $\pm 2$  on the scale used, i.e. less than  $11^\circ$  and  $34^\circ$  respectively. These are as follows:—

Steering deviation	Mean movement of low from $H_{-24}$ to $H_{+24}$	Movement of low from $H_0$ to $H_{+24}$
	%	%
$\leq 11^\circ$	12	25
$\leq 34^\circ$	48	57

Thus the crude application of the thermal steering principle gives a satisfactory guide to the movement of the depression in only about half the total number of cases,

**Movement of depressions in relation to their deepening and filling.**—It has been suggested that there may be a very broad connexion between the rate of deepening of a depression and its speed of movement, rapidly deepening systems tending to be slow moving while fast-moving systems show little tendency to deepen rapidly. To test this, certain data were extracted for major systems for those periods in which they were uncomplicated by processes of splitting or amalgamating with other systems including secondaries and break-aways, that is only simple systems, identifiable over a time interval of at least 12 hr., were considered. The data extracted were :—

- (i) Movement of the centre in hundreds of miles over a 12-hr. period
- (ii) Change of central pressure over the same period.

This was done for two separate periods of three months in the winter half year, namely January to March and October to December 1950. The results are shown in the frequency table, Table III. The two periods are almost exactly comparable, the total number of cases being respectively 191 and 186.

TABLE III—FREQUENCY TABLE SHOWING CHANGE OF PRESSURE IN RELATION TO THE MOVEMENT OF DEPRESSIONS OVER 12-HR. PERIODS

Movement of centre in 12 hr.	Change of pressure (mb.) in 12 hr.									Total
	+13	+12 to +9	+8 to +5	+4 to +1	0	-1 to -4	-5 to -8	-9 to -12	-13	
JANUARY-MARCH 1950										
miles	number of occasions									
0-100	0	0	2	3	1	0	0	1	1	8
200-300	5	1	5	17	15	21	14	3	2	83
400-500	1	1	3	5	15	16	6	7	6	60
600-700	0	1	2	4	7	7	8	5	0	34
800-900	0	1	0	0	1	1	0	0	0	3
1,000	0	0	1	0	0	0	1	1	0	3
miles per 12 hours										
Mean	280	550	390	320	410	400	420	510	360	..
OCTOBER-DECEMBER 1950										
miles	number of occasions									
0-100	0	0	2	2	6	4	1	0	1	16
200-300	2	2	9	27	21	21	14	5	1	102
400-500	1	0	3	9	16	12	4	3	4	52
600-700	0	0	0	0	6	4	1	1	0	12
800-900	0	0	0	0	1	0	2	0	0	3
1,000	0	0	0	0	1	0	0	0	0	1
miles per 12 hours										
Mean	320	250	260	290	360	330	350	360	350	..

Total numbers of occasions { January-March 191  
October-December 186

In the bottom row of each part of the table is entered the mean speed of movement for each rate of deepening. No relation is apparent apart from a slight tendency for deepening depressions to move a little faster than filling ones. There is no tendency for rapidly deepening systems to move slowly. On the other hand it is well known that very deep (occluded) systems are often slow moving; these results suggest that the slowing down often occurs after the process of deepening.

The last column of Table III shows that about half the movements considered were at speeds of about 20 to 30 m.p.h. Very small movements were rare.

**Deepening of depressions in relation to certain thermal features.**—*Thermal gradient over the centre.*—During the period January to March 1950 among the systems studied there were 25 cases of rapid deepening (10 mb. or over during a 12-hr. interval). The thickness gradient over the centre at the beginning of the 12-hr. interval was measured and compared with the 5-yr. mean thickness

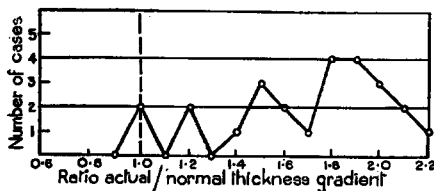


FIG. 21—FREQUENCY OF THE RATIO OF ACTUAL THICKNESS GRADIENT TO NORMAL THICKNESS GRADIENT OVER THE CENTRES OF RAPIDLY DEEPENING DEPRESSIONS

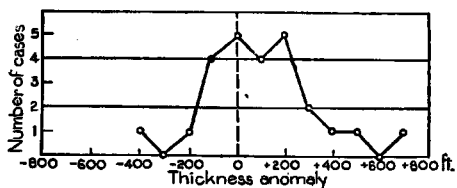


FIG. 22—FREQUENCY OF THICKNESS ANOMALY OVER THE CENTRES OF RAPIDLY DEEPENING DEPRESSIONS

gradient at the same place for the appropriate month. The result is shown in Fig. 21 which is a frequency curve of values of the ratio actual thickness gradient to this "normal" gradient. The values of this ratio varied from 1.0 to 2.2 with a mean of 1.7. There was no indication that the greater rates of deepening were associated with higher (or lower) values of this ratio. Though the number of data is limited it is probably significant that in four fifths of the total number of cases the ratio was equal to or greater than 1.5.

*Thickness anomaly over the centre.*—The thickness anomaly (actual thickness minus 5-yr. mean) over the deepening centre was evaluated for the 25 cases described above. Fig. 22 shows the resulting frequency curve. The thickness anomalies are expressed in feet for ranges centred on the values 0,  $\pm 100$ ,  $\pm 200$  ft., etc. (the ranges are  $-50$  to  $+50$ ,  $\pm 60$  to  $\pm 150$  and so on). The values show a slight bias towards positive values of the anomaly (14 cases of positive anomaly, 6 of negative). The mean value is  $+120$  ft. It might have been expected that, since vertical instability is to some extent favourable for the deepening of depressions (Sumner<sup>4</sup>), a greater tendency towards negative thickness anomalies would have been apparent in these cases.

*Relation of deepening depressions to thermal-pattern models.*—The 25 cases of rapid deepening given above were examined in relation to the thermal pattern in their vicinity. In all cases the thermal patterns were qualitatively consistent with the developmental ideas put forward by Sutcliffe<sup>1</sup> and Sutcliffe and Forsdyke<sup>5</sup> in the sense that the deepening was located in the "correct" relation to thermal troughs and ridges, diffuence and confluence. But the degree of deepening appeared to bear no relationship to the intensity of development estimated by eye from the thermal pattern, nor was there any easily recognizable pointer to the exact location of the deepening. It is evident that for further increase in accuracy of estimating development quantitative treatment of the thickness pattern is at least necessary, though it may not be sufficient.

**Conclusions.**—The following conclusions are drawn from this study.

(1) Depressions moving through the selected area L exhibit many of the features of evolution common to middle-latitude systems. While the systems move on the whole more or less eastward there is an important class which turns away sharply northward or north-westward and become slow moving. It is suggested that the peculiarity of the area in this respect arises from the presence of the Greenland massif which causes a sharper separation between the two classes than in localities where topographical factors are absent or less pronounced.

(2) The behaviour of depressions is not random; when the systems are classified according to their movement the various classes seem to occur in rather loosely defined spells or groups lasting from a few days to a week or more.

(3) Some of these spells are associated with characteristic hemispherical upper-flow patterns. The most definite of these is the pattern of slow-moving large-amplitude troughs and ridges associated with the stagnating depressions referred to above. Such a pattern usually persists throughout each spell, with persistent cyclonic or anticyclonic conditions in certain areas, but the geographical locations of the upper troughs and ridges and the corresponding surface systems vary from one spell to another.

(4) The greatest degree of steadiness in these well defined upper-flow patterns is often not attained until towards the end of the spell, that is after the surface patterns have themselves become steady. This suggests that the upper-flow pattern is not the antecedent in any causal relation there may be between it and the surface patterns.

(5) Regarded qualitatively the large-scale upper-flow patterns afford no consistent indications of impending changes of type such as would be useful in medium-range forecasting.

(6) The evolution of the surface systems usually conforms to the thermal developmental models put forward by Sutcliffe<sup>1</sup> and Sutcliffe and Forsdyke<sup>5</sup>, but in most cases the thermal and surface patterns evolve together and it is not possible to forecast one from the other.

(7) Differences in the behaviour of individual depressions appear to depend upon rather subtle factors including perhaps details of the thermal structure which are not apparent in a broad survey. It is an open question whether the quantitative study of thickness patterns would be a useful aid to forecasting in the area studied.

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