INTERRUPTIONS IN THE NORMAL WESTERLY FLOW OF THE GENERAL CIRCULATION OF THE ATMOSPHERE

Thesis by

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In Partial Fulfillment of the Requirements
for the Degree of
Doctor of Philosophy

California Institute of Technology
Pasadena, California

1948

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to the Office of Naval Research without whose support this investigation could not have been carried out. He is also indebted to Professor Robert D. Elliott for his original definition of the problem and to Dr. Irving P. Krick and Professor Elliott for their interest and helpful suggestions throughout the work. Much credit is due to Mesdames Garand, Dillon, Roberts, Gottlieb and Miss King for performing many of the tedious calculations necessary in this study.

ABSTRACT

Certain effects associated with the intrusion of stable, persistent high pressure cells into the normal westerly flow of the general circulation of the atmosphere are investigated. These intrusions are termed Blocking Action processes.

By means of empirical and semi-statistical procedures these processes are found to cause the development of long stable wave patterns in the atmosphere downstream from the point of inception. These wave patterns may exist for periods of a month or more. The wave length of these stationary long waves is found to be longer than that determined by other investigators. This is explained on the basis of the larger amplitude of the long waves associated with the Blocking Action process.

A theory of the formation of these blocking high cells is suggested based on the accumulation of heat in low latitudes and the necessity for the readjustment of the general circulation to redistribute this heat. One means of dissipation of the blocking cells is shown to be the formation of a wave pattern in the atmosphere which is out of phase with the stable wave pattern formed by the blocking High.

The optimum mean pressure chart is discussed in terms of the long period Blocking Action processes. The optimum length chart is found to cover a three day period or a period of greater than twenty days depending on the use to be made of the chart.

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INTRODUCTION

The following study is a portion of the research report submitted to the Office of Naval Research under Contract No. N6 onr-244. This work has been carried on for the past year by the Meteorology Department of the California Institute of Technology under the supervision of Professor Robert D. Elliott under the title of "Blocking Action."

For the purposes of this investigation the term Blocking Action has been used to characterize the disturbed state of the general circulation of the atmosphere during periods of strong, persistent, meridional type flow. On the daily weather map this disturbed state is discernible as intrusions of stationary or very slowly moving high pressure cells into the middle latitudes normally occupied by a general westerly flow and normally characterized by alternate passages of migratory cyclones and anticyclones. Since the blocking cell may be in existence for periods of a month or more this must constitute a major interruption in the normal eastward progress of the migratory cyclones and anticyclones, at least in the area dominated by the blocking High.

In another phase of the project Professor Elliott (1) has treated the seasonal variations in Blocking Action, lateral mixing and meridional heat transport by use of the broadscale lateral turbulence principles introduced by Defant and Lettau (2), (3). He has indicated that seasons with excessive Blocking Action are characterized by excessive mixing and large values for the meridional heat transport.

The phase of the study which will be treated here is the fluctuations during periods of twenty to thirty days of the general circulation preceding and following the inception of Blocking Action. The problem may be stated more explicitly as the study of:

1) Changes in the general circulation pattern antecedent to the formation of the blocking High,
2) Changes in the general circulation pattern effected by the establishment of the blocking High,
3) Changes in the general circulation pattern accompanying the dissipation of the blocking High.

From a consideration of the data available, two general methods of attack are possible in an investigation of the details of these changes in the general circulation. The first involves a careful three dimensional analysis of a few examples of Blocking Action. The second involves the analysis of a relatively large number of cases using only such data as can be obtained from surface weather charts. The source of the data for the first method is some six months of Northern Hemisphere daily surface maps and 500 mb. maps, three to four years of complete surface and upper level maps and aerological soundings for the North American continent only. Since the aspect of greatest interest is the change in circulation pattern at points considerably removed from the immediate area of the blocking High, the source of three dimensional data is restricted to such an extent that the first method has been considered unsatisfactory for the purposes of this investigation. The source of the data for the second method is the forty year series of daily Historical Northern

Hemisphere sea level charts from which sea level pressures and to a limited extent surface temperature data can be obtained. The basic data taken from these charts have been sea level pressures at the intersections of each ten degrees of longitude and five degrees of latitude in the area bounded by longitudes 140° E and 40° E (through 180°) and by latitudes 60° N and 35° N. This area comprises the largest area on the forty year Northern Hemisphere map series for which the analyses can be considered as reliable. Extensions of the area through Siberia and north of 60° N would be highly desirable but are not practicable from this series of maps.

The pressure data taken from the above intersections have been used to compute daily departures from the normal pressure at each of these intersections for the forty January-February "seasons" included in the Northern Hemisphere map series. The data have been divided, in general, into the even years as a development sample and the odd years as a check sample. These pressure departures have formed the basis for most of the work undertaken in this investigation.

The data are treated by a grouping of examples with statistical procedures being used whenever conditions permit. Data in the form of sea level pressures are not readily adaptable to the application of the numerous kinematical and dynamical principles which may apply in the Blocking Action case. Any such application must be made by inference from the observed sea level pressure distributions.

The value of the investigation, then, lies in the recognition of some of the processes associated with Blocking Action through a consideration of a relatively large number of cases. These processes may then be studied in more detail in individual examples where a more adequate network of data is available. Due to the character of the available data and due to the complexity of the interactions between various Blocking Action high cells, it can hardly be expected that this study will have much semblance of completeness. It is hoped, however, that there have been a sufficient number of new ideas introduced to stimulate interest toward further research in this field.

PART I. THE EFFECTS OF THE ESTABLISHMENT OF THE BLOCKING HIGH

The General Problem

In order to visualize the importance of the introduction of a semi-stationary high pressure cell into the latitudes normally occupied by a westerly flow the effects of this disturbance on the circulation patterns upstream and downstream from the blocking High will be discussed first. In the later sections some of the details of the changes in the circulation patterns accompanying the formation and dissipation of the blocking high cell will be investigated.

Objective Criteria

In order to segregate those cases which will be treated from those which are of less importance some objective definition of the existence of Blocking Action must be formulated. Using sea level pressure data this definition can take many forms depending on the magnitude desired, the amount of movement of the high center permitted, etc. Several criteria have been used in the investigation and each will be discussed in the section to which it applies. According to the concept of a blocking high cell, the general criterion that must be satisfied is the existence of persistent, abnormally high pressure in the belt usually occupied by strong westerly flow. This belt under average conditions extends between latitudes 45° N and 50° N in the Pacific Ocean area, being displaced northward slightly in the North

American continental area and reaching 55° to 60° N in the eastern Atlantic Ocean and western European areas. Persistent high pressure in any portion of this band then constitutes a major interruption in the normal westerly flow of the general circulation of the atmosphere.

Blocking in the Northeastern Atlantic Area

A check of the geographical distribution of Blocking Action shows the highest frequency of occurrence in the longitude band from 0° to 25° W in the northeast Atlantic Ocean. This region is followed in importance by the eastern Pacific area. The northeastern Atlantic area was therefore selected as the first region to be investigated.

The objective criterion in this case is as follows: "A band fifteen degrees of longitude wide and covering 55° N and 60° N latitudes must experience pressure departures of plus 20 mb. or more for at least three consecutive days." The requirement of plus 20 mb. or more eliminates all but the extreme cases of Blocking Action. The continuation for at least three days is for the purpose of excluding the possibility of the high cell being migratory in nature where the mean period from one trough of low pressure to the next is normally three days.

The examples satisfying this criterion have been divided into two classes designated by High Latitude and Low Latitude Blocking where the distinction is obviously the latitudinal position of the center of the blocking high cell. The High Latitude cases are the more extreme disturbance being characterized by a high pressure cell far to the north and trapped low pressure areas along its southern periphery. In terms of the displacement of the west wind belt they may be considered as displacements far to the north around the northern limb of the blocking High or displacements far to the south around the southern limb of the trapped low pressure areas. The Low Latitude cases are characterized by a northward extension of the sub-tropical high cell where the connection with this cell is not broken; any trapped low pressure centers are formed well to the east of the blocking high cell. In terms of the displacement of the west wind belt these cases represent a less extreme northward displacement of the belt.

The inception date for each example satisfying the above criterion is listed below. The figure in parentheses represents the duration of the blocking eddy in days.

<u>Even Years</u>

High Latitude		Low Latitude	
Jan. 30, 1902	(12)	Jan. 13, 1902	(4)
Jan. 11, 1914	(5)	Jan. 20, 1904	(3)
Feb. 21, 1916	(3)	Jan. 19, 1906	(4)
Feb. 23, 1928	(7)	Feb. 4, 1908	(6)
Feb. 7, 1930	(6)	Jan. 2, 1922	(3)
Feb. 8, 1932	(23)		
Feb. 12, 1934	(10)		

Odd Years

High Latitude		Low Latitude	
Feb. 7, 1901	(16)	Jan. 26, 1905	(4)
Jan. 13, 1903	(7)	Feb. 13, 1909	(3)
Jan. 30, 1911	(10)	Jan. 16, 1911	(4)
Feb. 16, 1915	(3)	Jan. 18, 1923	(3)
Jan. 20, 1917	(5)	Feb. 11, 1933	(4)
Feb. 8, 1917	(4)		
Jan. 16, 1935	(8)		

It is apparent from this that the High Latitude type is a considerably more stable development even though it represents the more extreme disturbance. It would therefore be expected to exert more influence on the circulation patterns in other regions of the Northern Hemisphere than the less extreme, less persistent Low Latitude type.

In order to eliminate some of the small scale fluctuations caused by migratory cyclones and anticyclones from the larger scale fluctuations caused by the Blocking Action process, three day mean pressure departure charts have been prepared for consecutive three day periods following the inception of each type of Atlantic blocking. The use of such charts is discussed in greater detail in Part IV. These charts are shown in Figs. I to X. Solid lines surround areas for which the total departure (sum of the even year cases and odd year cases) during the given three day period exceeded an average of + 5 mbs. per day. Dotted lines surround areas for which

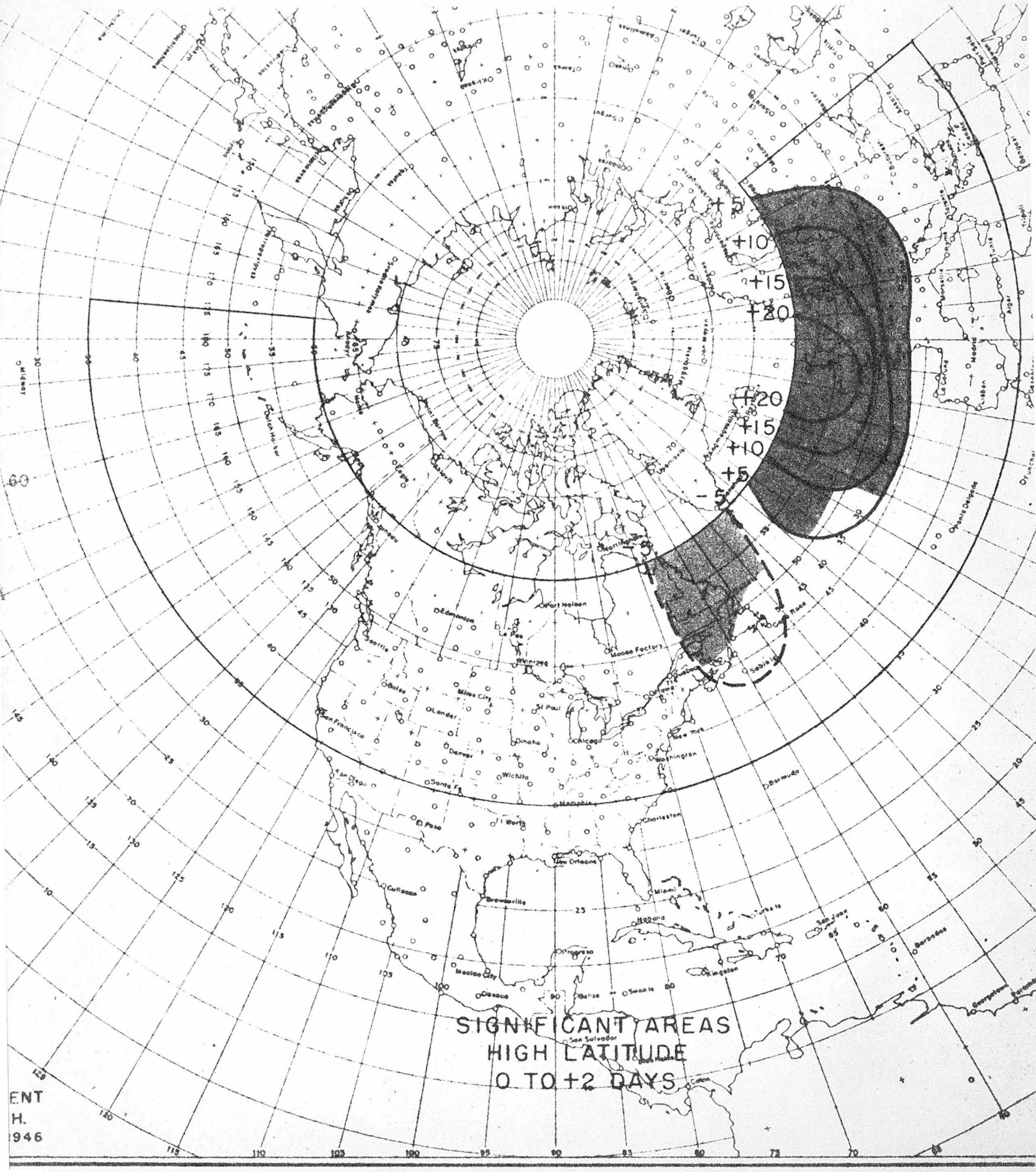

SIGNIFICANT AREAS
HIGH LATITUDE
0 TO +2 DAYS
+5
+10
+15
+20
+20
+15
+10
+5
-5

Fig. I

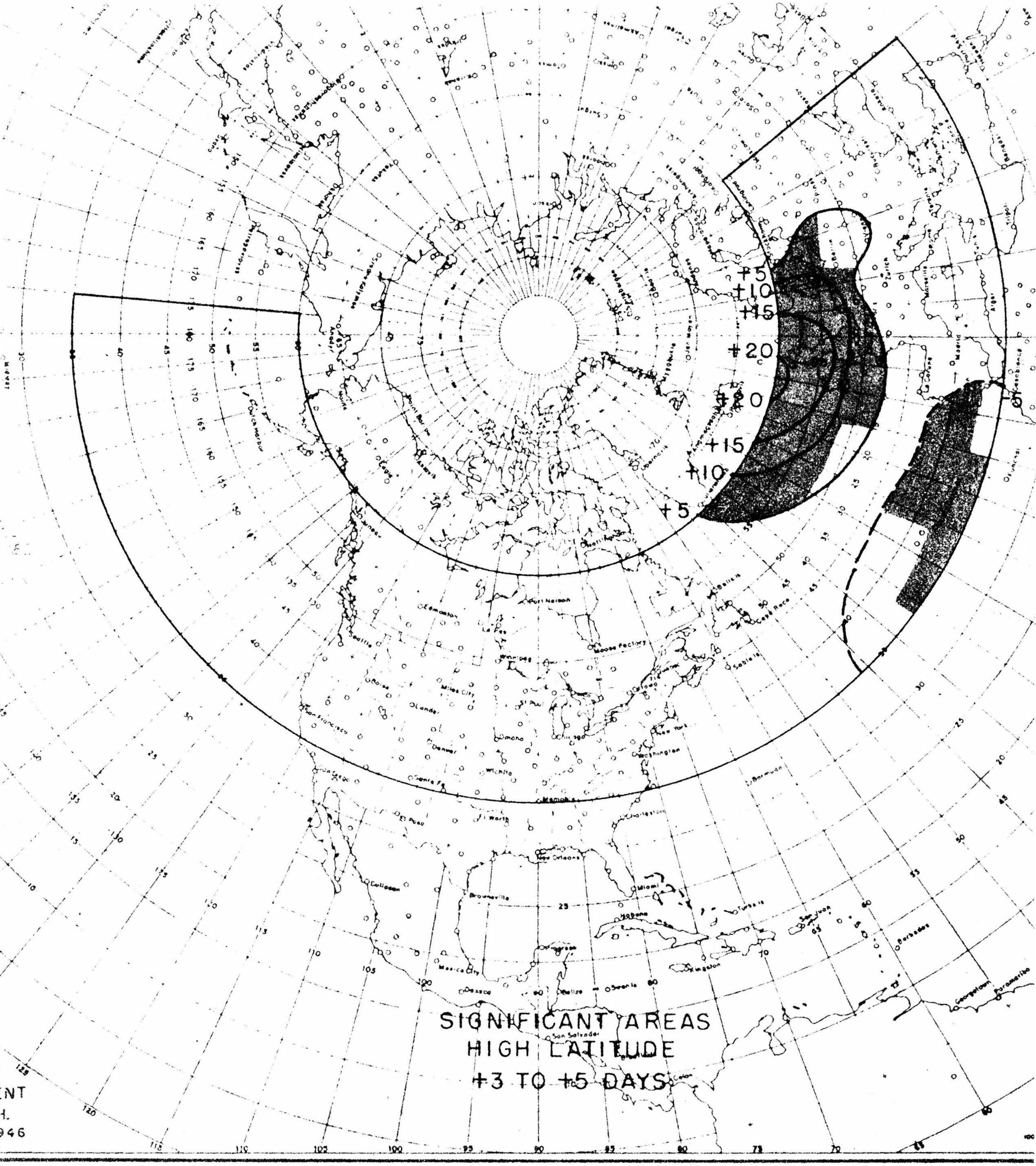

SIGNIFICANT AREAS
HIGH LATITUDE
+3 TO +5 DAYS
+5
+10
+15
+20
+20
+15
+10
+5

Fig. II

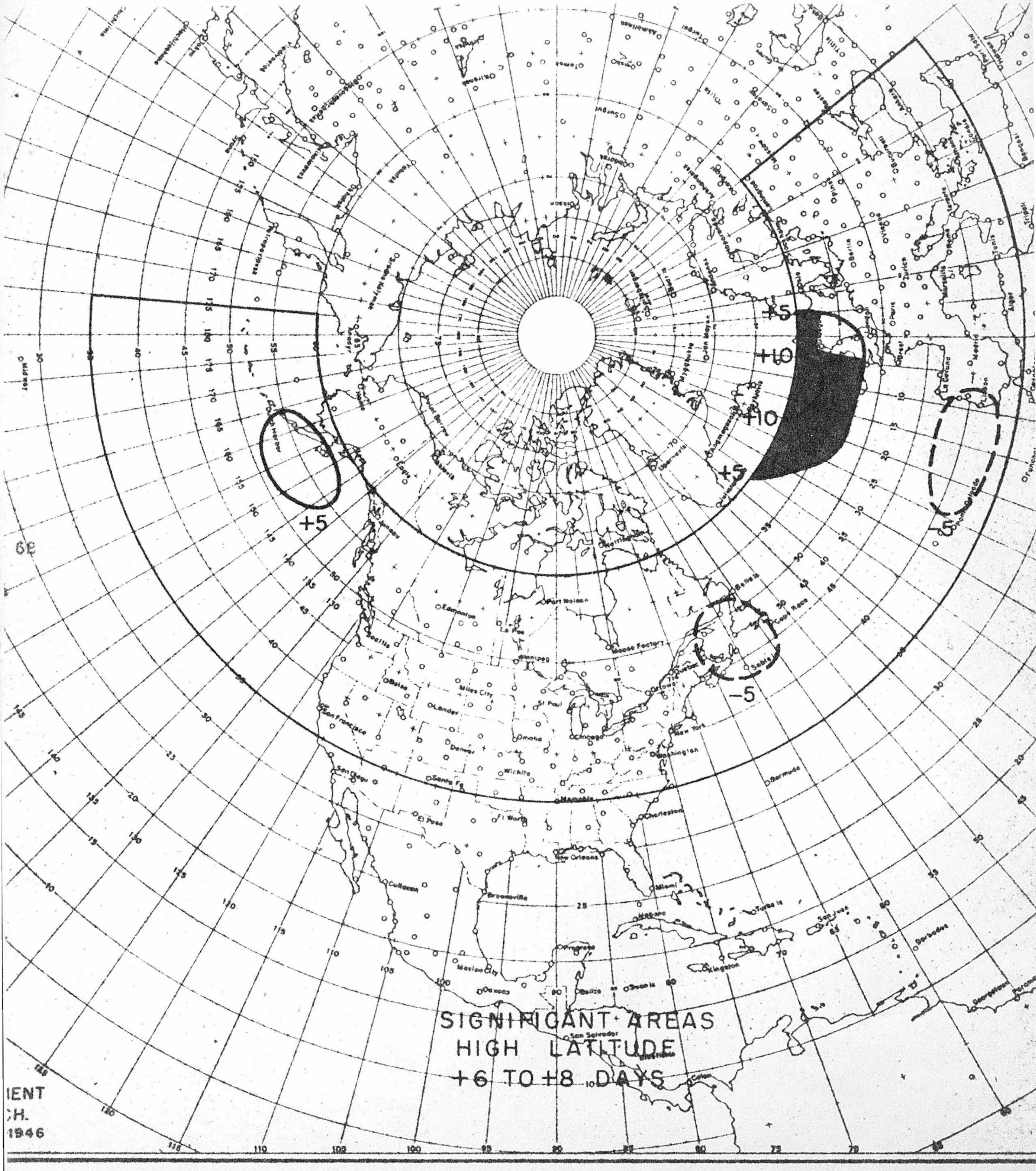


Fig. III

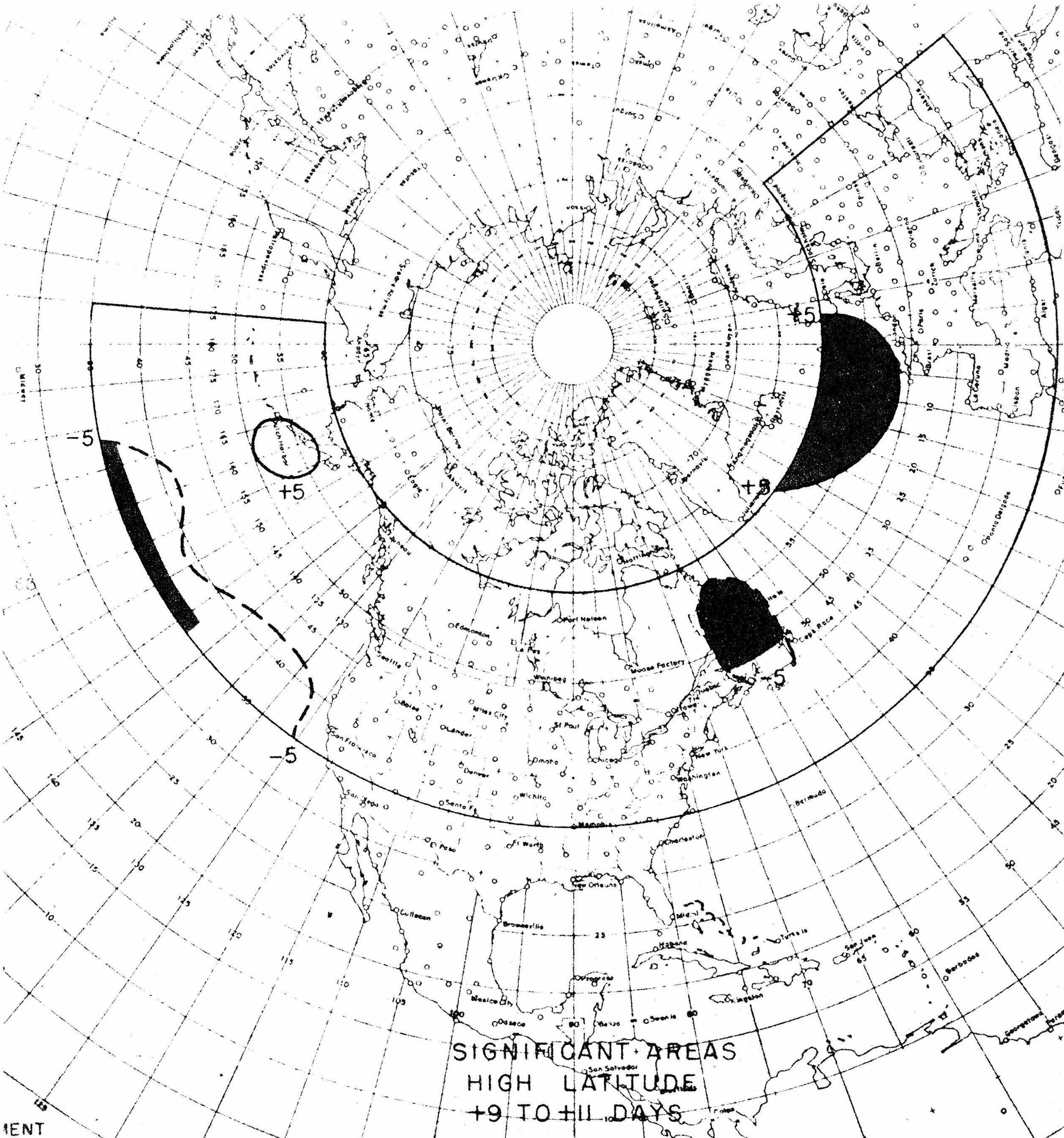

SIGNIFICANT AREAS
HIGH LATITUDE
+9 TO +11 DAYS
+5
-5
+9
MENT
CH.
1946

Fig. IV

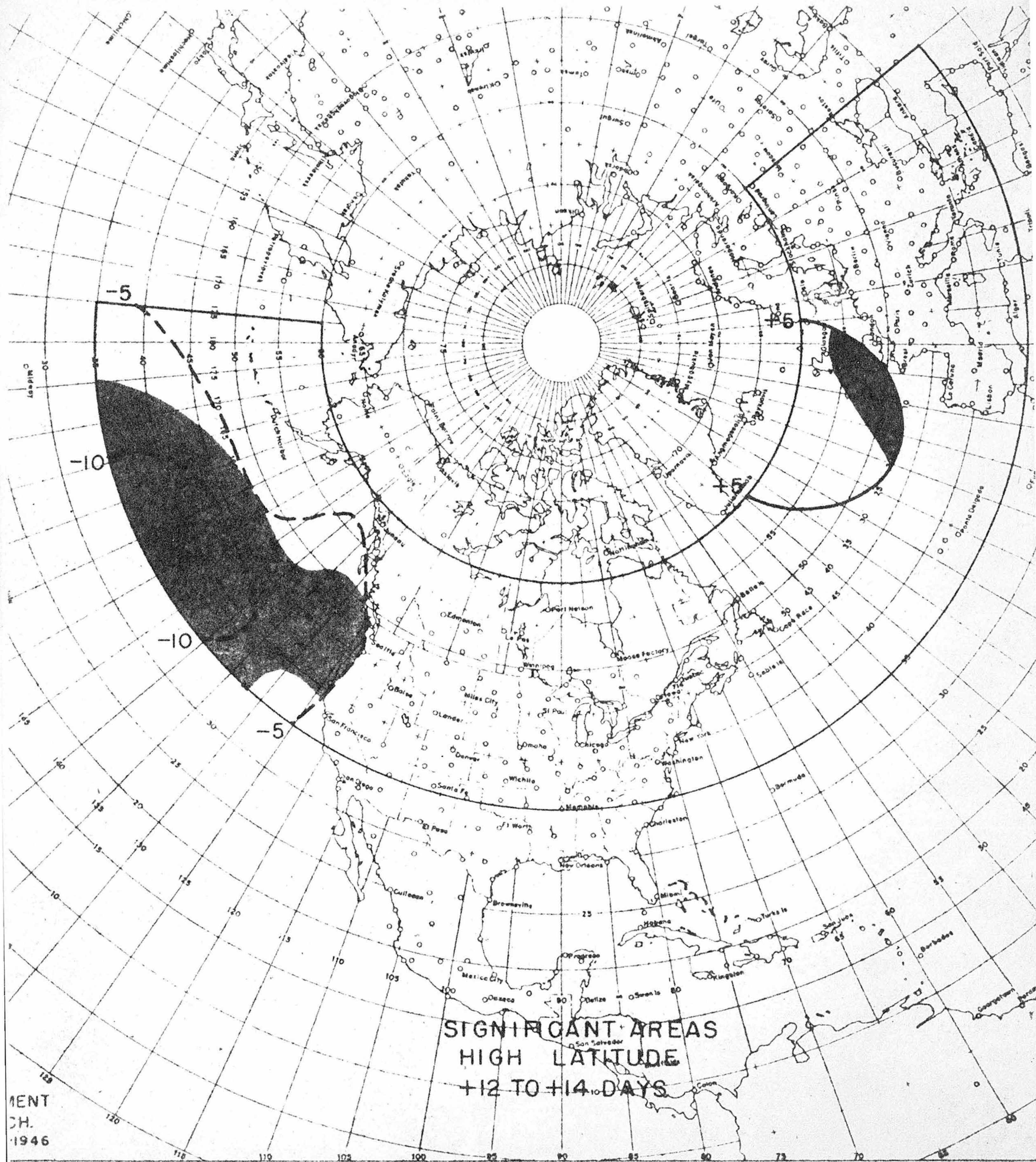

SIGNIFICANT AREAS
HIGH LATITUDE
+12 TO +14 DAYS
-5
-10
-10
-5
+5
+5
Edmonton
Winnipeg
San Francisco
Denver
Omaha
Chicago
New York
Washington
New Orleans
Miami
Mexico City
Habana
Kingston
Bermuda
Cape Race
Berlin
Paris
London
Madrid
Lisbon

Fig. V

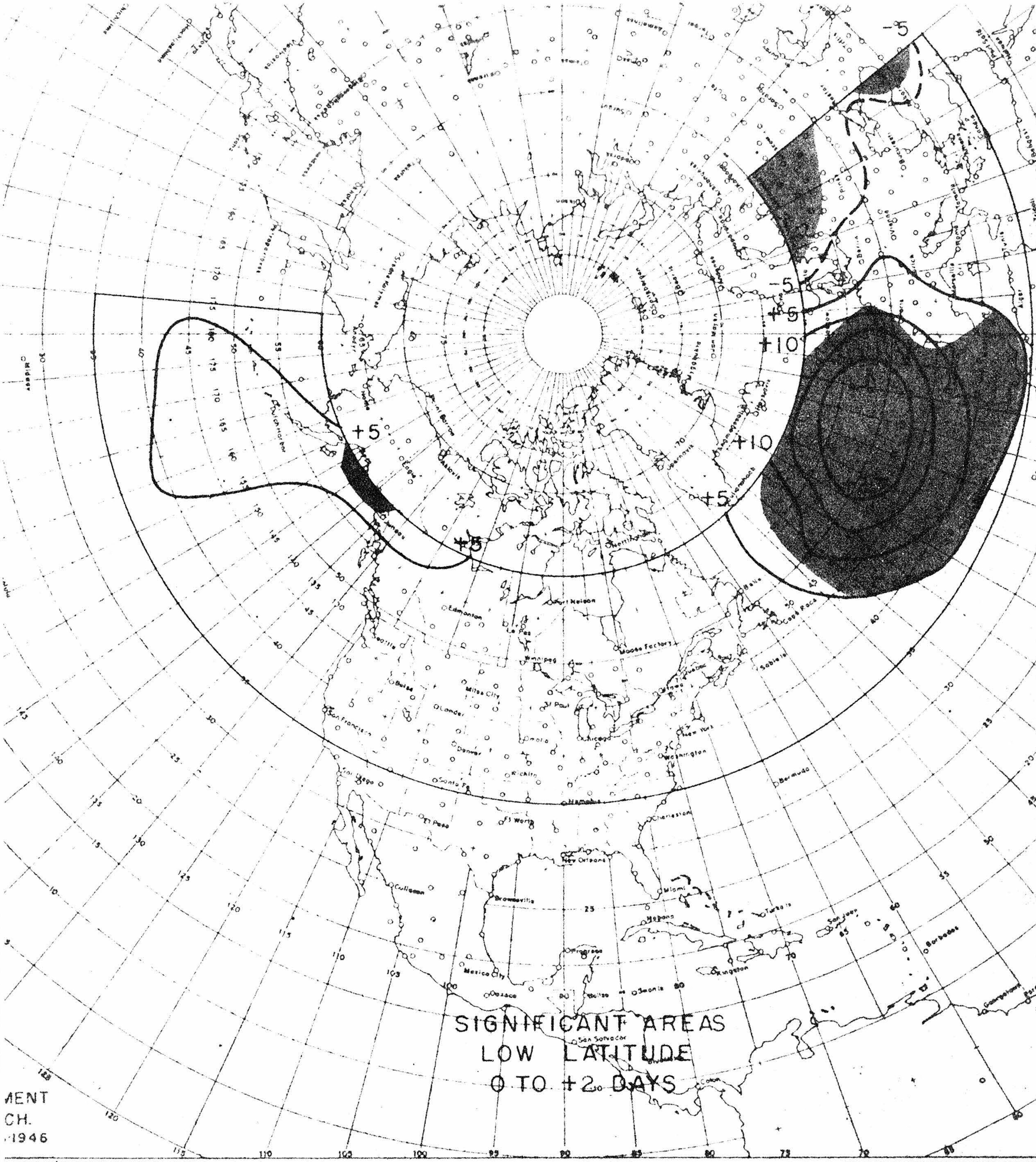

SIGNIFICANT AREAS
LOW LATITUDE
0 TO +2 DAYS
-5
+5
+10
Edmonton
Winnipeg
San Francisco
Denver
Chicago
New York
Washington
New Orleans
Miami
Mexico City
Bermuda
Kingston
Barbados

Fig. VI

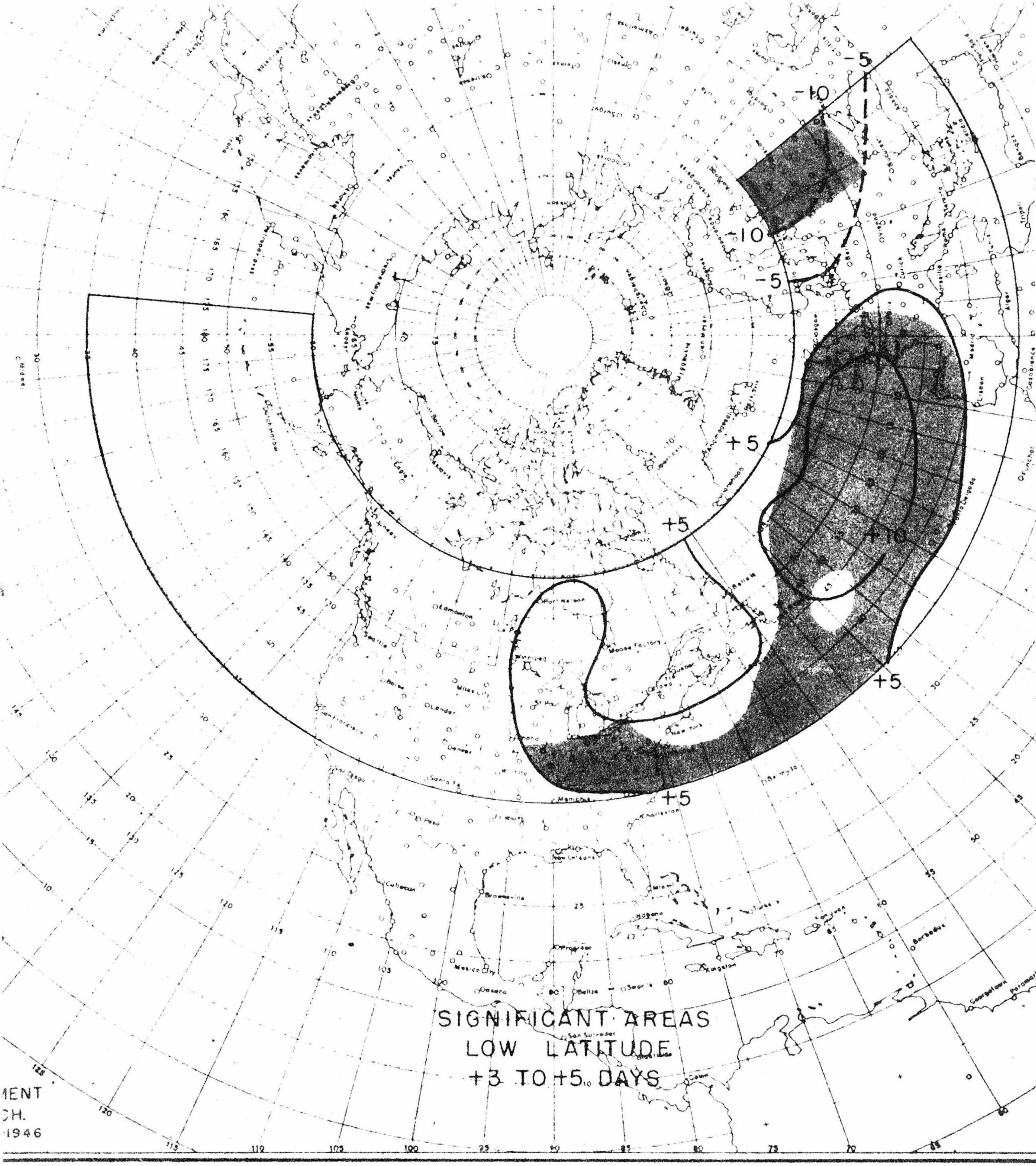


Fig. VII

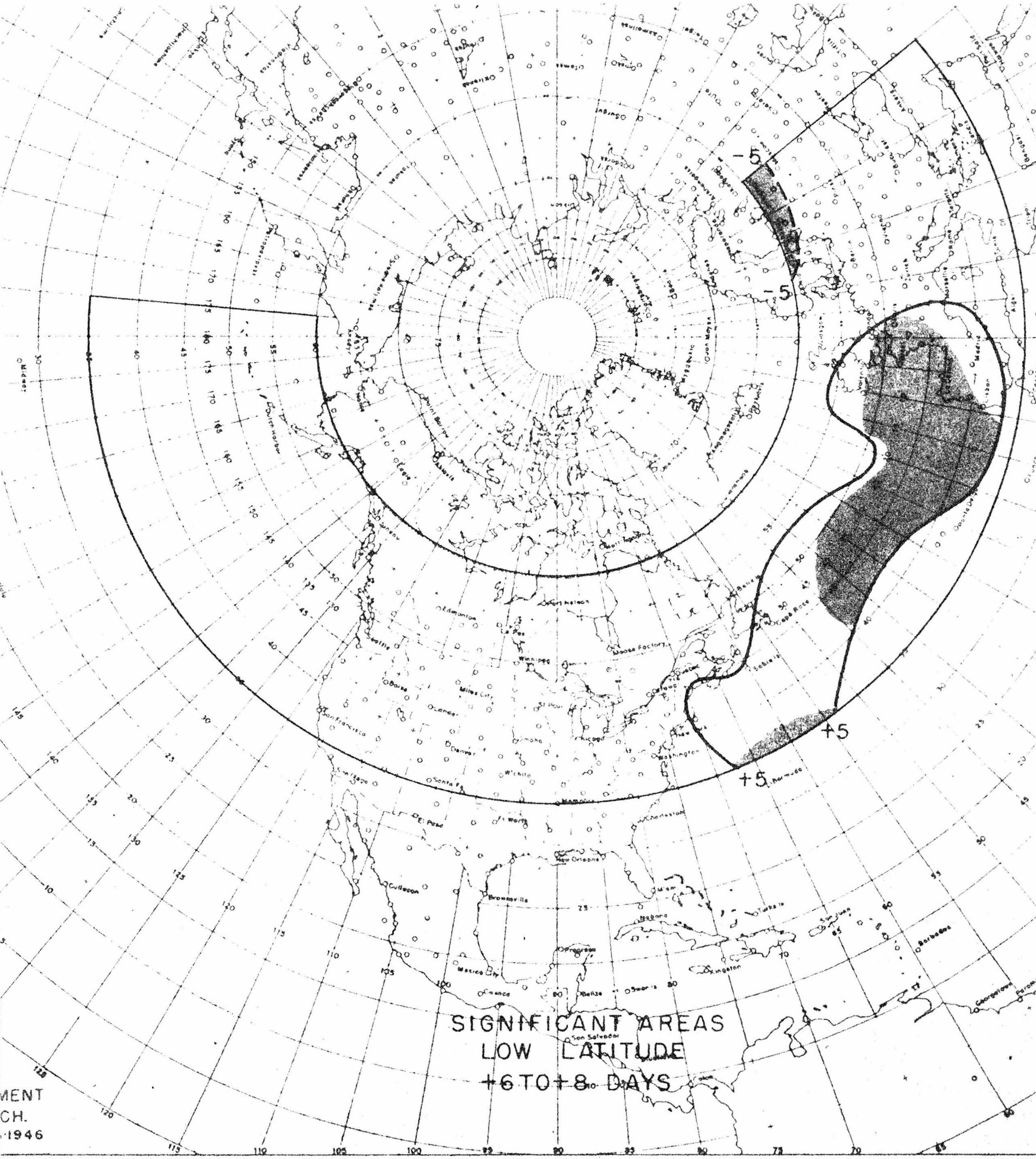


Fig. VIII

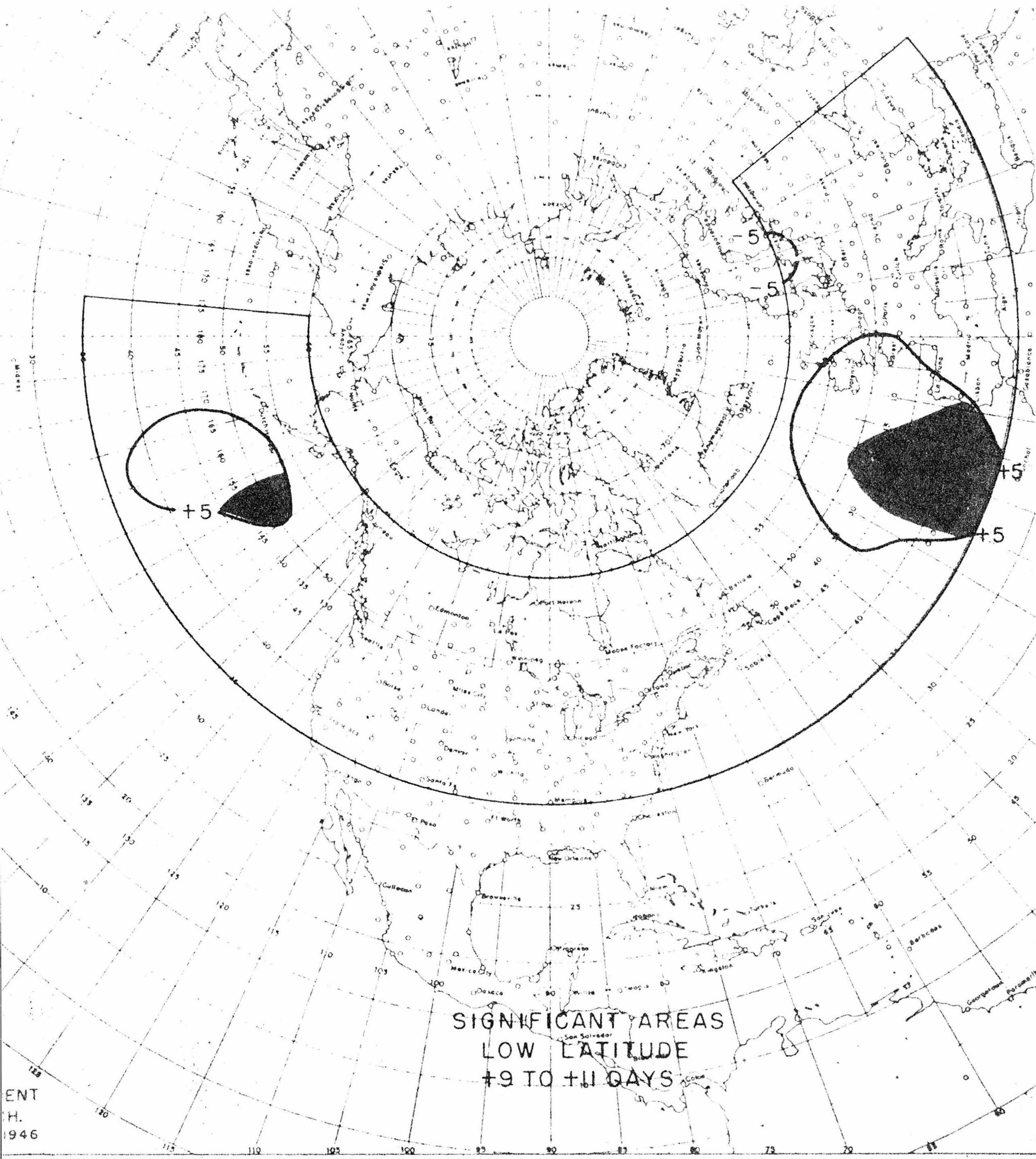


Fig. IX

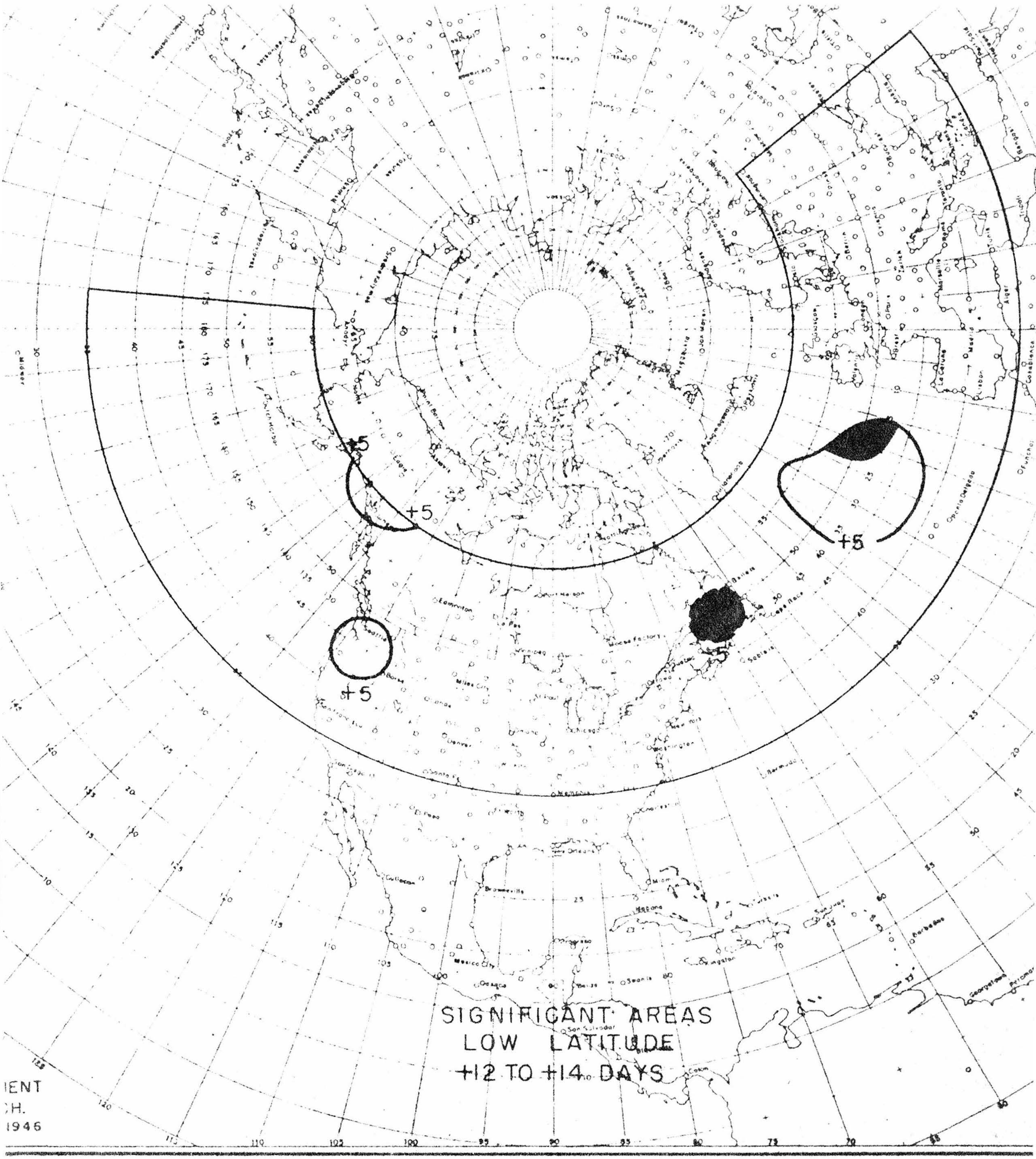


Fig. X

the total departure exceeded an average of - 5 mbs. per day. Shaded areas are those areas where an average departure of at least 5 mbs. per day was observed independently in both odd and even years. These areas are considered particularly significant. Areas showing no large anomalies were omitted for clarity.

A check has been made at the point 60° N - 140° W of the statistical significance of an average deviation from the normal pressure such as is indicated by the shaded areas of the figures. (See Appendix A). This check has indicated that at that particular point an average deviation of about 7 mbs. per day calculated from a total of ten independent three day periods is statistically significant at the five percent level. Since the standard deviation of the pressure at this point is larger than that of most of the points in the area under consideration it is believed that most of the shaded areas represent statistically significant deviations from the normal pressure.

Comparison of the High and Low Latitude classes in the Atlantic-European region shows the latitude variation between the two classes and the effect of this variation in producing a widespread low pressure area in the vicinity of the Azores in Fig. II, in contrast to the above normal condition in the corresponding area in Fig. VII. In the west Atlantic-southeast United States sector an important difference between the classes may be noted. Fig. VII shows a long east-west belt of abnormally high pressure extending westward from the vicinity of the British Isles to the Mississippi Valley. From a consideration of the individual weather maps involved and of some of the surface temperatures included on these maps, it appears that the western portion of this belt is made up of a warm high pressure cell in the initial stages followed by cold polar outbreaks. This corresponds to the picture already formed of the distinction between the High and Low Latitude classes. The Low Latitude type being a less intense deformation of the normal pressure field extends its influence farther in a longitudinal direction than the more disturbed High Latitude type.

No further large significant areas are observed until Figs. IV and V. In the High Latitude case only, an extensive low pressure area begins to develop in the east Pacific and continues into Fig. V. From the check of the statistical significance at the point 60° N - 140° W mentioned above, the peak average deviation of over 10 mbs. per day reached on Fig. V is considered highly significant in a statistical sense. It should be noted that there is no evidence on the charts to show that this deviation is produced by any effects acting upstream from the blocking High. The possible methods of formation then, are an upstream effect from the blocking High at latitudes north of 60° N or a downstream effect through Siberia. Either method could lead to the development of high pressure in the Alaskan area (outside of the network of available data) and a subsequent displacement of the west wind belt in the Pacific Ocean toward the south. The examination of some of the Northern Hemisphere sea level charts for which an adequate network of data is available in Siberia has shown that the downstream method of formation is the more probable.

An excellent example of this High Latitude development is afforded in a recent example which may serve as an independent illustration. During mid-January of 1947 a high pressure cell developed in the eastern Atlantic area reaching the High Latitude Blocking Action stage over the British Isles about January 19, 1947 with the pressure remaining predominantly high in that area into March. An extensive low pressure area subsequently developed in the eastern Pacific Ocean at low latitudes with the pressure remaining abnormally low in that region from February 1 through February 14. A more normal pattern was reestablished for a short period in the Pacific but beginning again about February 22 and continuing into the middle of March, pressures were again predominantly low at low latitudes in the eastern Pacific. In general terms, then, once the Blocking Action eddy is established it continues to exert its controlling influence on the overall circulation pattern at least until the disturbing eddy is dissipated.

Blocking in the Mid-Pacific Area

The investigation of Atlantic blocking described in the preceding paragraphs has shown the probability of downstream effects originated by the introduction of a disturbance in the form of a blocking high pressure cell. In order to study this downstream effect a region was selected for investigation for which a large downstream area of data was available. The region selected is bounded by the longitudes 180° and 170° W. The strong west wind belt normally lies between 50° N and 45° N latitude in this sector of the hemisphere so that these latitudes form the other boundaries of the region. In the

Atlantic criterion the restrictive requirements regarding high pressure departures have probably excluded some cases which should be included in the Blocking Action category. These restrictions are necessary in order to produce disturbances of sufficient strength to carry through the blank area of data in Siberia and be observable in the Pacific region where data are available. When the immediate downstream effects of the disturbance are observable the objective criterion may be weakened considerably and the disturbance may still be expected to produce meaningful pressure deviations at least for a short distance downstream.

The following objective criterion was therefore formulated for the Pacific blocking: "The total pressure departure of the four intersections formed by 180° and 170° W with 50° N and 45° N must average 5 mbs. above normal for a two day period. This average must be maintained for at least three days." This is obviously an extremely weak definition. It could allow negative departures on any given day providing the positive departures on the preceding and following days overbalance the negative values to the extent of an average of plus 5 mbs. for the two day period. This is for the purpose of allowing a minor trough passage after which the surface pressure is reestablished. In terms of the upper level flow, the controlling wave pattern may still exert its influence on the circulation even though a minor low pressure trough has passed.

Another illustration of the weakness of the definition lies in the small area it encompasses. The center of the blocking cell may lie anywhere outside of the given area and the definition may still be satisfied. An obvious advantage of the definition is that it allows the inclusion of a larger number of cases so that some of the disadvantages mentioned above tend to be smoothed out.

The cases which satisfy this criterion are listed in Table I (the figure in parentheses represents the total length in days for each case).

The downstream effects of this disturbance are shown in Figs. XI through XV. These figures are again presented in the form of three day mean maps. Solid lines enclose areas where the average daily pressure during the three day interval is 2 mb., 4 mb., etc. above normal and which are common to both the odd year and even year samples. Dashed lines enclose similar areas of below normal pressure. In order that no extraneous influences accompanying the breakdown of this process would be introduced, individual examples were eliminated from consideration as soon as the criterion was no longer satisfied although it is probable that the effect of this breakdown is propagated downstream rather slowly and is not immediately apparent at distances far downstream. In this way the number of cases considered is gradually reduced from about twenty for Fig. XI to eight for Fig. XV for the even year examples and similarly for the odd year examples.

Figs. XI through XV show the gradual establishment of a consistent wave pattern downstream becoming well established in the period twelve to fourteen days following inception. The pressure ridge observed in eastern Canada in this period has been found to exist for periods longer than twelve to fourteen days and represents the first downstream crest of the stable wave pattern. The wave length

Table I

Mid-Pacific Blocking Dates

Even Years		Odd Years	
Jan. 21, 1900	(6)	Jan. 18, 1899	(15)
Jan. 29, 1904	(31)	Feb. 7, 1899	(4)
Jan. 5, 1906	(5)	Dec. 30, 1900	(6)
Jan. 12, 1906	(12)	Feb. 3, 1901	(14)
Feb. 23, 1908	(7)	Jan. 2, 1903	(7)
Dec. 28, 1909	(36)	Feb. 7, 1903	(9)
Jan. 1, 1912	(9)	Jan. 6, 1907	(12)
Jan. 4, 1914	(5)	Jan. 25, 1907	(12)
Jan. 19, 1914	(10)	Jan. 5, 1909	(32)
Dec. 26, 1915	(37)	Jan. 3, 1911	(37)
Feb. 11, 1918	(7)	Jan. 1, 1913	(16)
Jan. 8, 1920	(22)	Jan. 9, 1915	(6)
Feb. 4, 1922	(25)	Jan. 18, 1915	(8)
Jan. 30, 1924	(19)	Jan. 29, 1915	(22)
Dec. 31, 1929	(6)	Jan. 14, 1917	(6)
Jan. 25, 1930	(20)	Jan. 2, 1921	(24)
Jan. 9, 1932	(7)	Feb. 10, 1921	(5)
Jan. 9, 1934	(8)	Jan. 9, 1923	(19)
Feb. 1, 1936	(7)	Feb. 12, 1923	(12)
Jan. 21, 1938	(25)	Jan. 9, 1925	(13)
		Feb. 7, 1925	(13)
		Feb. 21, 1929	(5)
		Jan. 11, 1933	(20)
		Feb. 22, 1933	(24)
		Jan. 6, 1935	(15)
		Feb. 24, 1935	(10)
		Jan. 6, 1937	(13)
		Jan. 23, 1937	(26)

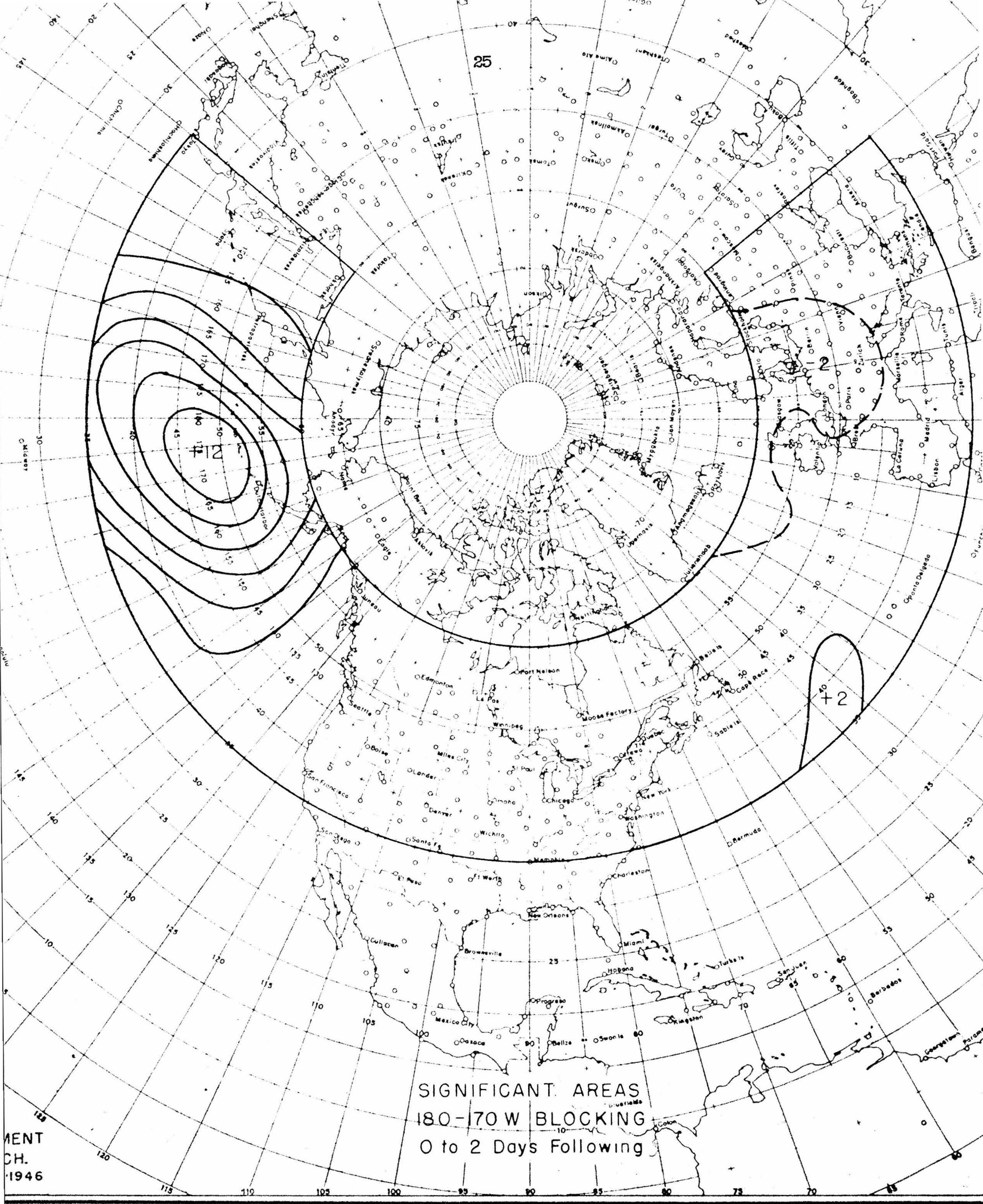

25
+12
-2
+2
SIGNIFICANT AREAS
180-170 W BLOCKING
0 to 2 Days Following
MENT
CH.
1946

Fig. XI

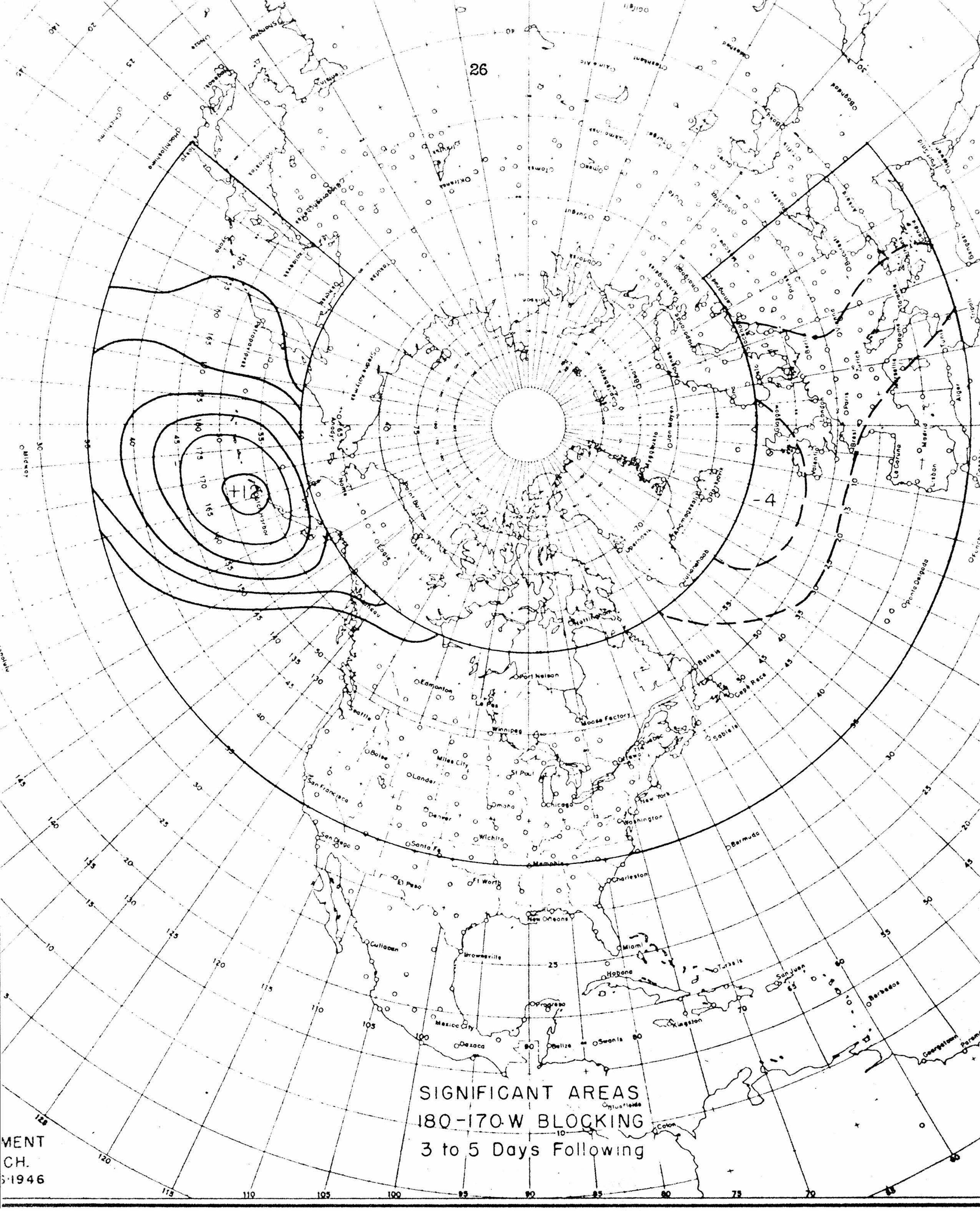
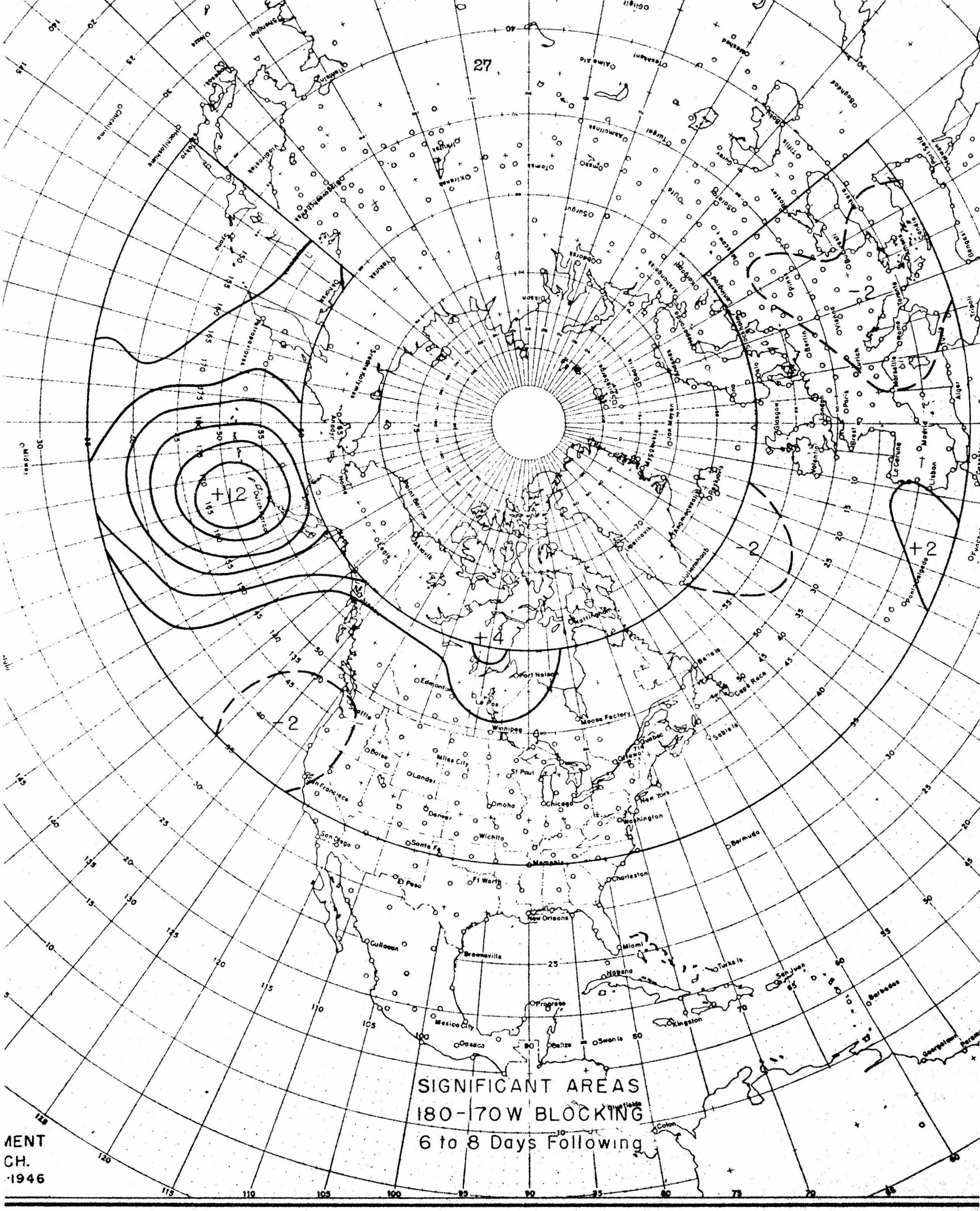

SIGNIFICANT AREAS
180-170 W BLOCKING
3 to 5 Days Following
+12
-4
MENT
CH.
1946

Fig. XII



27
SIGNIFICANT AREAS
180-170 W BLOCKING
6 to 8 Days Following

Fig. XIII

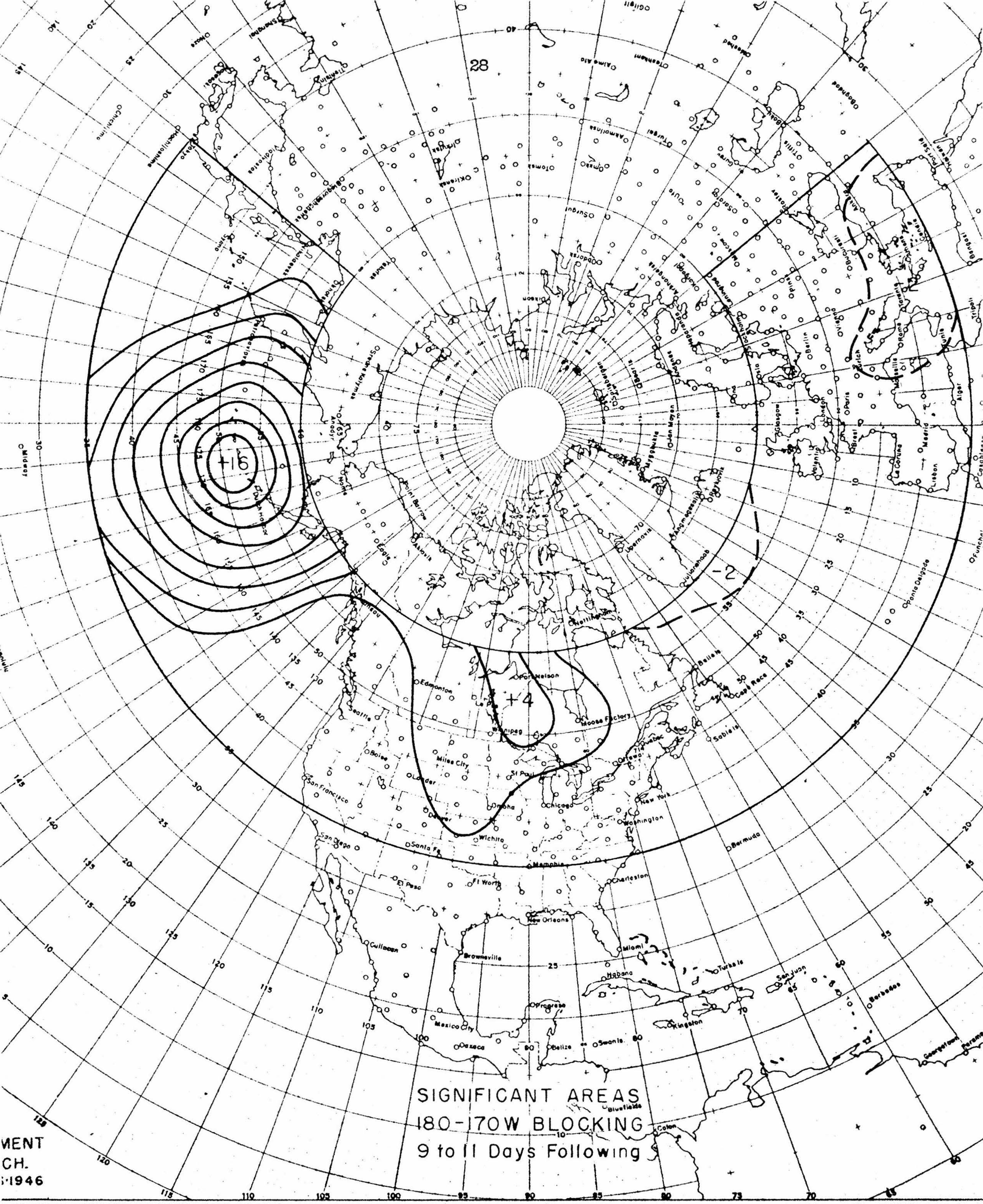

28
+16
+4
-2
SIGNIFICANT AREAS
180-170W BLOCKING
9 to 11 Days Following

Fig. XIV

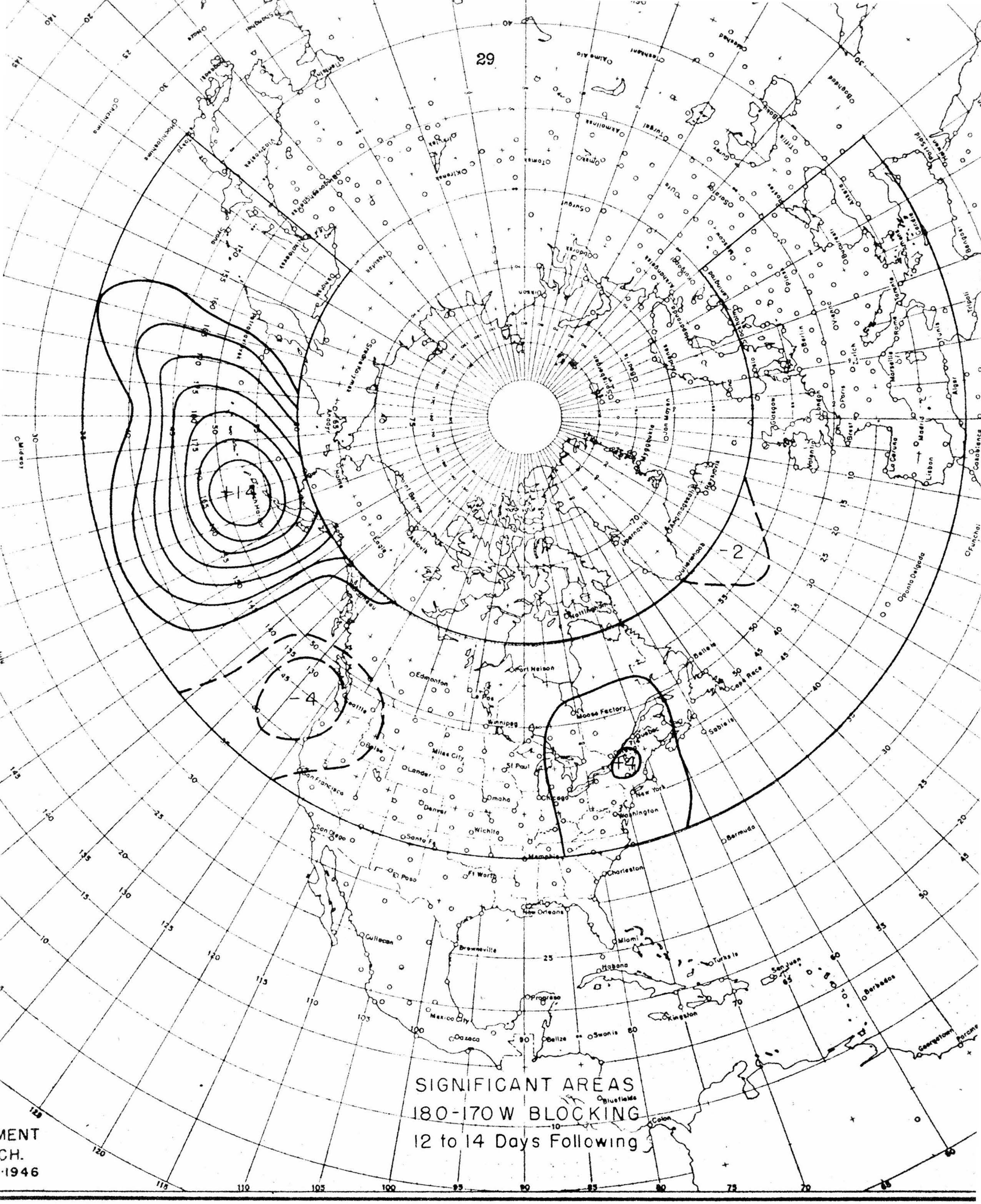

SIGNIFICANT AREAS
180-170 W BLOCKING
12 to 14 Days Following
+14
-4
-2

Fig. XV

for this pattern is about 100^{o}. While the pressure abnormalities observed are not large, account should be taken of the extreme weakness of the objective criterion. Larger deviations could be produced with a more rigid definition.

An independent illustration of this process occurred in March-April 1948. Beginning about March 8 pressures in the critical area ranged generally above normal and the wave pattern downstream resembled the pressure departure pattern shown with the principal differences occurring following marked pressure fluctuations in the controlling area. Beginning the latter part of March and continuing through the middle of April, pressures in the critical area were well and consistently above normal. During this period the above pressure departure pattern was followed closely, breaking down only following the breakdown of the Pacific blocking High.

Examples of Stable Wave Patterns

The development of three types of stable wave patterns is shown in Fig. XVI through XXX. These examples were chosen by a consideration of the tracks of positive pressure anomalies in the Atlantic area. The criteria for selection of these examples are as follows: only anomalous areas containing a center of plus 10 mbs. or more were considered. Upon charting the tracks of these centers they are occasionally observed to have no appreciable eastward movement for a period of three days or more. These are the cases treated in Figs. XVI through XXX with a separation being made on the basis of

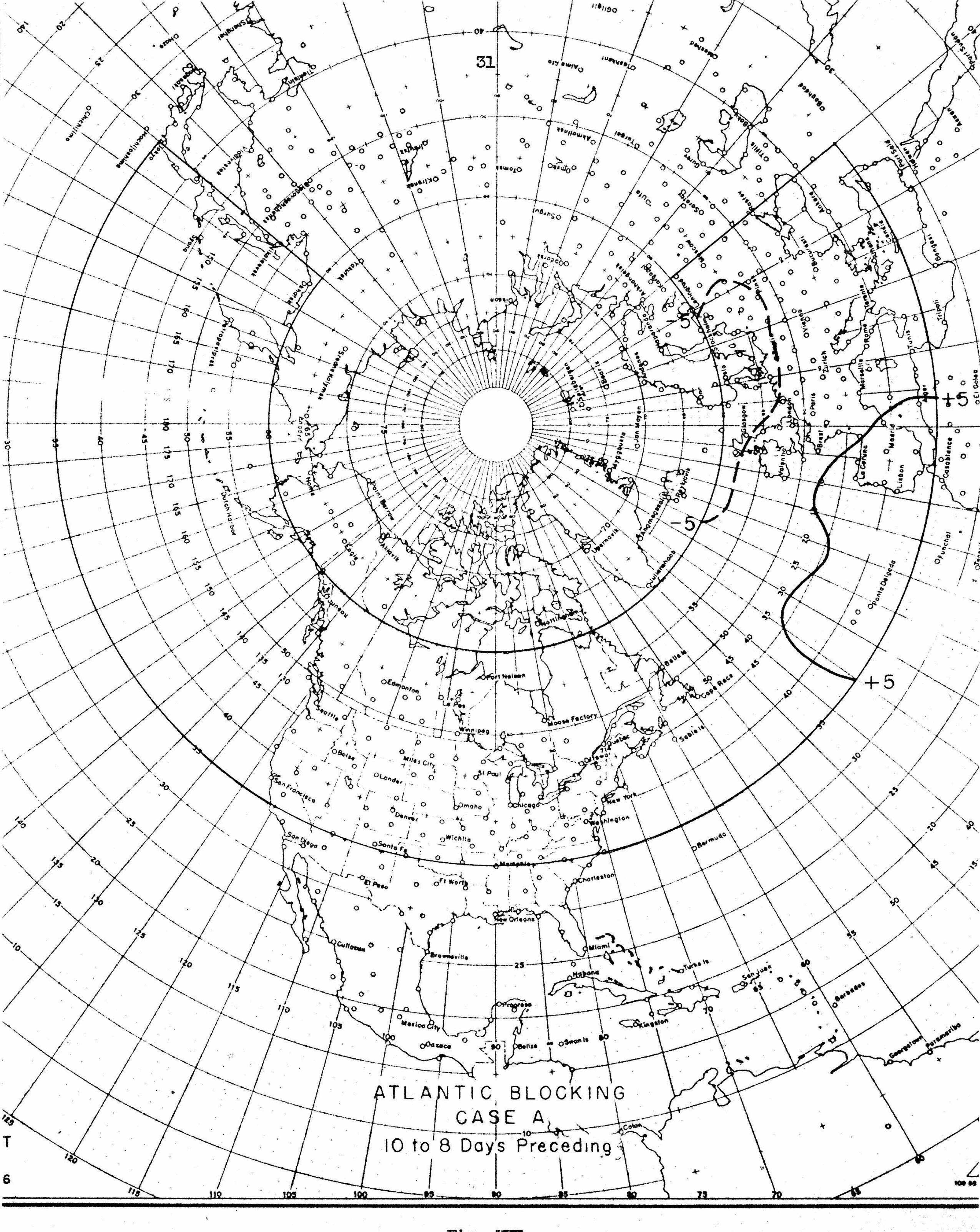


Fig. XVI

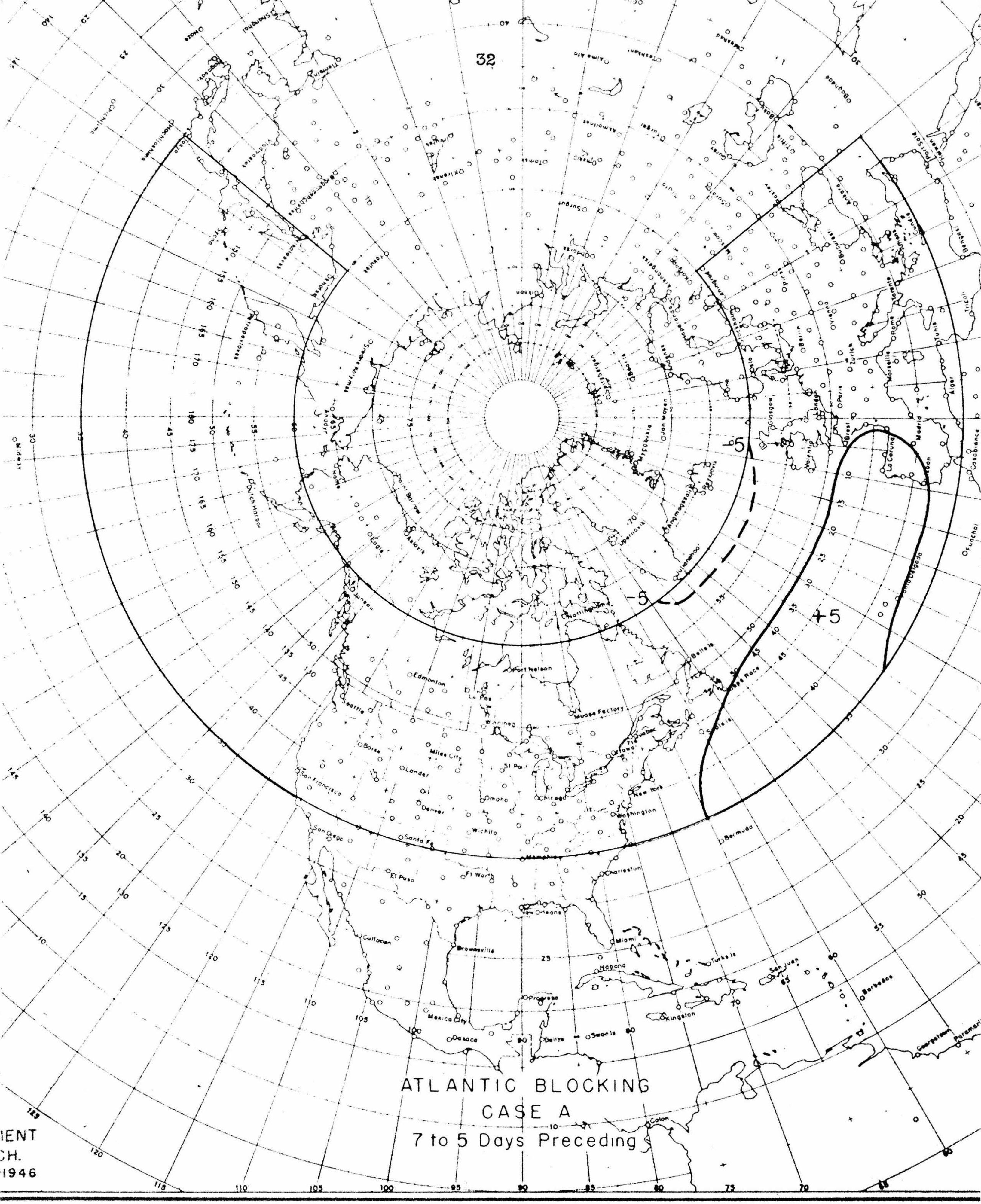
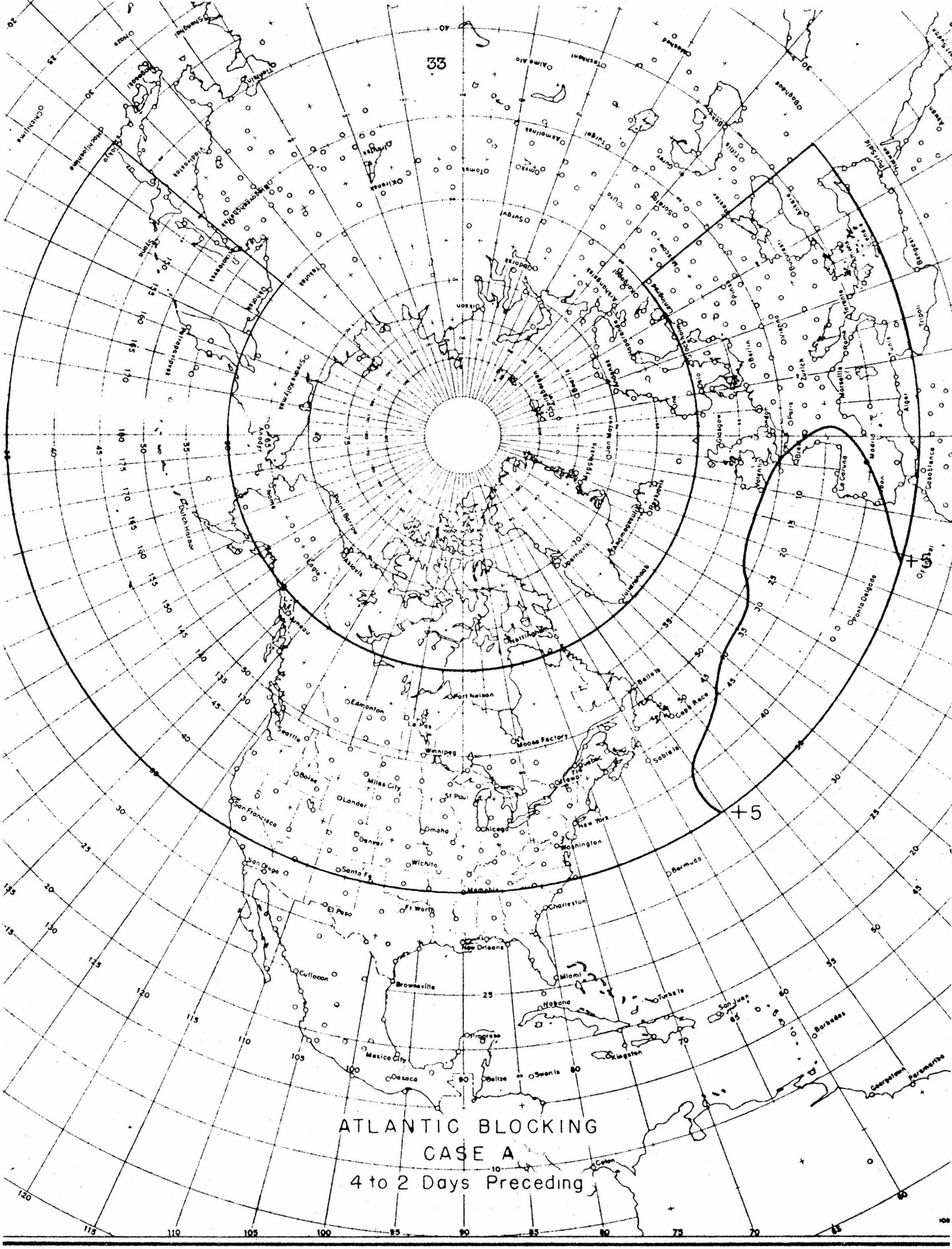


Fig. XVII



ATLANTIC BLOCKING
CASE A
4 to 2 Days Preceding
+5
Edmonton
Fort Nelson
Le Pas
Winnipeg
Moose Factory
Seattle
Boise
Miles City
Lander
St Paul
San Francisco
Denver
Omaha
Chicago
New York
Washington
San Diego
Santa Fe
Wichita
Memphis
Bermuda
El Paso
Ft Worth
Charleston
New Orleans
Miami
Brownsville
Culiacan
Habana
Turks Is
San Juan
Barbados
Progreso
Kingston
Mexico City
Oaxaca
Belize
Swan Is
Colon
Georgetown
Paramaribo
Sable Is
Cape Race
Belle Is
Nottingham
Juneau
Dutch Harbor
Nome
Point Barrow
Aklavik
Eagle
Julianehaab
Angmagssalik
Reykjavik
Jan Mayen
Ponta Delgada
Lisbon
Madrid
La Coruna
Casablanca
Alger
Tripoli
Tunis
Rome
Marseille
Zurich
Paris
London
Glasgow
Valentia
Brest
Berlin
Oslo
Stockholm
Leningrad
Arkhangelsk
Yakutsk
Anadyr
Omsk
Tomsk
Turgai
Tashkent
Alma Ata
Baghdad
Vladivostok
Okhotsk
Petropavlovsk
Irkutsk

Fig. XVIII

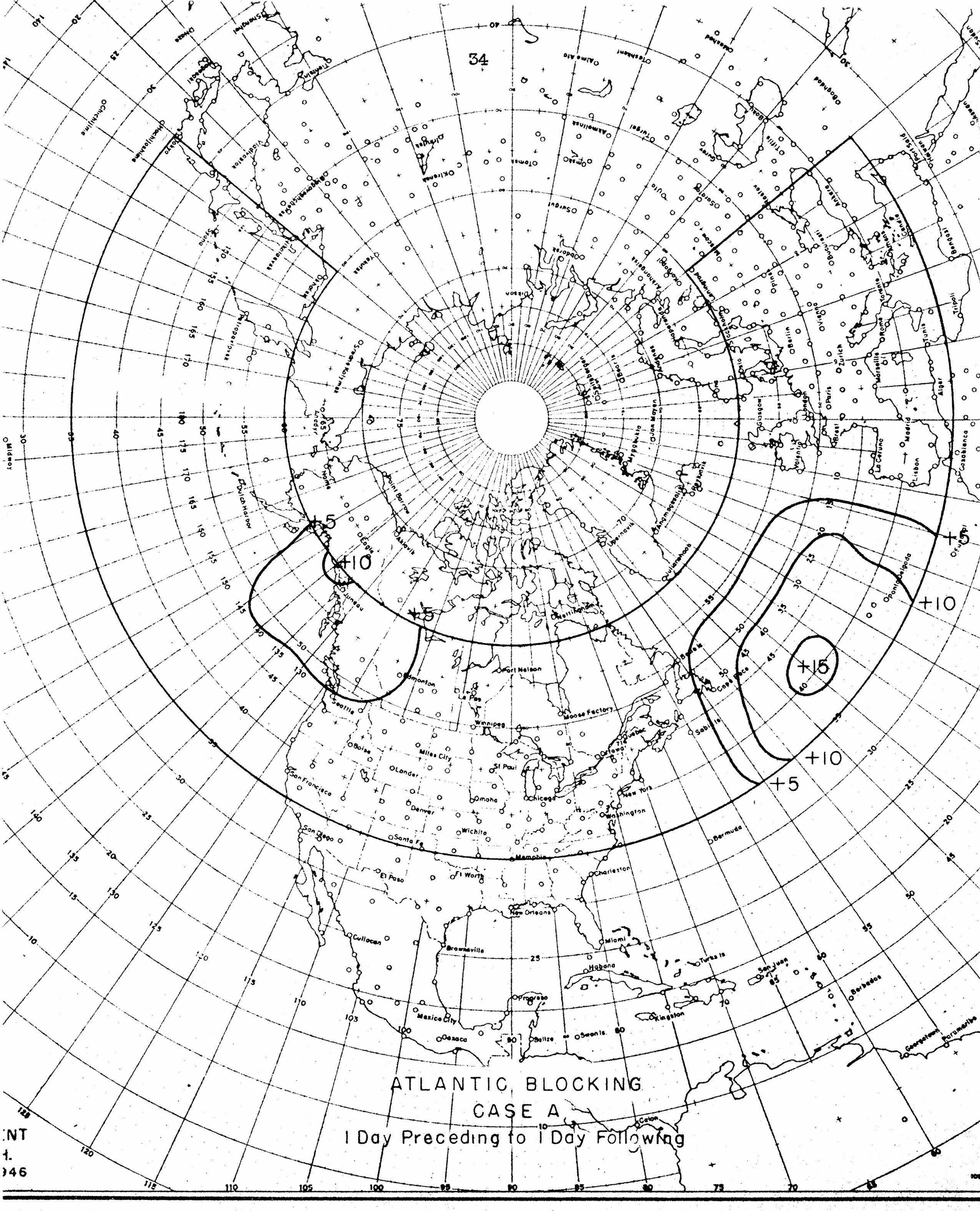

ATLANTIC BLOCKING
CASE A
1 Day Preceding to 1 Day Following
+5
+10
+15

Fig. XIX

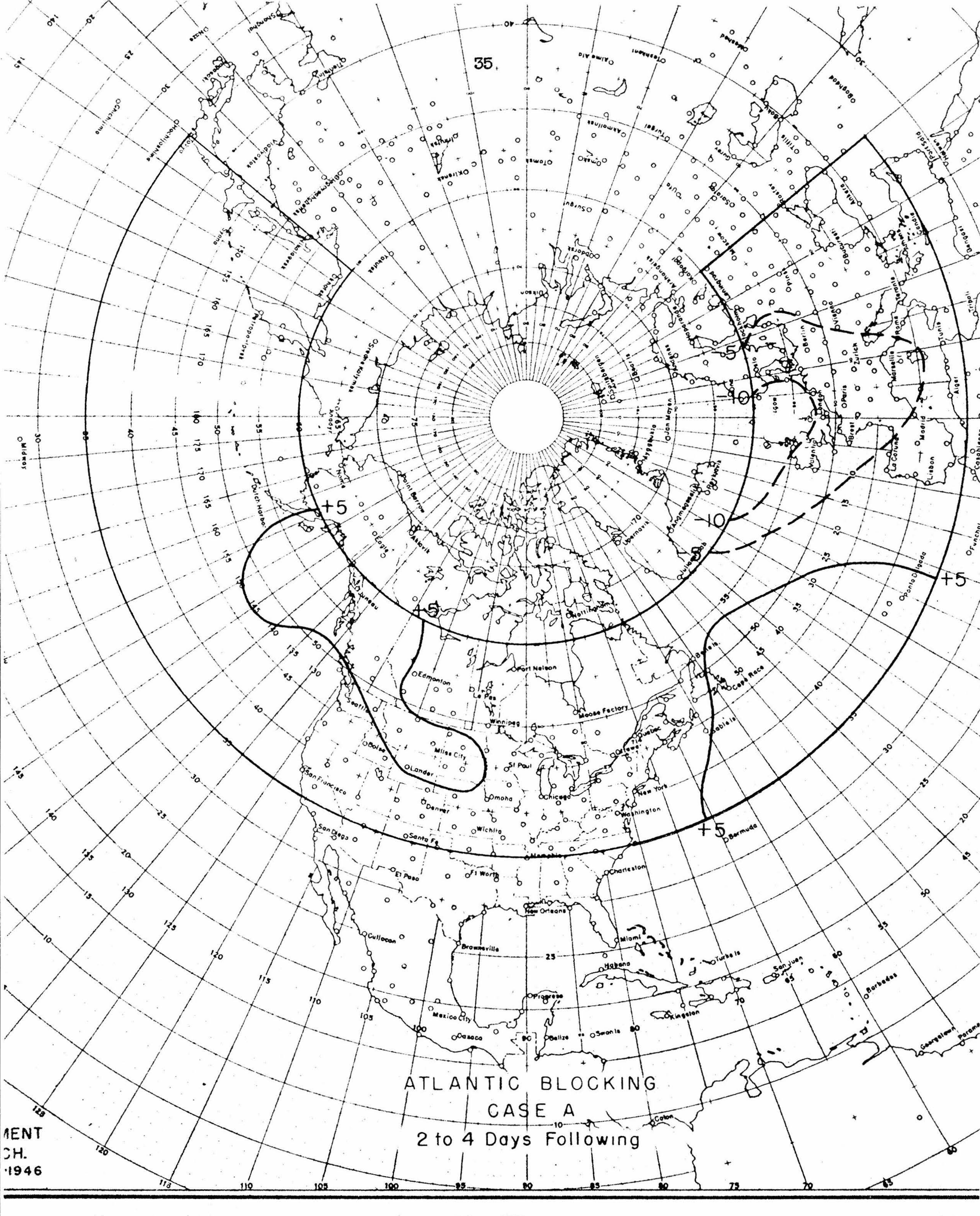

ATLANTIC BLOCKING
CASE A
2 to 4 Days Following
+5
-5
-10
-10
+5
+5
+5
35
MENT
CH.
1946

Fig. XX

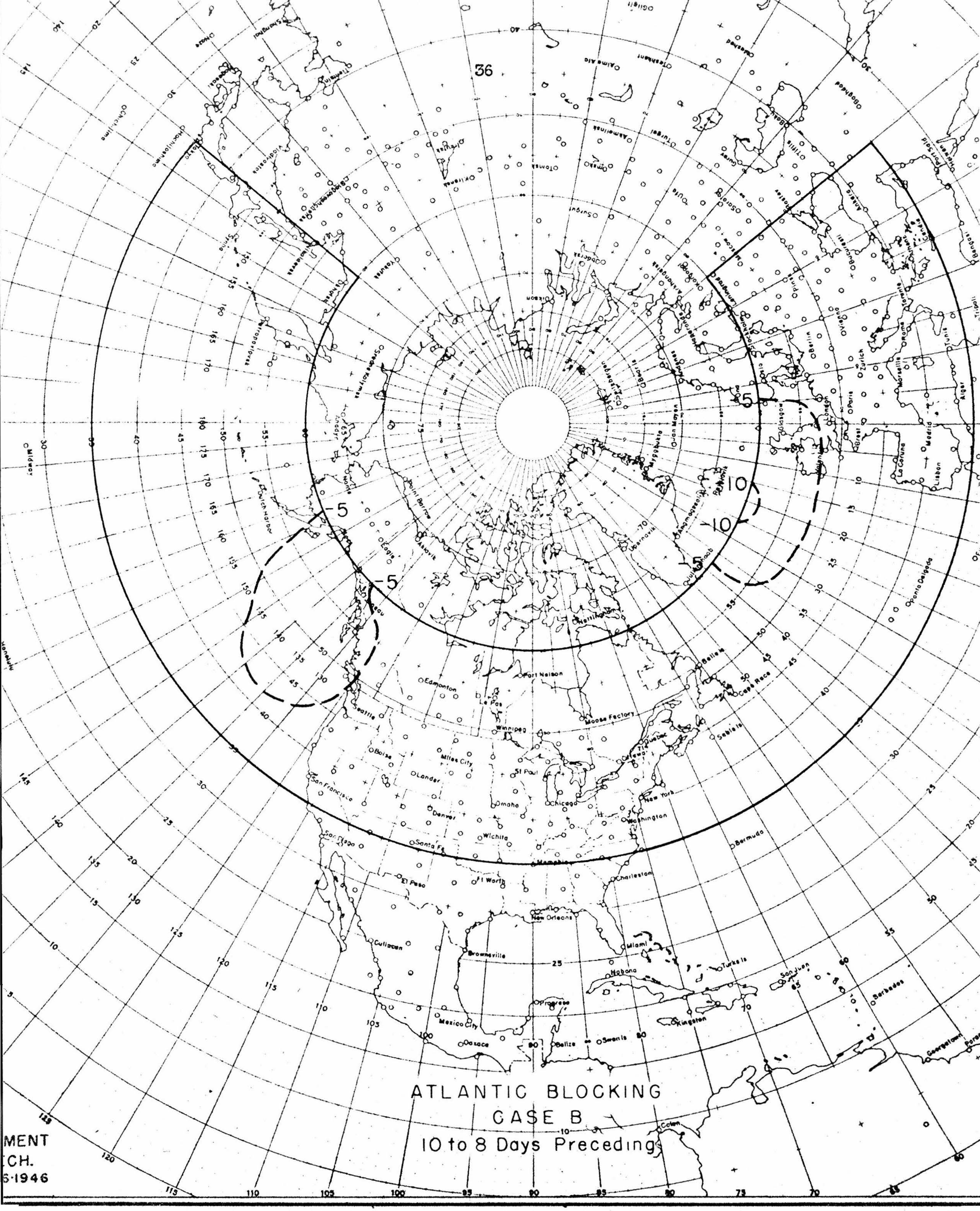
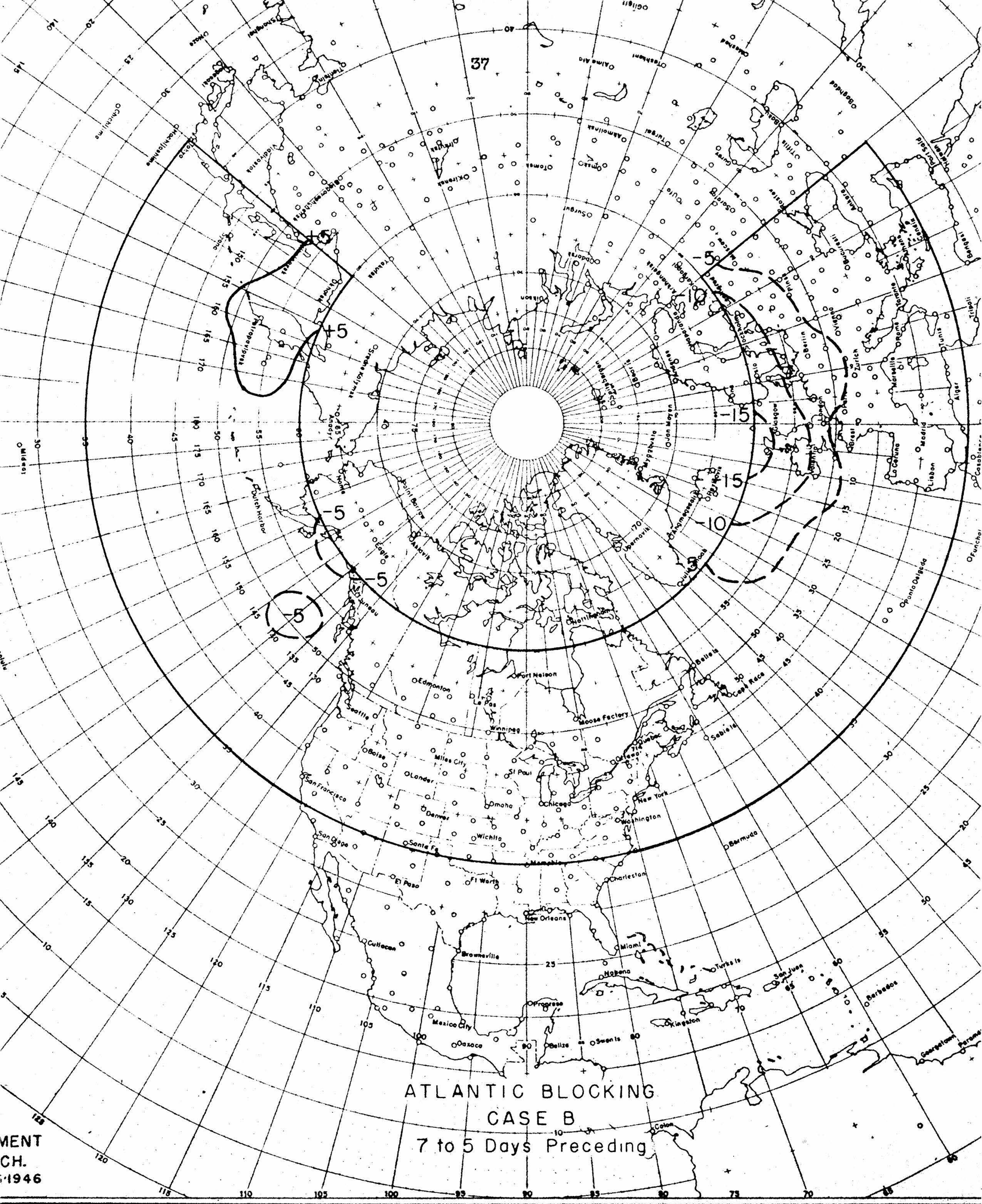

ATLANTIC BLOCKING
CASE B
10 to 8 Days Preceding
MENT
CH.
6-1946

Fig. XXI



37
ATLANTIC BLOCKING
CASE B
7 to 5 Days Preceding
MENT
CH.
-1946
+5
-5
-10
-15
Edmonton
Port Nelson
Winnipeg
Moose Factory
Seattle
Boise
Miles City
Lander
St Paul
San Francisco
Omaha
Chicago
Denver
New York
Washington
Wichita
San Diego
Santa Fe
Memphis
Bermuda
Charleston
El Paso
Ft Worth
New Orleans
Culiacan
Brownsville
Miami
Habana
Turks Is
San Juan
Barbados
Progreso
Kingston
Mexico City
Oaxaca
Belize
Swan Is
Georgetown
Colon
Sable Is
Cape Race
Belle Is
Juneau
Edmonton
Lisbon
Madrid
Berlin
Zurich
Marseille
Alger
Tunis
Ponta Delgada
Funchal

Fig. XXII

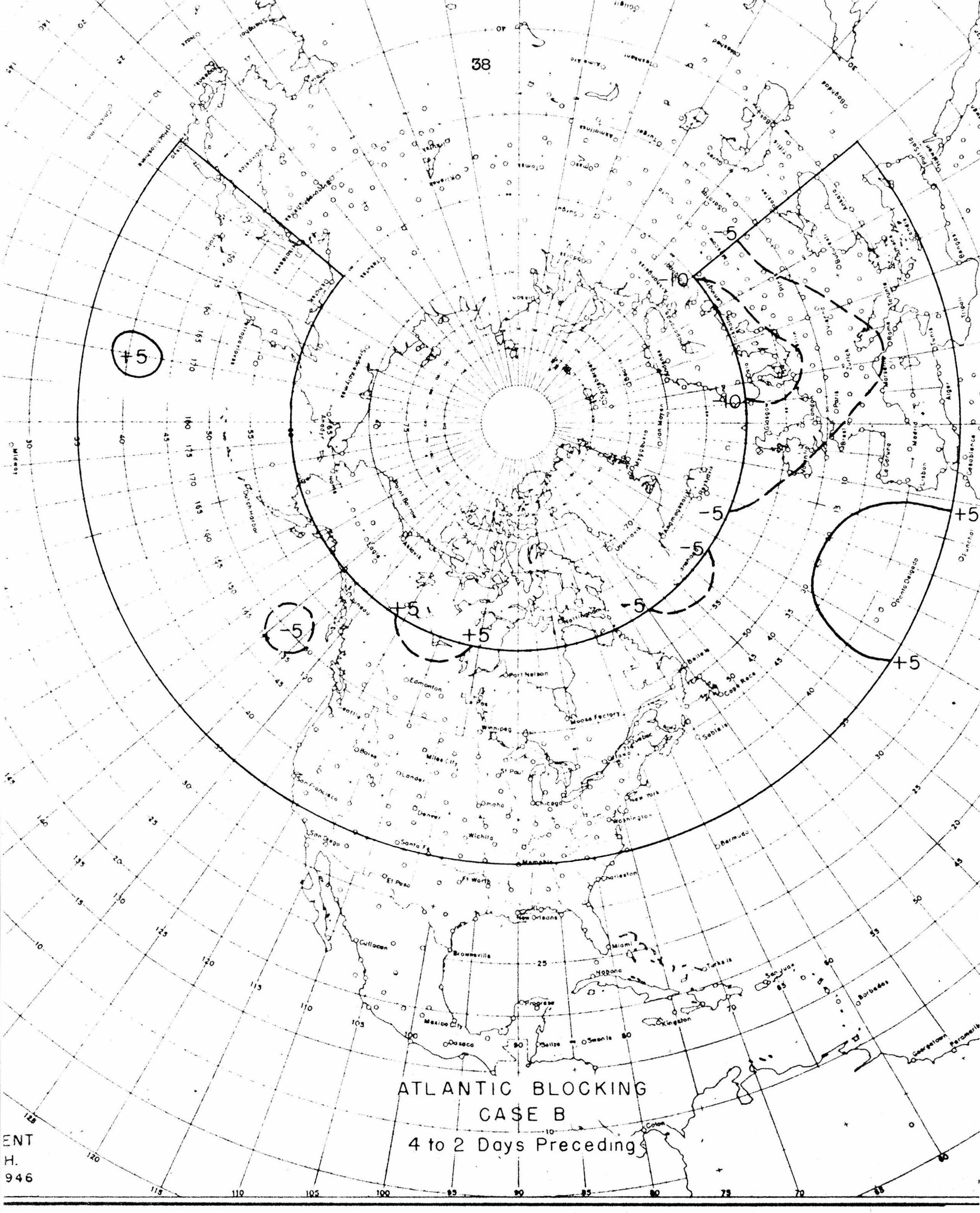


Fig. XXIII

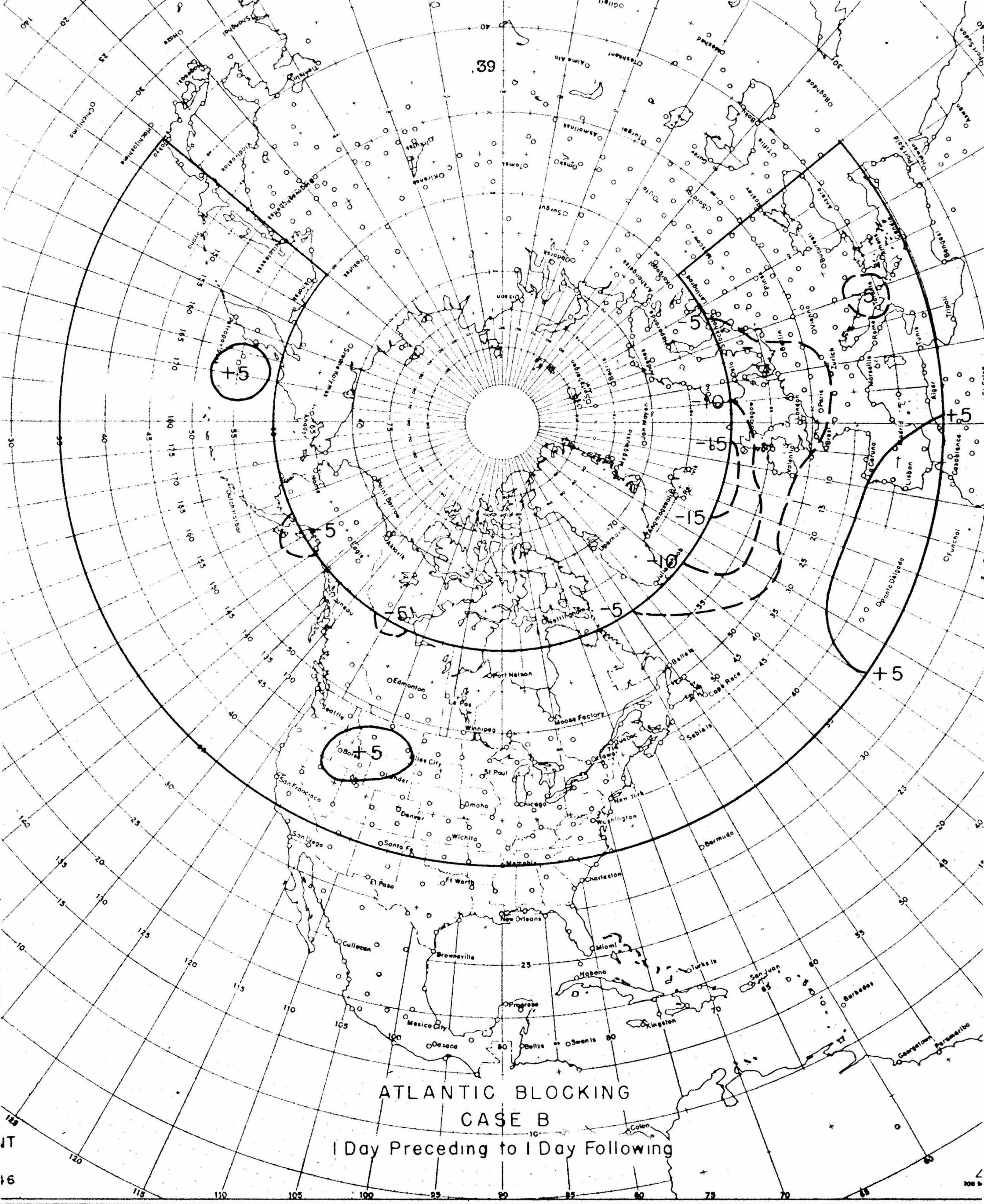

ATLANTIC BLOCKING
CASE B
I Day Preceding to I Day Following
+5
-5
-10
-15

Fig. XXIV

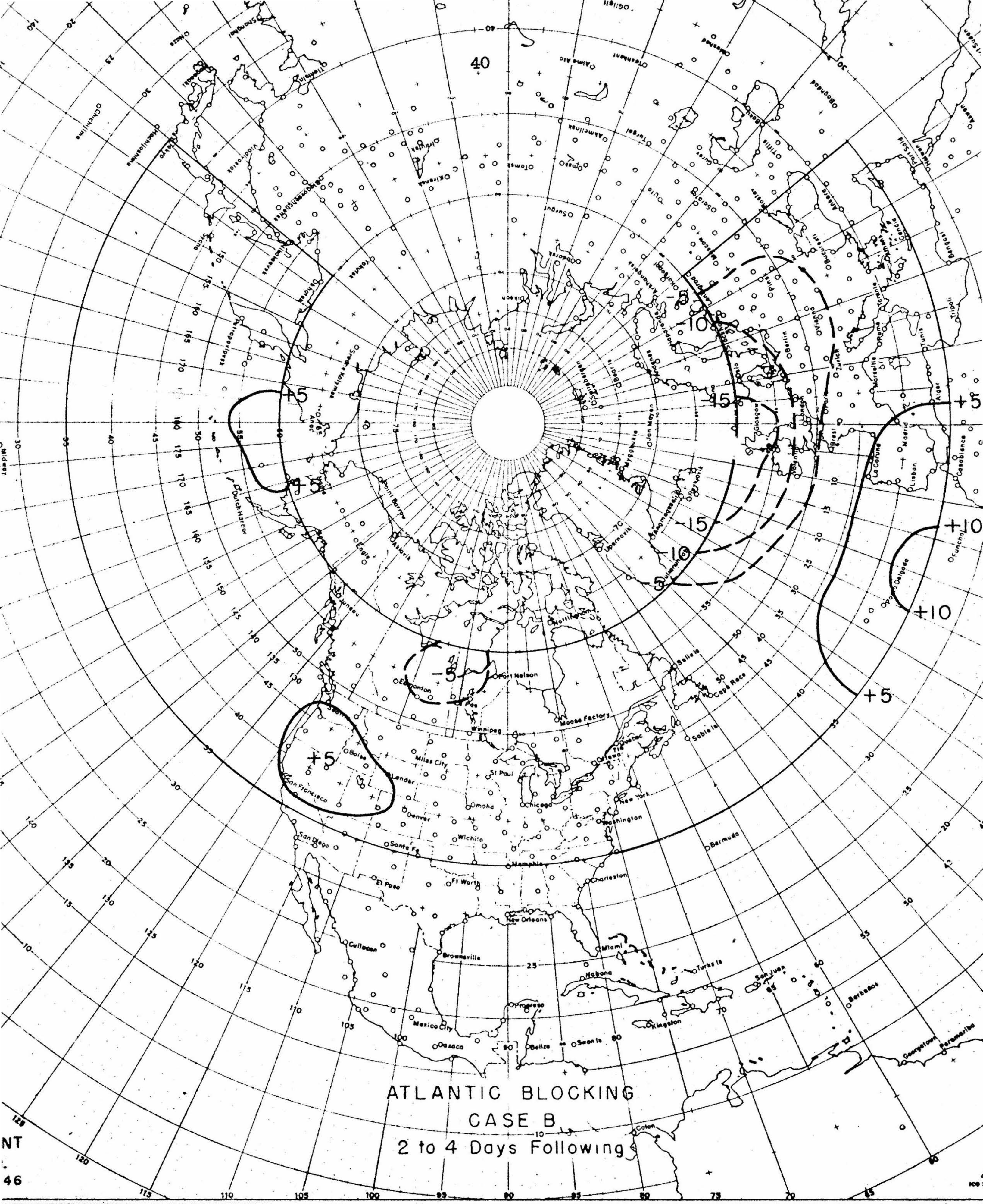


Fig. XXV

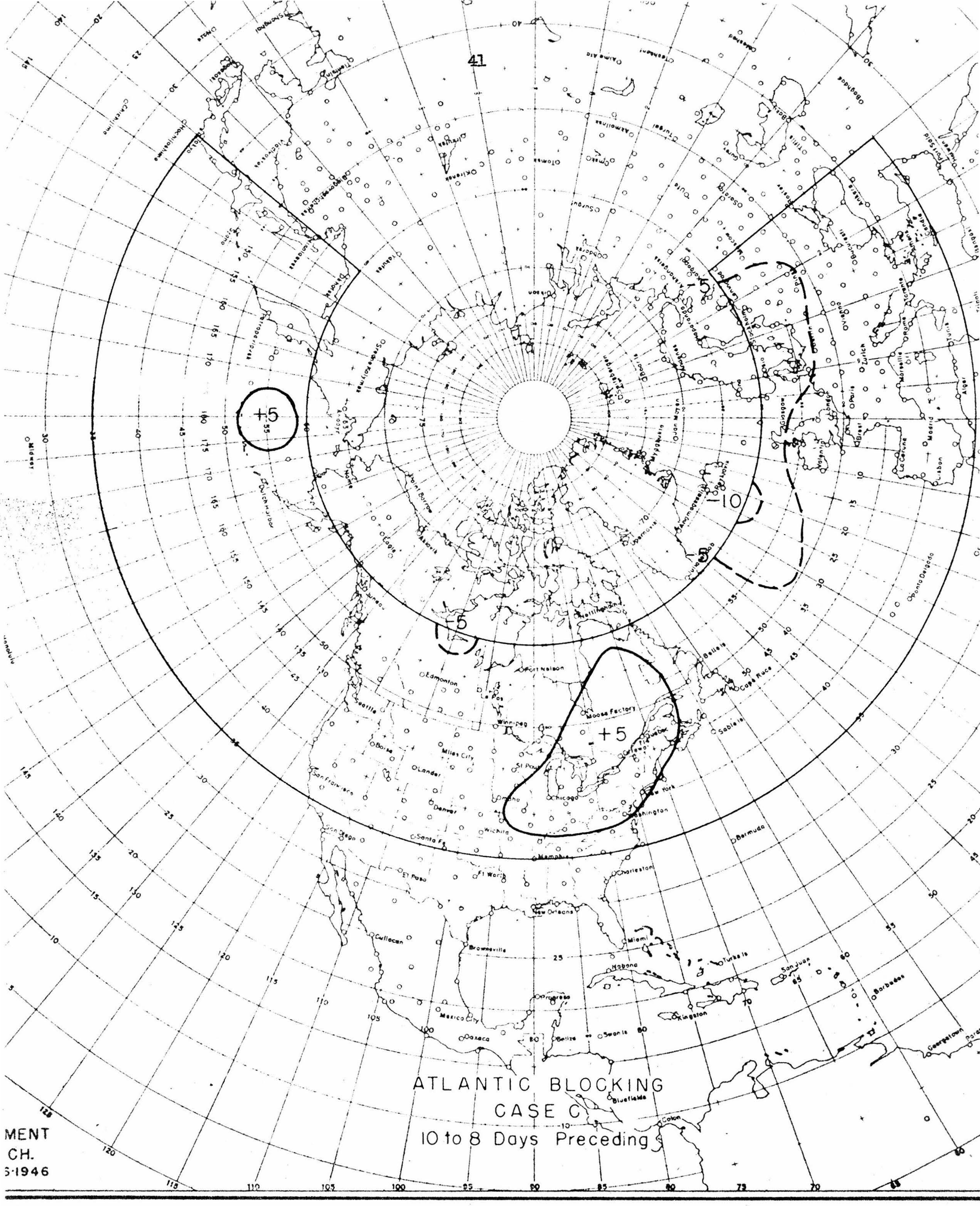

ATLANTIC BLOCKING
CASE C
10 to 8 Days Preceding
+5
+5
-5
-5
-10
-5
MENT
CH.
Edmonton
Seattle
San Francisco
Denver
Winnipeg
Moose Factory
Chicago
New York
Washington
Memphis
New Orleans
Miami
Bermuda
Habana
Kingston
Mexico City
Brownsville
El Paso
London
Paris
Madrid
Lisbon
Brest
Zurich
Nome
Point Barrow
Fort Nelson

Fig. XXVI

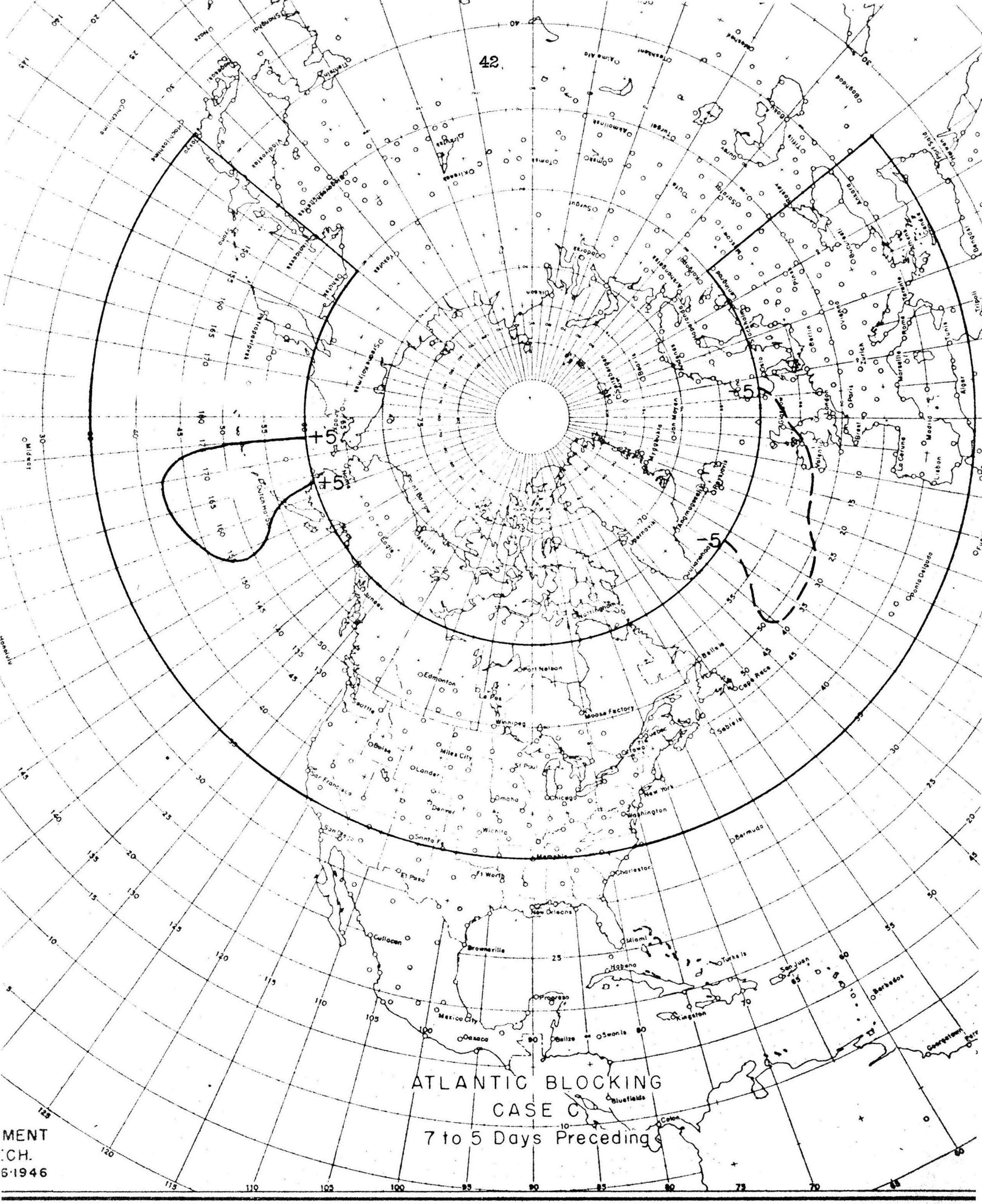

ATLANTIC BLOCKING
CASE C
7 to 5 Days Preceding
+5
+5
+5
-5
MENT
CH.
6·1946
Edmonton
Winnipeg
Seattle
San Francisco
Denver
Omaha
Chicago
New York
Washington
Bermuda
Charleston
Memphis
New Orleans
Miami
Brownsville
Habana
Kingston
Mexico City
Oaxaca
Belize
Bluefields
Colon
Barbados
San Juan
Cape Race
Sable Is
Moose Factory
Port Nelson
Juneau
Nome
Berlin
Paris
London
Rome
Madrid
Lisbon
Algier
Tunis
Ponta Delgada
Valentia
Brest
La Coruna
Marseille
Zurich

Fig. XXVII

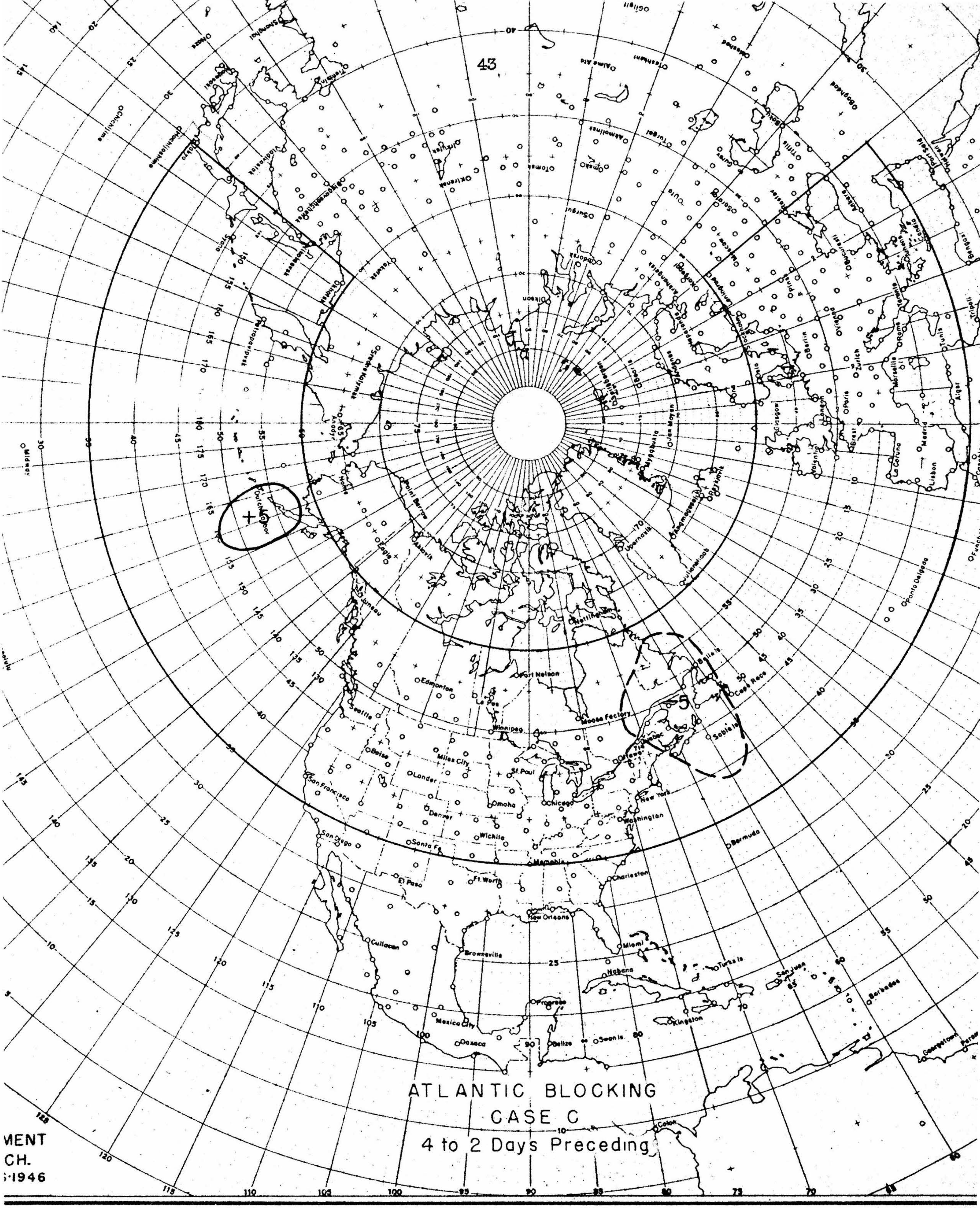

ATLANTIC BLOCKING
CASE C
4 to 2 Days Preceding
MENT
CH.
-1946
43

Fig. XXVIII

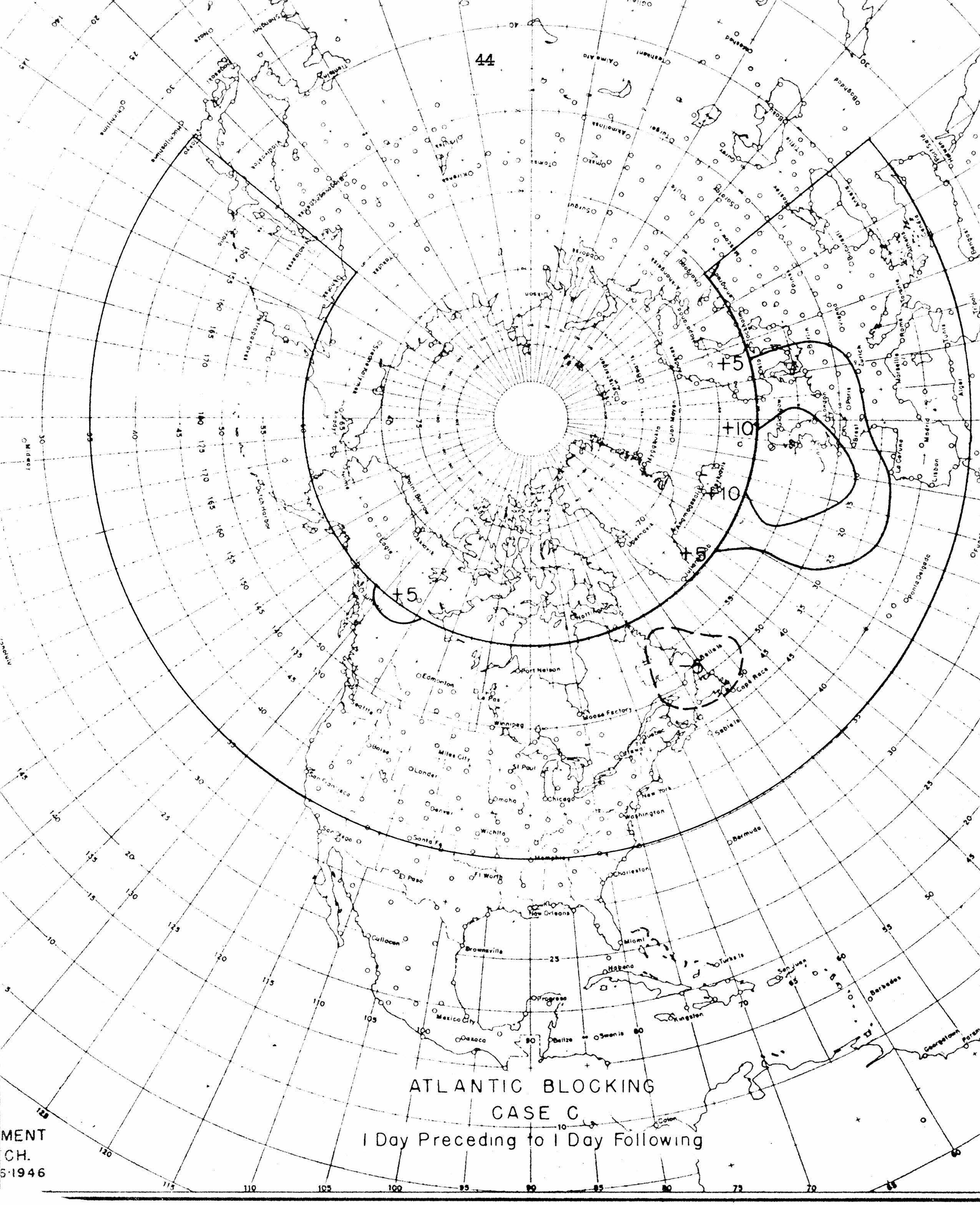

ATLANTIC BLOCKING
CASE C
I Day Preceding to I Day Following
+5
+10
+10
+5
+5
MENT
CH.
5·1946

Fig. XXIX

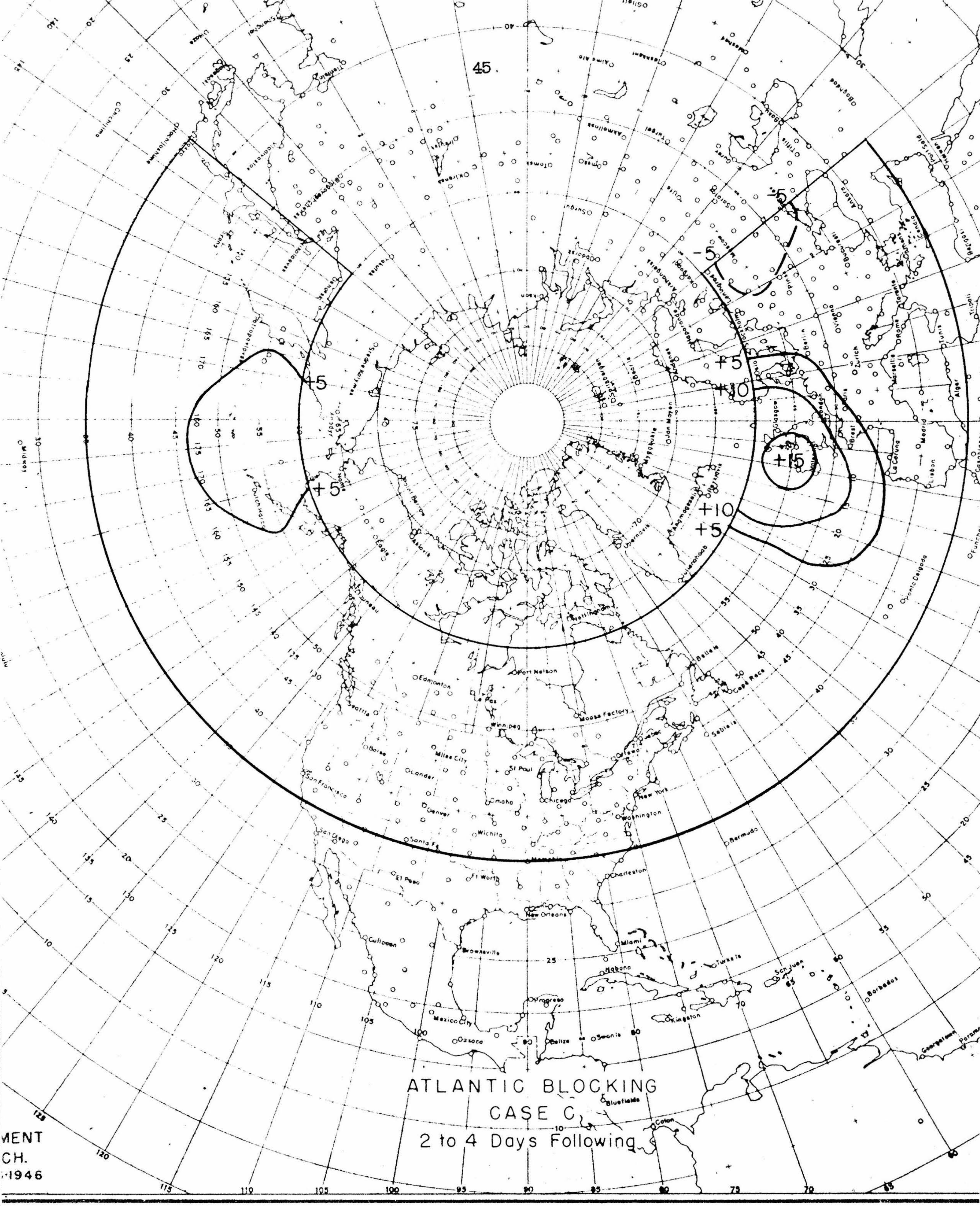

ATLANTIC BLOCKING
CASE C
2 to 4 Days Following
+5
+10
+15
-5
MENT
CH.
-1946

Fig. XXX

the area in which the moving anomaly center stopped. Zero day is determined by the first day during which the center had no appreciable movement to the east. Cases A, B and C represent averages of sixteen, nine and twelve examples respectively.

Each case is seen to have at least one stable wave crest upstream. For Case A the wave length is 100°, for Case B 90° and for Case C about 170° although for this case this may be a multiple of the basic stable wave.

It is difficult to interpret Figs. XVI through XXX in terms of a downstream or an upstream effect. In Cases A and B the formation of the two pressure crests appears to be almost simultaneous. No further attempt will be made to delineate these effects. For the purposes of this investigation Figs. XVI through XXX represent examples of stable wave patterns.

Such stable wave patterns have been studied by numerous investigators. Rossby (4) and co-workers have pointed out that under the assumption of small horizontal divergence, the wave length of stable long waves in the atmosphere should be given by:

$$L^2 = \frac{4U\pi^2}{\beta}$$

where L is the wave length, U the zonal wind speed and β the northward rate of change of the Coriolis parameter. In a recent paper Cressman (5) has investigated a number of properties of these long waves. He has found an average wave length of about seventy-eight degrees of longitude for the stationary waves on the basis of upper level flow patterns. The stationary wave lengths found in the study of Blocking Action processes are considerably longer, being of the order of ninety to one hundred degrees of longitude. These Blocking Action processes are normally associated with closed cyclonic and anticyclonic centers in the upper level flow pattern and as Cressman has pointed out, this characteristic makes the use of the above formula questionable due to the difficulty in the determination of the mean zonal wind speed U. Cressman himself has eliminated these upper level flow patterns from his study so that no conflict exists between the two investigations. The larger amplitude, more extreme stable waves in the atmosphere are apparently characterized by longer wave lengths than the less disturbed stationary stable waves.

Energy Propagation in the Atmosphere

The problem of the rate of propagation of energy in atmospheric waves has recently come into considerable prominence due to the work of Rossby (6) and others. Some information on this subject can be gained from the preceding discussions of Blocking Action processes by considering the intrusion of a blocking High into the normal westerly circulation as an energy source. The use of three day mean maps and the consequent elimination of the smaller scale pressure fluctuations serves also to eliminate most of the effects of propagation of energy downstream at a speed greater than that of the wave velocity such as are hypothesized by Rossby. The three day mean maps then show the propagation of energy with the speed of the waves associated with the Blocking Action processes.

This is most clearly shown in Figs. XI to XV for the mid-Pacific blocking case where the disturbance reaches the north-eastern Canadian area twelve to fourteen days after the inception of the disturbance in the Pacific. This is a distance of about one hundred degrees of longitude traveled at the latitude of about 60° N so that its velocity is apparently less than the mean zonal flow. The High Latitude Atlantic blocking case is less clearly defined since the low pressure forming in the Pacific twelve to fourteen days following inception is assumed to be a secondary effect of the production of high pressure in Alaska at latitudes outside of the network of data. However, the rate of downstream propagation is comparable to the Pacific example when consideration is given to the more northerly latitude traversed through Siberia and Alaska.

The introduction of a disturbance of the form shown in the Hudson Bay area of Fig. XIV has been studied in more detail. The area considered was bounded by longitudes 90° and 100° W and by latitudes 55° and 60° N. Days were selected for investigation on which an average pressure departure of 7.5 mbs. above normal for the four corners of the area was first realized. The effect of this relatively weak disturbance on the pressure patterns in the Atlantic area has been studied by a consideration of the total disturbed state of the sector bounded by 50° W to 40° E longitudes and 35° N to 60° N latitudes. A measure of the magnitude of this disturbed state, representing a measure of the turbulent energy in the sector, is given by the standard deviation from the mean of all the pressure departures within the sector. Thus the largest standard deviation is produced by the simultaneous occurrence of large positive and negative variations from the normal pressure field of the sector. The average standard deviation in mbs. for the sector for a total of twenty-nine examples is shown below as a function of the number of days following the introduction of the disturbance:

0 days	1 day	2 days	3 days	4 days	5 days	6 days	7 days
10.69	11.43	11.75	11.51	11.45	11.49	10.88	10.44

where the average standard deviation for the sector over a long period of time is 11.00 mbs. These examples were taken regardless of pressure pattern on which the disturbances were superimposed. The maximum effect is observed two days following the introduction of the disturbance. By this time the effect of the disturbance has apparently been diffused throughout the entire area although the sector remains considerably disturbed for the following three days decreasing rather rapidly six and seven days following the introduction of the disturbance. From the standpoint of energy propagation the rapid increase in the disturbed state from zero to two days must be taken as an effect of energy propagated faster than the zonal flow while the maintenance of the highly disturbed state from three to five days may be explained on the basis of inertial effects or by the slower rate of energy propagation moving with velocities less than or equal to the zonal flow.

The effects of a generally disturbed pressure field in the North American sector bounded by 60° W and 130° W longitudes and by 35° N and 60° N latitudes have also been considered. The standard deviations characteristic of this sector have been correlated with those of the aforementioned Atlantic sector for two separate January-February "seasons." These are shown below as correlation coefficients with zero, one or two day lags, the lag corresponding to the North American sector value occurring first. (See Appendix B).

	0 lag	1 day lag	2 day lag
1914	.339	.485	.325
1938	.038	.016	----

In the 1914 case, comparison with the results of the preceding paragraph shows that the maximum correlation between sectors now exists for a one day lag or the disturbances in the North American sector producing their maximum effect one day later in the Atlantic sector. This may be explained on the basis of an overweighting in favor of those disturbances which exist in the eastern portion of the North American sector and which will produce larger effects in the Atlantic than any existing in the central or western portion of the North American sector.

The difference between the two years 1914 and 1938 is very striking. 1938 is characterized by large distortions from the normal pressure field in the Atlantic sector brought about by long periods of Blocking Action. In 1914 however, only about five days during the two month period may be described as having any significant Blocking Action. One might infer from this that energy is not as easily propagated downstream during periods of Blocking Action although a more thorough investigation is needed to verify this point.

PART II. THE FORMATION OF THE BLOCKING ACTION EDDY

The general characteristics of the pressure field leading to the development of a blocking High in the northeastern Atlantic area are shown in Figs. XXXI to XXXVI. These figures represent the average pressure departures for the even year cases listed in Part I. The figures show clearly that the principal origin of the Blocking Action High in this region is the Atlantic sub-tropical high pressure cell and that the principal dynamic development is an abnormally high zonal flow directly to the north of the sub-tropical cell. This high zonal flow increases through the early stages of the development and is deflected gradually to a more northwesterly flow thus representing a gradual change from a strong zonal flow to a strong meridional flow. The anticyclonic deflection and the subsequent formation of the low pressure area in western Europe is explainable in a qualitative sense by the zonal flow acquiring anticyclonic vorticity in the horizontal divergent area of extreme western Europe. This is not the only means by which the blocking High may form. Another method will be discussed briefly in a later paragraph. One important fact should be pointed out in connection with this case. The start of the development takes place at least twelve to fifteen days prior to the actual formation of the high cell at high latitudes. If one attempts an explanation of the formation on the basis of extraterrestrial radiation, the change in that radiation should occur over a comparable period. This would appear to rule out such short period phenomena as solar flares, daily fluctuations in magnetic numbers, etc.

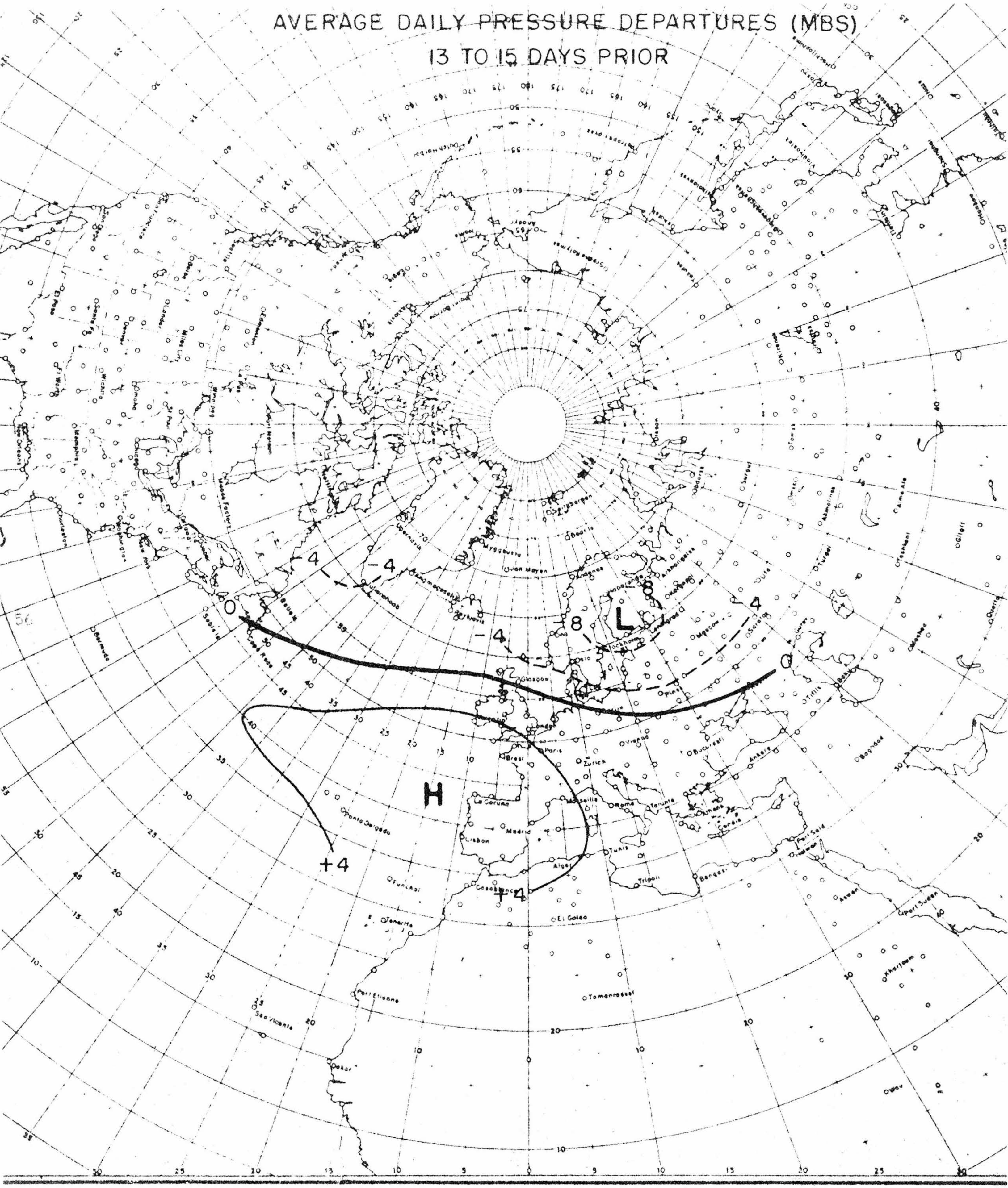

AVERAGE DAILY PRESSURE DEPARTURES (MBS)
13 TO 15 DAYS PRIOR
H
L
+4
+4
0
0
-4
-4
-4
-8
-8
4
4

Fig. XXXI

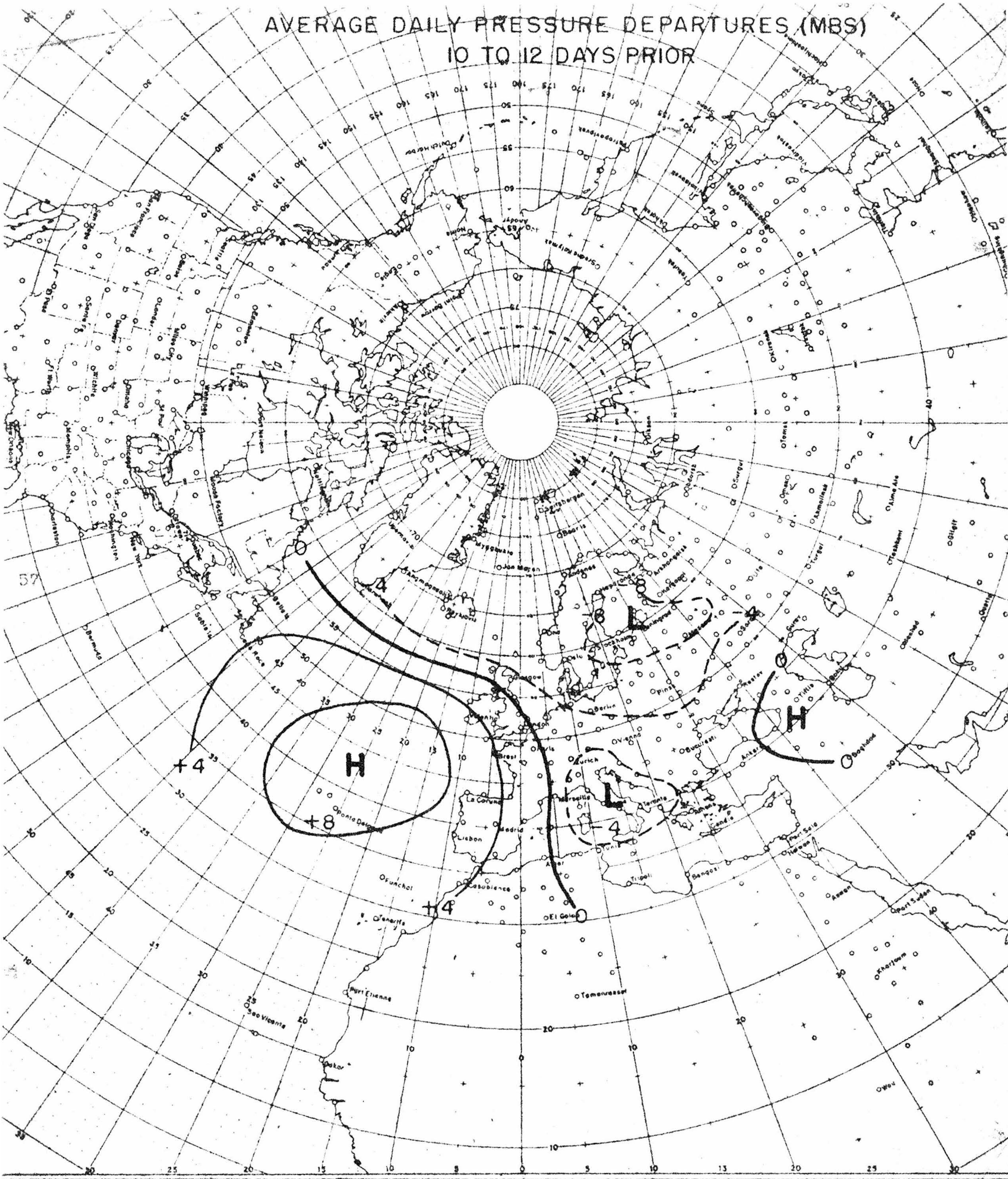

AVERAGE DAILY PRESSURE DEPARTURES (MBS)
10 TO 12 DAYS PRIOR
H
H
H
L
L
+4
+8
+4
0
0
0
-4
-4
-8
-4

Fig. XXXII

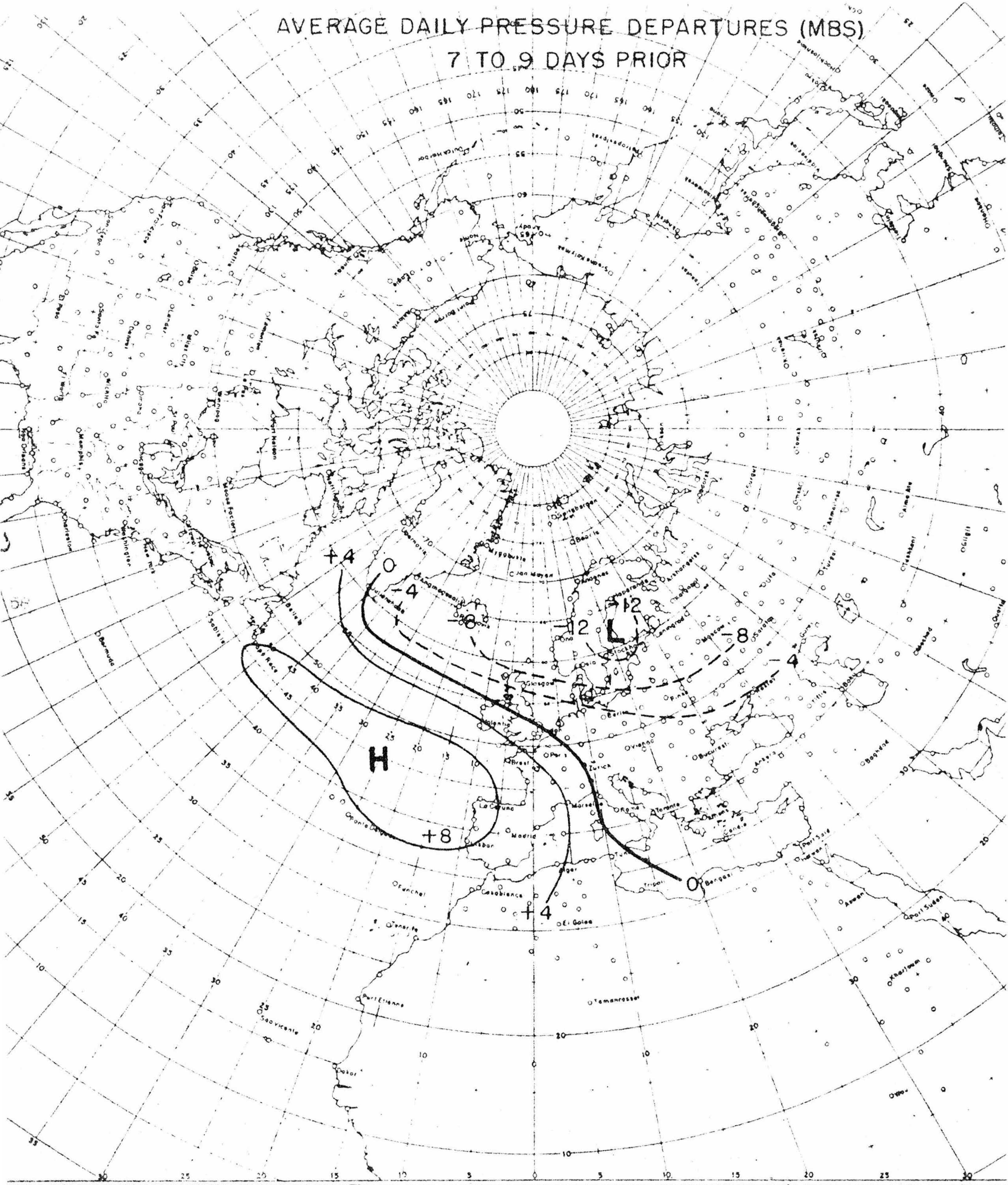

AVERAGE DAILY PRESSURE DEPARTURES (MBS)
7 TO 9 DAYS PRIOR
H
L
+8
+4
0
-4
-8
-12
+4
0
-4
-8
-12

Fig. XXXIII

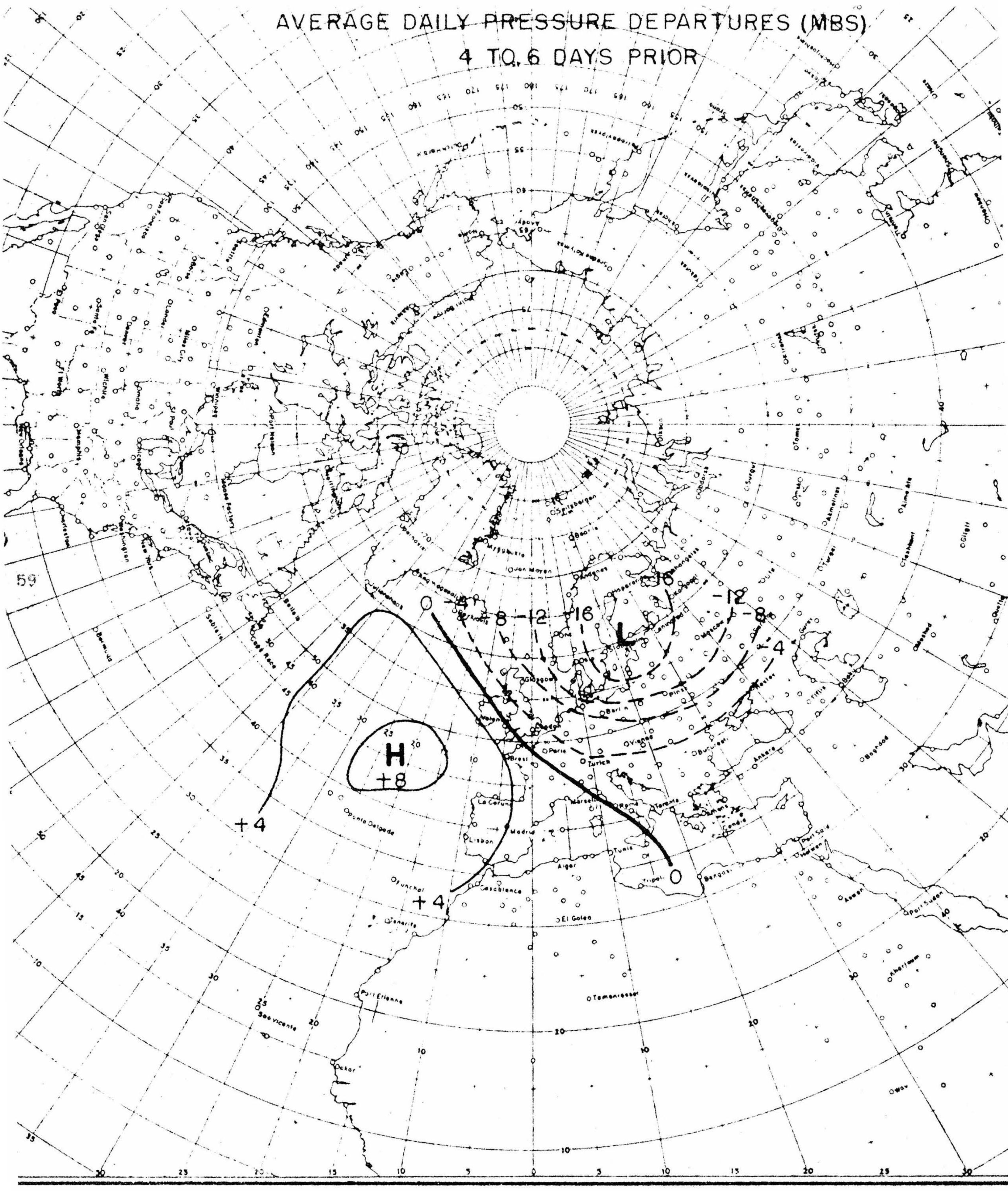

AVERAGE DAILY PRESSURE DEPARTURES (MBS)
4 TO 6 DAYS PRIOR
H
+8
+4
+4
L
0
0
-4
-8
-12
-16
-16
-12
-8
-4
Paris
Brest
Zurich
Berlin
Vienna
Bucuresti
Moscow
Lisbon
Madrid
La Coruna
Marseille
Roma
Tunis
Alger
Casablanca
Funchal
Tenerife
Ponta Delgada
Spitsbergen
Jan Mayen
El Golea
Tamanrasset
Port Etienne
Sao Vicente
Dakar
Port Sudan
Bagdad
Ankara
New York
Washington
Bermuda
Sable Is.
Cape Race
Belle Is.
Moose Factory
Winnipeg
Port Nelson
Omaha
St Paul
Memphis
New Orleans
Wichita

Fig. XXXIV

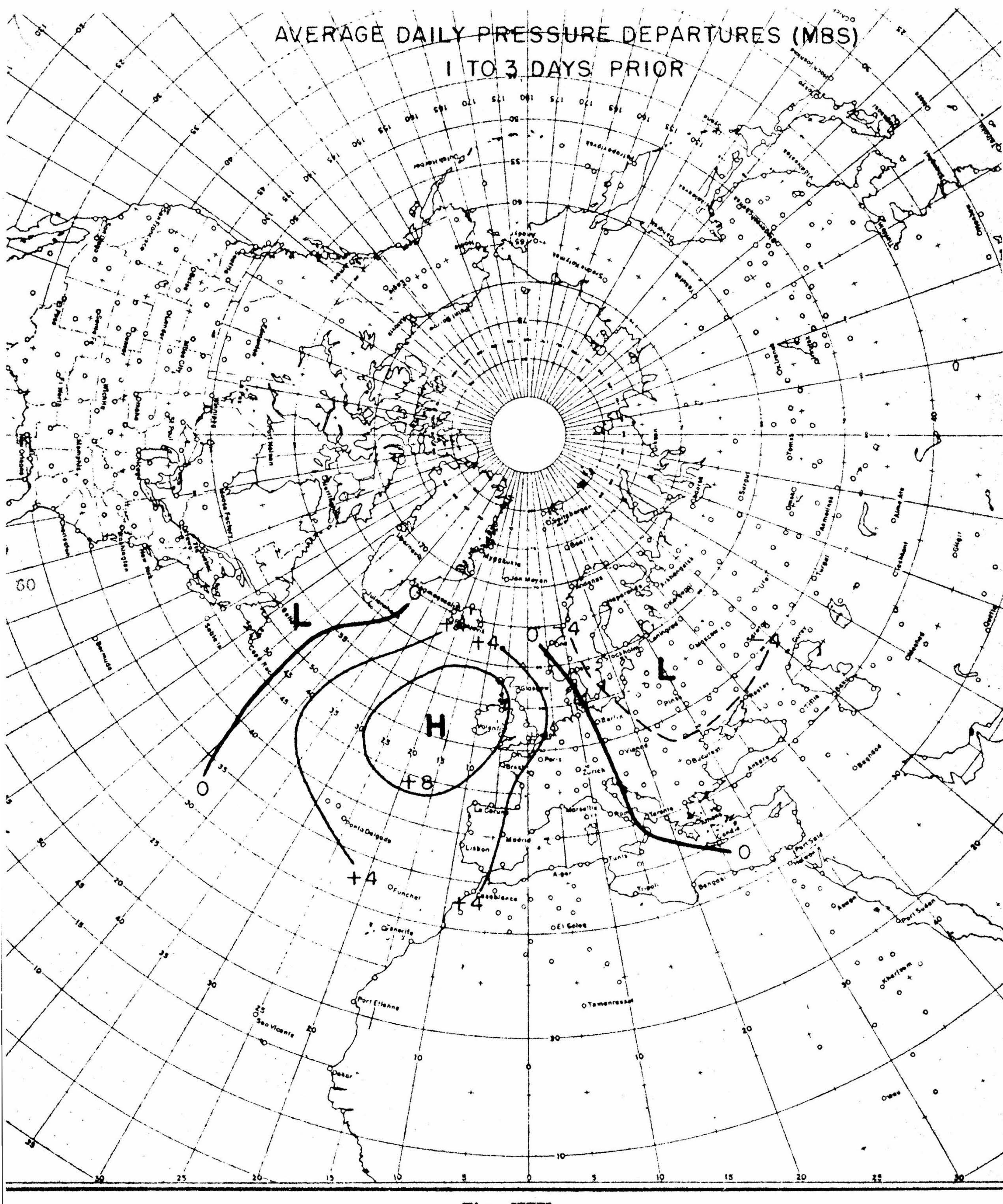

AVERAGE DAILY PRESSURE DEPARTURES (MBS)
1 TO 3 DAYS PRIOR
H
L
L
+8
+4
+4
+4
0
0
0
-4
-4
Glasgow
Paris
Brest
Zurich
Berlin
Vienna
Bucurest
Madrid
Lisbon
La Coruna
Marseille
Tunis
Tripoli
Bengasi
Port Said
Port Sudan
Khartoum
El Golea
Tamanrasset
Port Etienne
Dakar
Sao Vicente
Funchal
Ponta Delgada
Casablanca
Jan Mayen
Stockholm
Leningrad
Moscow
Bermuda
Wichita
Memphis
Omaha
Winnipeg
Port Nelson
Moose Factory
New York
Washington
Ankara
Bagdad
Tiflis
Surgut
Tomsk
Omsk
Semipalatinsk
Tashkent
Turgai
Dutch Harbor

Fig. XXXV

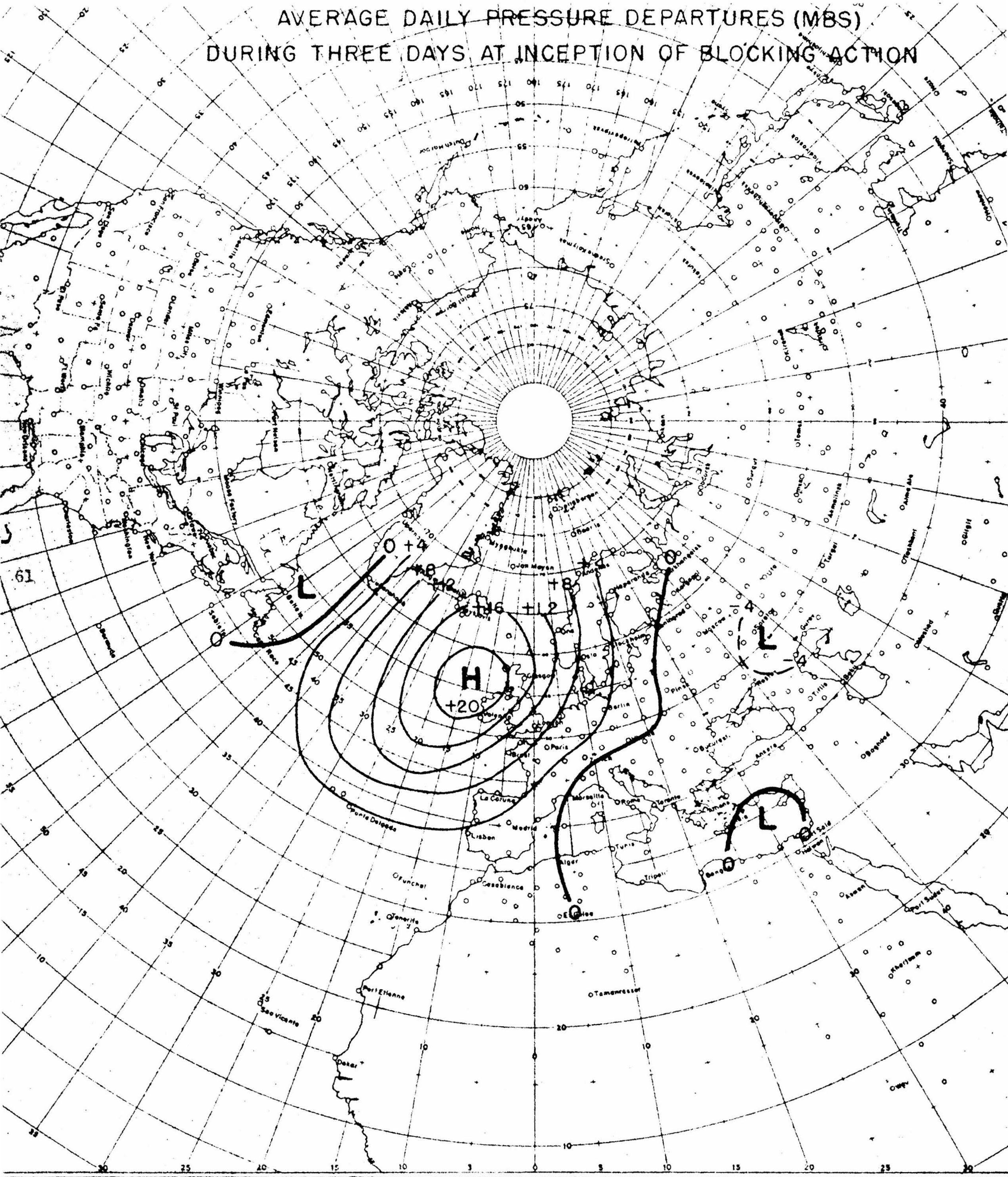

AVERAGE DAILY PRESSURE DEPARTURES (MBS)
DURING THREE DAYS AT INCEPTION OF BLOCKING ACTION
H
+20
+16
+12
+8
+4
0
L
-4
Jan Mayen
Paris
Berlin
Madrid
Lisbon
La Coruna
Ponta Delgada
Marseille
Roma
Taranto
Alger
Tunis
Tripoli
Funchal
Casablanca
Tenerife
Port Etienne
Sao Vicente
Dakar
Tamanrasset
Aswan
Port Sudan
Khartoum
Baghdad
Ankara

Fig. XXXVI

The mean pressure gradient between 50° N and 60° N for the cases mentioned above is investigated in more detail in Fig. XXXVII. The large magnitude of this gradient corresponding to the strong zonal flow occurring in the Atlantic area is clearly shown. The only suggestion of a consistent, meaningful pattern upstream from this strong flow is that occurring between fifteen to seven days prior in the neighborhood of longitude 110° W. This suggests the existence of a stable wave of length ninety to one hundred degrees upstream from the sub-tropical high cell which may aid in its development into the blocking stage.

The surface temperature anomalies characteristic of the area occupied by the sub-tropical cell during the formative stages of blocking have been investigated with results depicted in Fig. XXXVIII. The area is bounded by latitudes 50° N and 40° N and by longitudes 30° W and 10° W. The temperatures were taken from ship reports in the area and are necessarily subject to some inaccuracy. The values were averaged in five degree squares over the entire area and then averaged for the various three day periods prior to the inception of blocking. While the total number of five Blocking Action examples used is a very small sample the consistency of the results leads to the belief that the general characteristics of the temperature field are satisfactorily represented. Fig. XXXVIII shows the temperature averaging above normal in the area continuously in the twenty-one days prior to the inception of blocking. While the average of one to two degrees is small in itself it represents a considerable amount of excess heat when summed over the entire area.

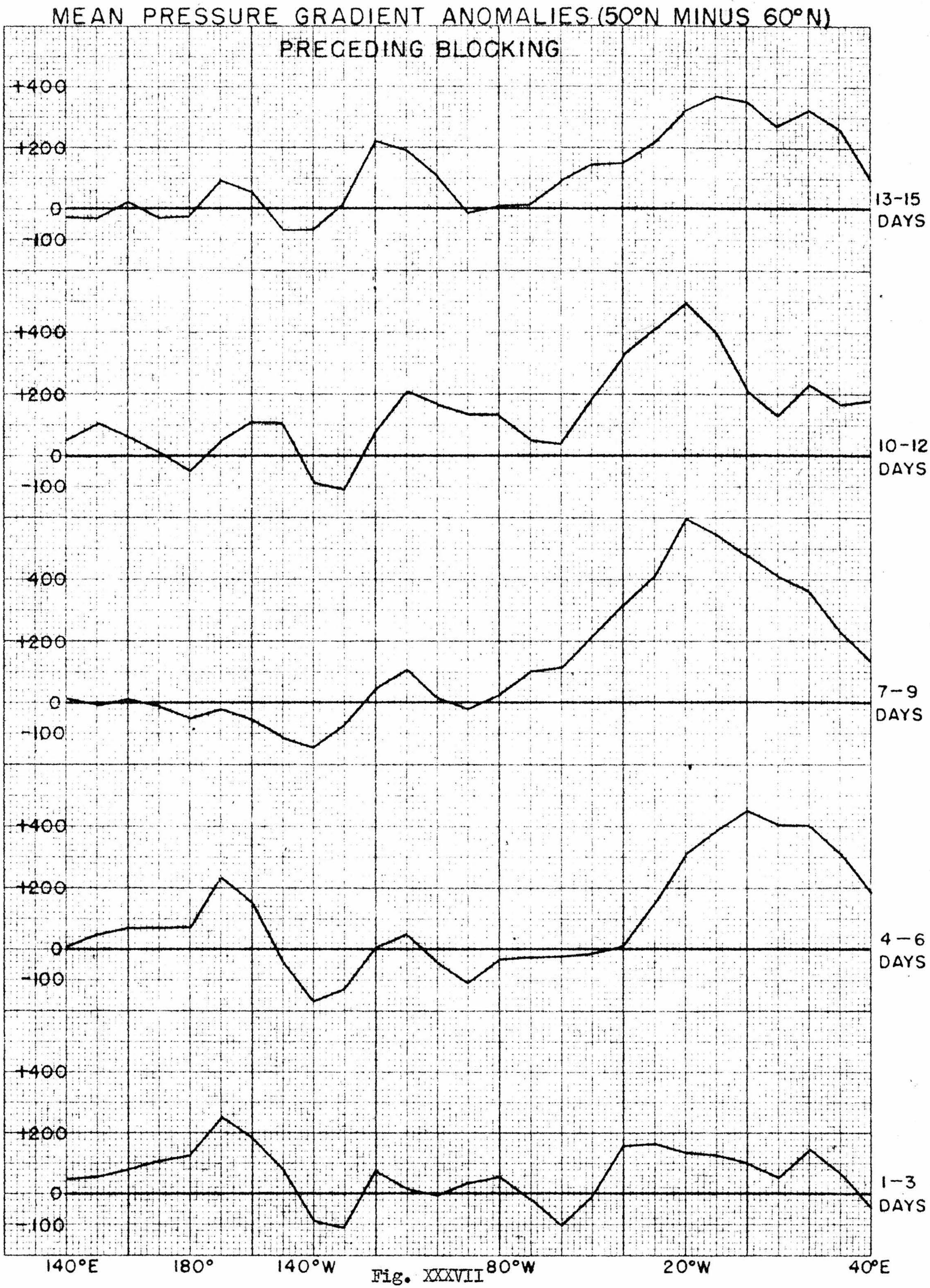

MEAN PRESSURE GRADIENT ANOMALIES (50°N MINUS 60°N)
PRECEDING BLOCKING
+400
+200
0
-100
13-15 DAYS
10-12 DAYS
7-9 DAYS
4-6 DAYS
1-3 DAYS
140°E
180°
140°W
80°W
20°W
40°E

Fig. XXXVII

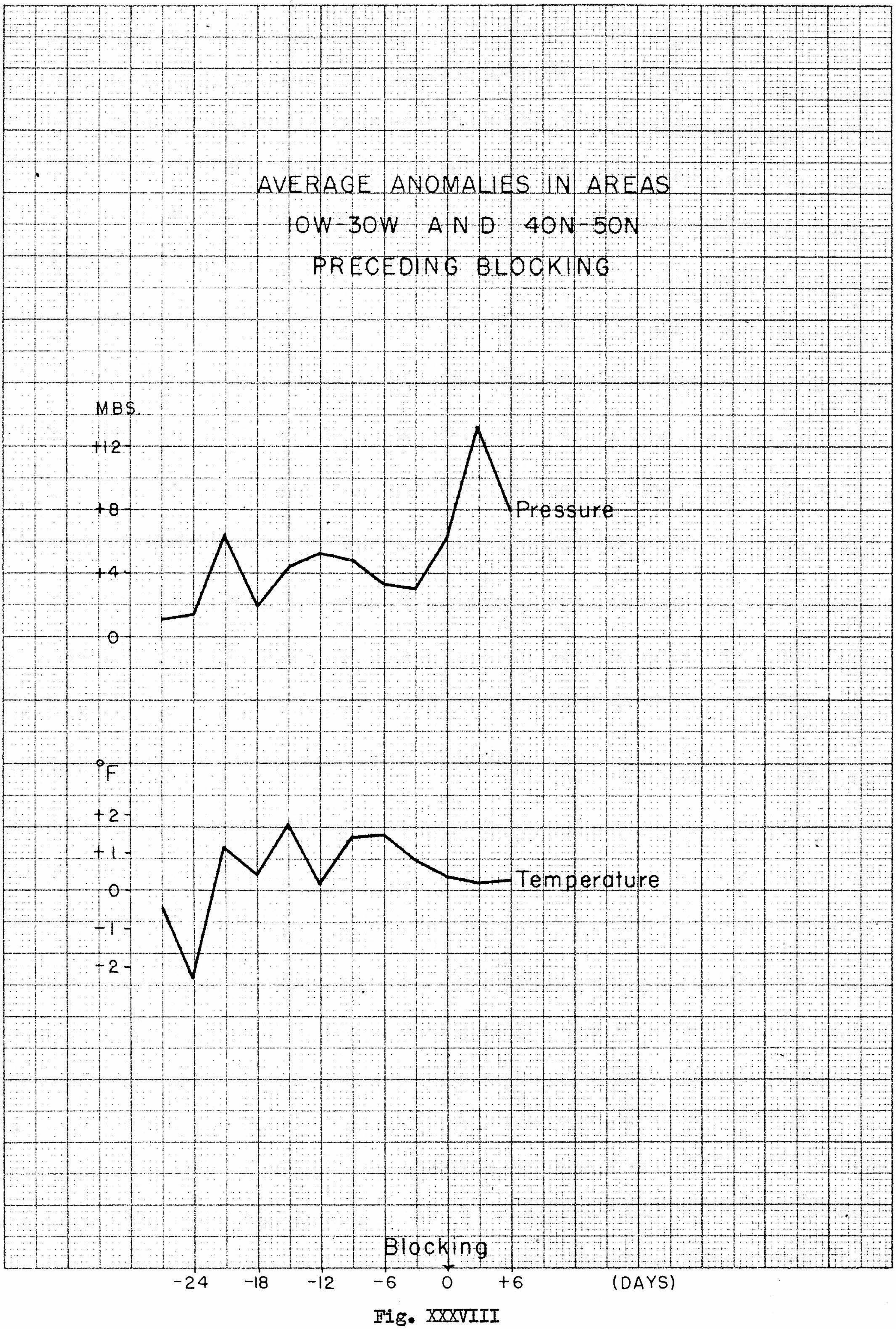

AVERAGE ANOMALIES IN AREAS
10W-30W AND 40N-50N
PRECEDING BLOCKING
MBS.
+12
+8
+4
0
Pressure
°F
+2
+1
0
-1
-2
Temperature
Blocking
-24
-18
-12
-6
0
+6
(DAYS)

Fig. XXXVIII

Fig. XXXVIII also gives the average pressure departure for the same square for similar periods prior to the inception of the blocking high cell. The pressure is seen to average above normal during the formative stages as has been discussed previously. The slow development of the Blocking Action stage is again shown in this figure.

Two suggestions have been offered for the explanation of this dynamical development consisting of the abnormal extension of the sub-tropical high cell into the region normally occupied by a westerly flow. The first explains the development as an instability phenomenon associated with the introduction of a pressure disturbance into an abnormally strong westerly flow. The extension of the sub-tropical high cell toward the northwest in Figs. XXXIII and XXXIV indicates the existence of such a disturbance. However, a general investigation of disturbances superimposed on similar strong zonal flows shows many which are not unstable in the sense that the disturbances disappear rapidly. These cases are mainly those where no well developed sub-tropical high cell exists. The characteristic flow pattern for these cases is a large low pressure system in the higher latitudes which dominates the entire Atlantic sector. Pressures are predominantly low throughout the sector. The abnormally high zonal gradients exist but no abnormally high pressures develop subsequently at high latitudes. Additional information in regard to the thermal structure of the circulation apparently must be assumed and a pure instability phenomenon similar to the breakdown of laminar flow has therefore been discarded. The second suggestion offered involves the accumulation of heat in the region occupied by the sub-tropical cell. If the characteristics of the general circulation are such as to lead to an accumulation of heat in a given area, the Blocking Action process is postulated as the mechanism by which the circulation adjusts itself in order to redistribute this heat. The process may be visualized as follows: the accumulated heat in the sub-tropical high cell causes an increase in the latitudinal temperature gradient and consequently an increase in the zonal flow. This increased zonal flow is brought about by the transformation into kinetic energy of a small portion of the potential energy which exists in the form of the abnormal latitudinal temperature gradient. The mechanism by which this excess heat can be transported northward and redistributed is assumed to be the pressure disturbance superimposed on the zonal flow. The additional meridional velocity component brought about by this disturbance is apparently sufficient to allow the flow of heat northward and to lead to the formation of the high pressure at the higher latitudes. The maintenance of the high pressure at these high latitudes is not considered here.

Fig. XXXVIII, although not conclusive proof, indicates that this postulate is a possible explanation. The excess heat is seen to remain sensibly constant for a period of about nine days being gradually dissipated within the given area in the days immediately preceding the inception of blocking. A general investigation of all cases of abnormally high pressure in the area described by Fig. XXXVIII. has shown that if the abnormality continues over a period of five to six days and hence can be considered as an excess accumulation of heat, the sub-tropical high cell develops into high pressure at high latitudes virtually without exception. The length of time involved in this process, the longitudinal location and the persistence of the high pressure at high latitudes vary but the mechanism of the formation of the high pressure at high latitudes seems to be a necessary development after the persistence of the abnormally high pressures in the sub-tropical high cell.

The pressure departures for three day intervals prior to the inception of the twenty even year cases of mid-Pacific blocking are shown in Figs. XXXIX to XLII. The dates of the cases are listed in Part I. The origin of the high cell which subsequently becomes the blocking High is in Siberia and moves out to the blocking area in a general west to northwest flow. There is no evidence for the gradual northward extension of the belt of the sub-tropical High as was the case in the Atlantic. The extreme disturbed state of the entire pressure pattern during the fifteen days leading up to inception should be noted. This suggests that the circulation is already in a highly disturbed state prior to the inception of this type of blocking and that a slight readjustment of the long wave patterns such as is discussed in Part III results in the destruction of the blocking in one area and its re-formation in the new area. This type of formation would then be considered as a secondary effect rather than as the introduction of a primary disturbance. It should be mentioned here that a few of the High Latitude Atlantic cases are apparently formed in this way, the high cell coming down from the Greenland sea area. They show little relation to the Atlantic sub-tropical high cell and should be considered as secondary in origin.

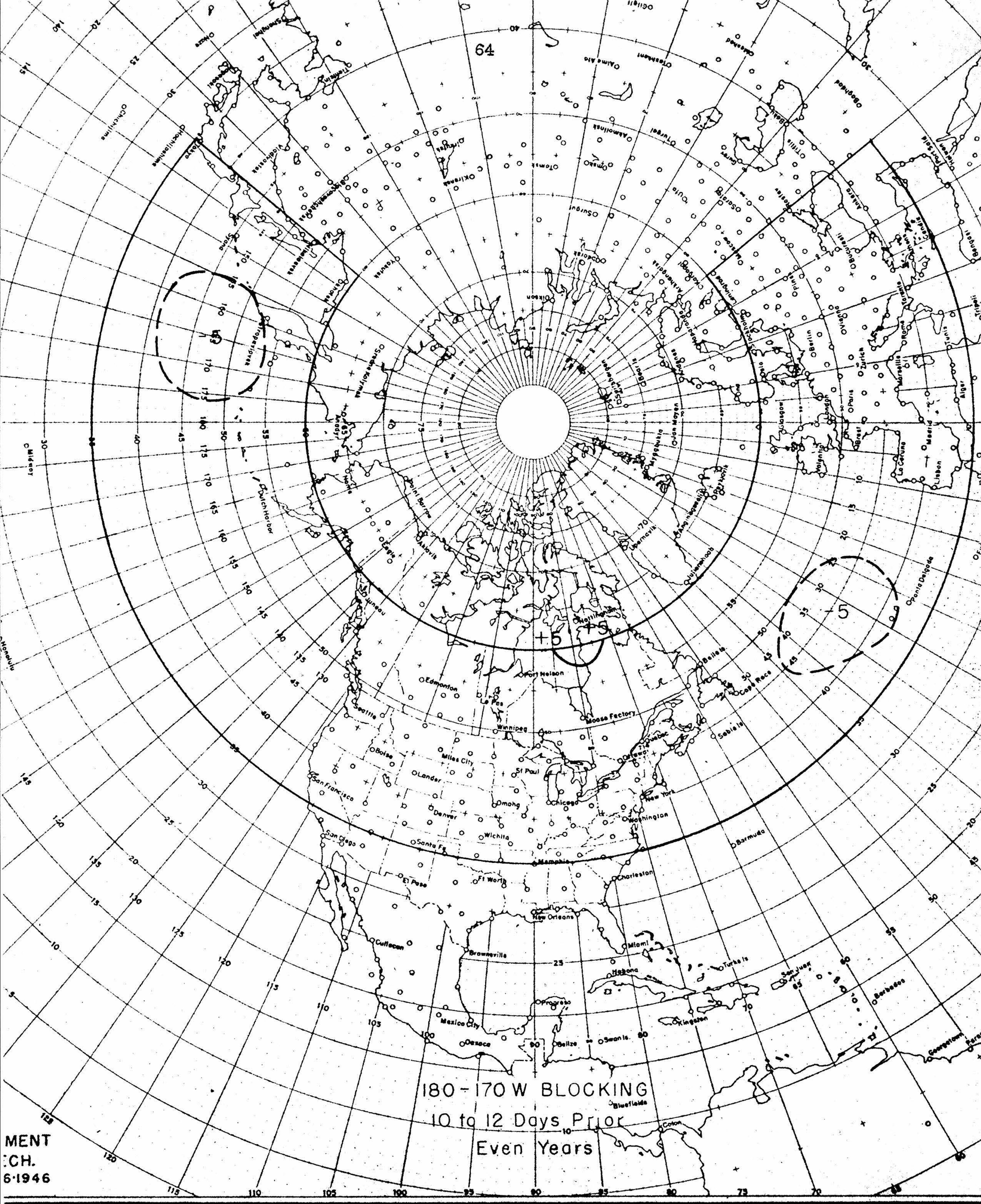

64
180-170 W BLOCKING
10 to 12 Days Prior
Even Years
+5
+5
-5
MENT
CH.
6·1946

Fig. XXXIX

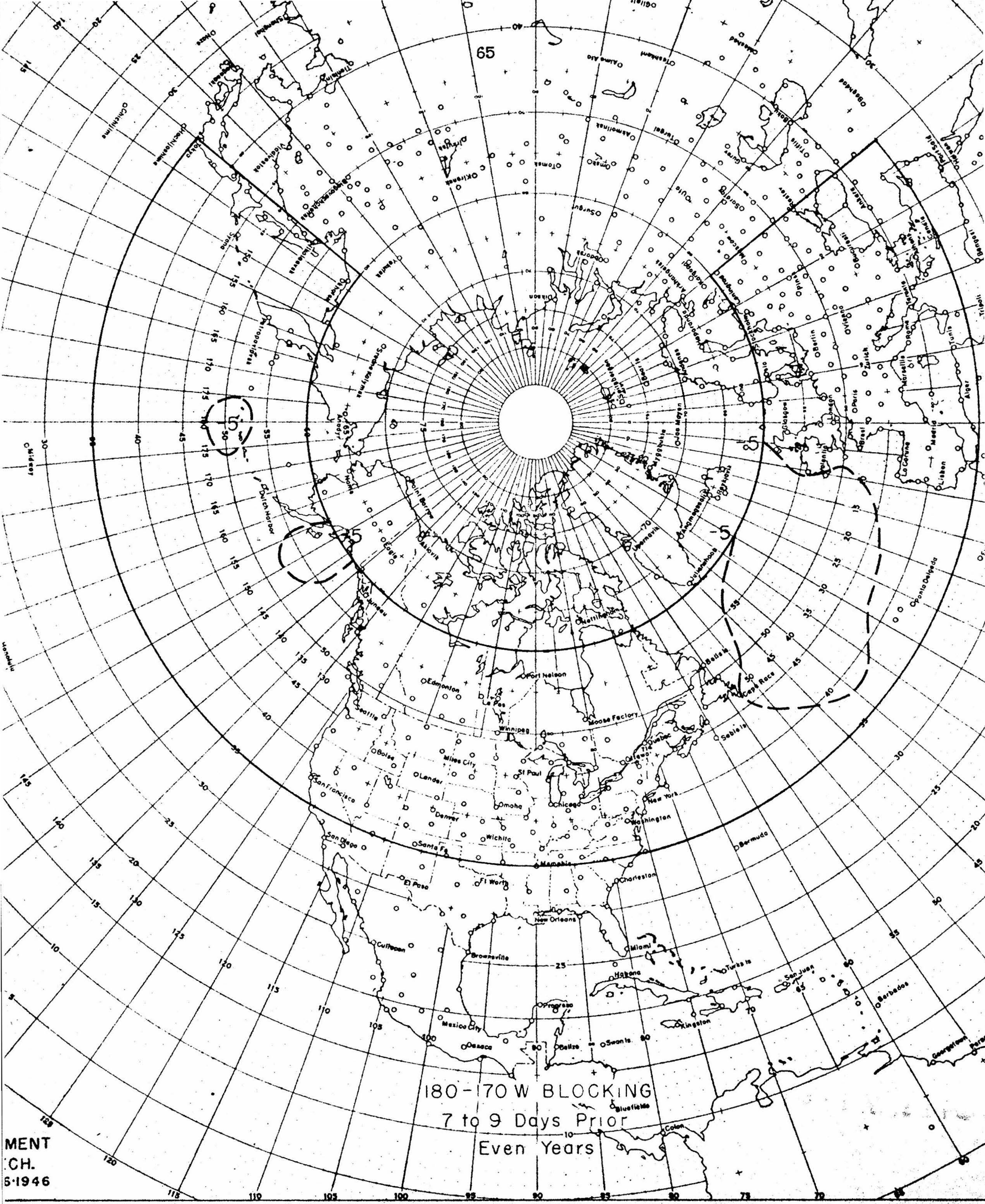

180-170 W BLOCKING
7 to 9 Days Prior
Even Years
-5
MENT
CH.
6·1946
Edmonton
Port Nelson
Winnipeg
Moose Factory
Seattle
San Francisco
San Diego
Denver
Omaha
Chicago
New York
Washington
Memphis
Ft Worth
El Paso
New Orleans
Charleston
Miami
Brownsville
Habana
Kingston
Mexico City
Oaxaca
Belize
Bermuda
Barbados
San Juan
Turks Is
Cape Race
Sable Is
Belle Is
Juneau
Dutch Harbor
Point Barrow
Aklavik
Eagle
Nome
Midway
Honolulu
Lisbon
Madrid
Paris
London
Berlin
Zurich
Marseille
Tunis
Alger
Ponta Delgada
Julianehaab
Upernavik
Jan Mayen
Dikson
Tomsk
Omsk
Surgut
Baghdad
Tashkent
Alma Ata
Vladivostok
Tokyo

Fig. XL

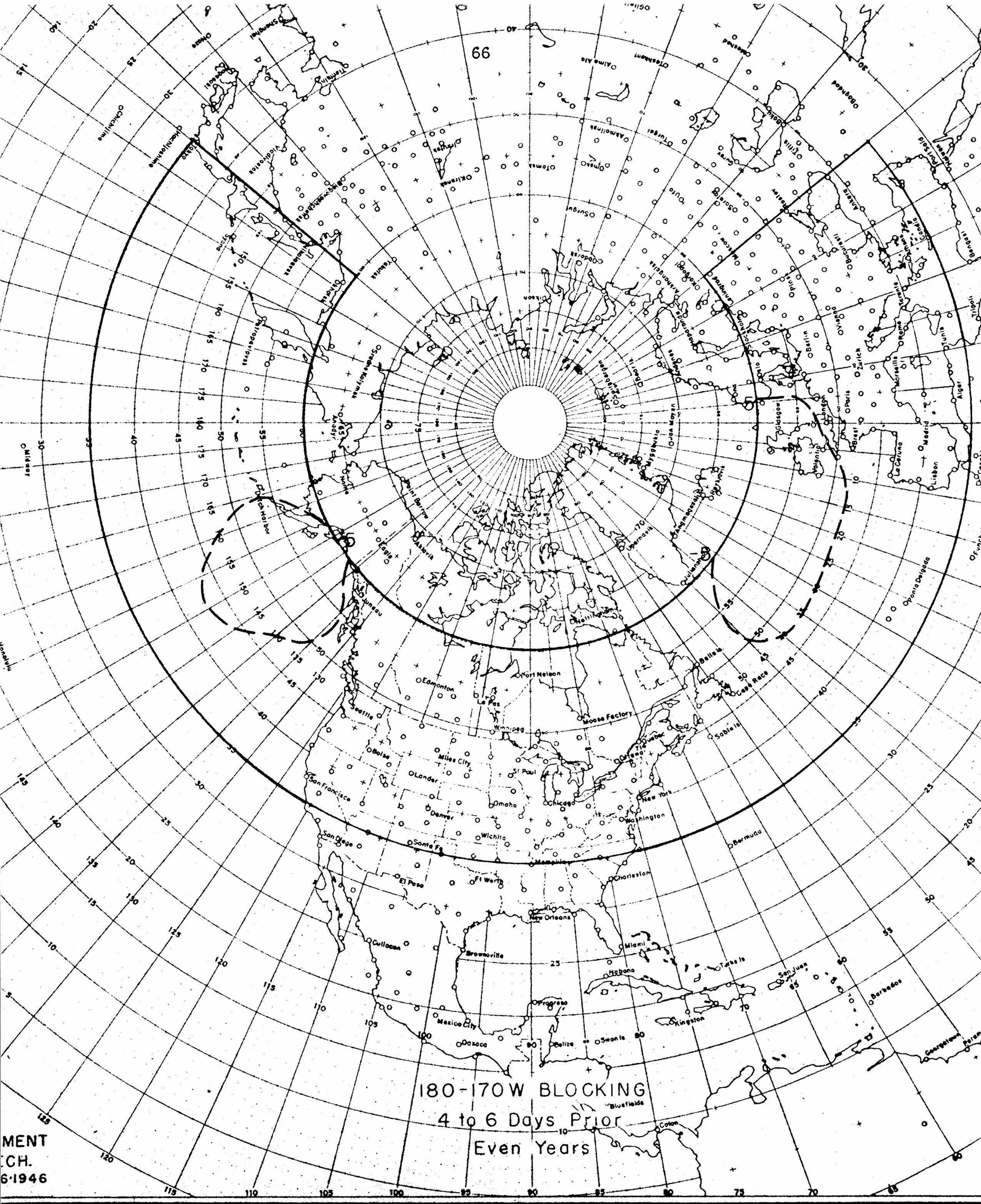


Fig. XLI

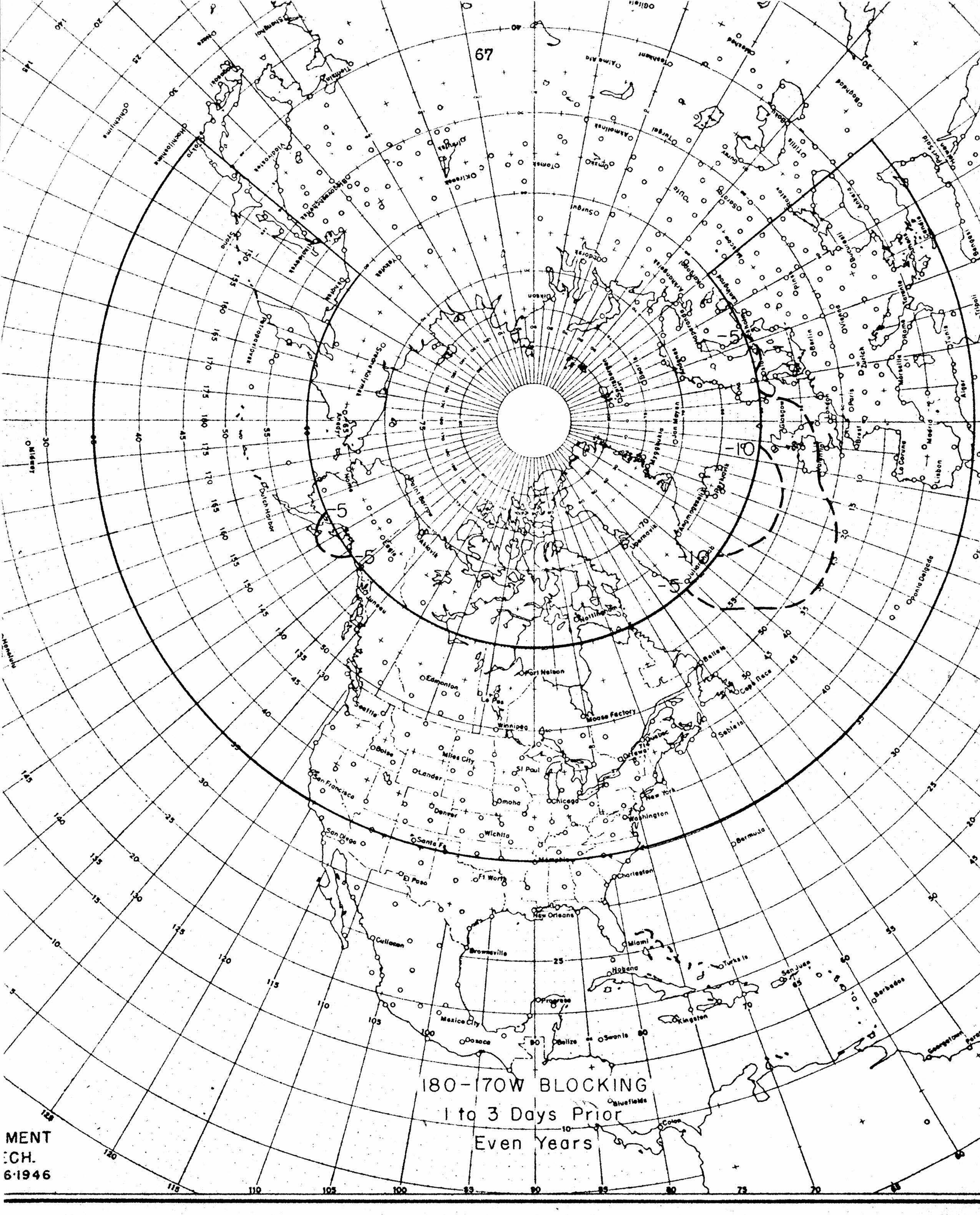

180-170W BLOCKING
1 to 3 Days Prior
Even Years
MENT
:CH.
6·1946
-5
-10
Edmonton
Fort Nelson
Winnipeg
Moose Factory
Seattle
San Francisco
Denver
Chicago
New York
Washington
New Orleans
Miami
Mexico City
Juneau
Nome
Point Barrow
London
Paris
Berlin
Madrid
Lisbon
Glasgow
Bermuda
Kingston
Havana
Dutch Harbor
Midway

Fig. XLII

PART III. THE DISSIPATION OF THE BLOCKING ACTION EDDY

Only a small amount of information has been obtained as yet on the mechanism of the dissipation of the blocking high cells. Aside from the natural degradation to a zonal type flow through the dissipative action of migratory systems, interaction between Blocking Highs in two different regions might lead to the destruction of the weaker if it were not located at the correct wave length from the stronger. This process is shown in Figs. XLIII to XLVI and represents the deterioration of about one half of the cases of mid-Pacific blocking for the even years. Although it must be considered as only one breakdown process, it must represent one of the most common types. The pressure departures are again presented in groups of three days. Fig. XLIII shows the average daily departures for the final three days of blocking in the mid-Pacific. In the Atlantic the sub-tropical high cell is considerably above normal in pressure with an abnormally high zonal flow to the north, a condition strikingly analogous to that leading to the formation of the blocking High in the northeastern Atlantic, although displaced slightly to the west. The Atlantic sub-tropical cell continues its analogous development in Fig. XLIV while the mid-Pacific blocking cell deteriorates considerably in intensity. The Atlantic high cell does not remain as an important blocking cell in Figs. XLV and XLVI but a new, important high cell apparently develops in northwest Canada.

The mechanism visualized in this transition is as follows: As shown in Part I the first stable wave crest downstream

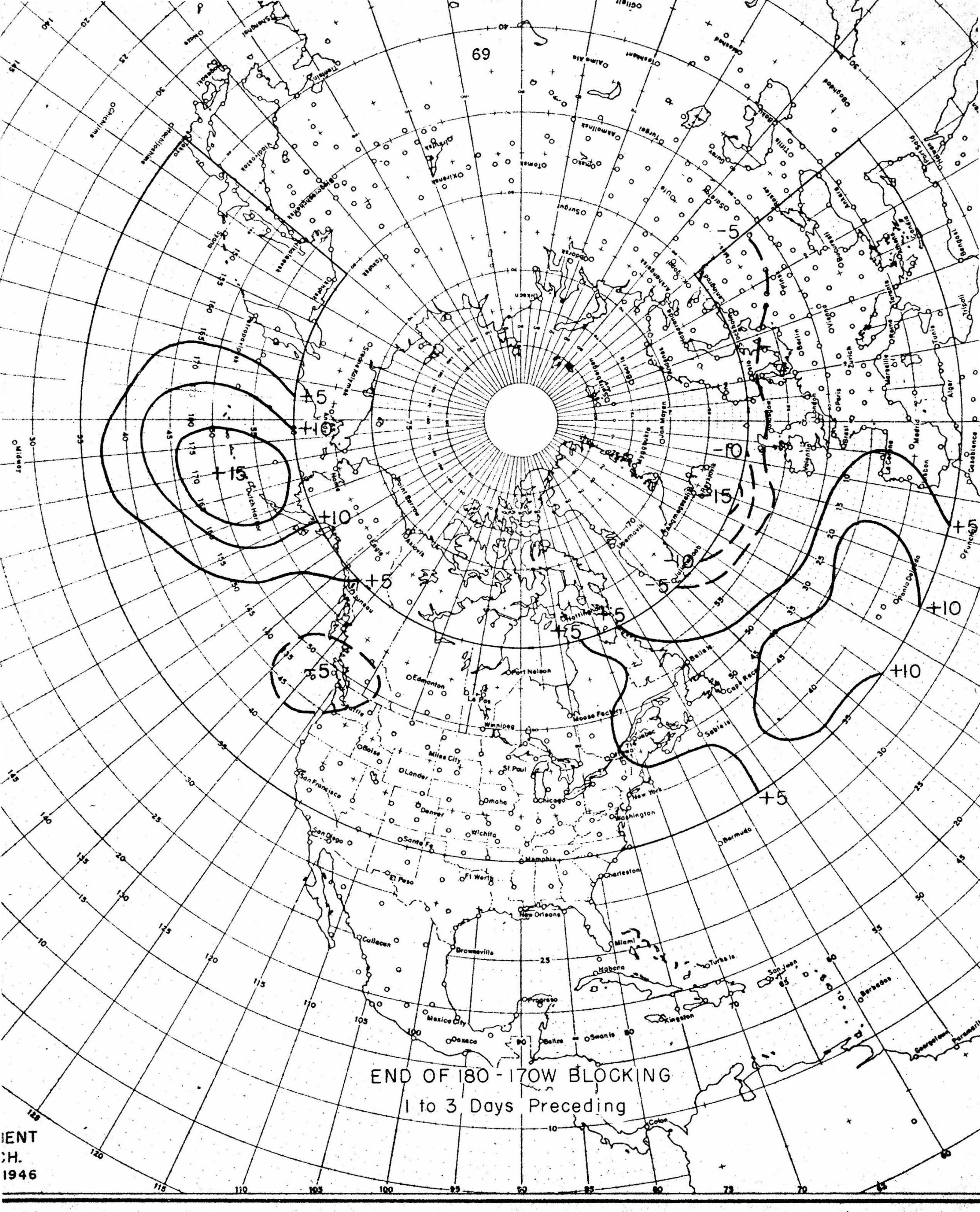

END OF 180 - 170W BLOCKING
1 to 3 Days Preceding
+15
+10
+5
-5
-10
-15
69
ENT
CH.
1946
Edmonton
Winnipeg
Fort Nelson
Moose Factory
Boise
Miles City
Lander
St Paul
San Francisco
Denver
Omaha
Chicago
New York
Washington
San Diego
Santa Fe
Wichita
Memphis
El Paso
Ft Worth
Charleston
New Orleans
Miami
Brownsville
Habana
Culiacan
Mexico City
Oaxaca
Progreso
Belize
Kingston
San Juan
Barbados
Bermuda
Colon
Georgetown
Juneau
Nome
Dutch Harbor
Point Barrow
Reykjavik
Berlin
Paris
London
Madrid
Lisbon
Casablanca
Rome
Algier
Tunis
Marseille
Zurich
Vienna
Brest
Valentia
Funchal
Ponta Delgada
Sable Is
Cape Race
Belle Is
Jan Mayen
Oslo
Stockholm
Tripoli
Benghazi
Baghdad
Tiflis
Ankara
Omsk
Surgut
Dikson
Turgai
Tomsk
Vladivostok
Midway

Fig. XLIII

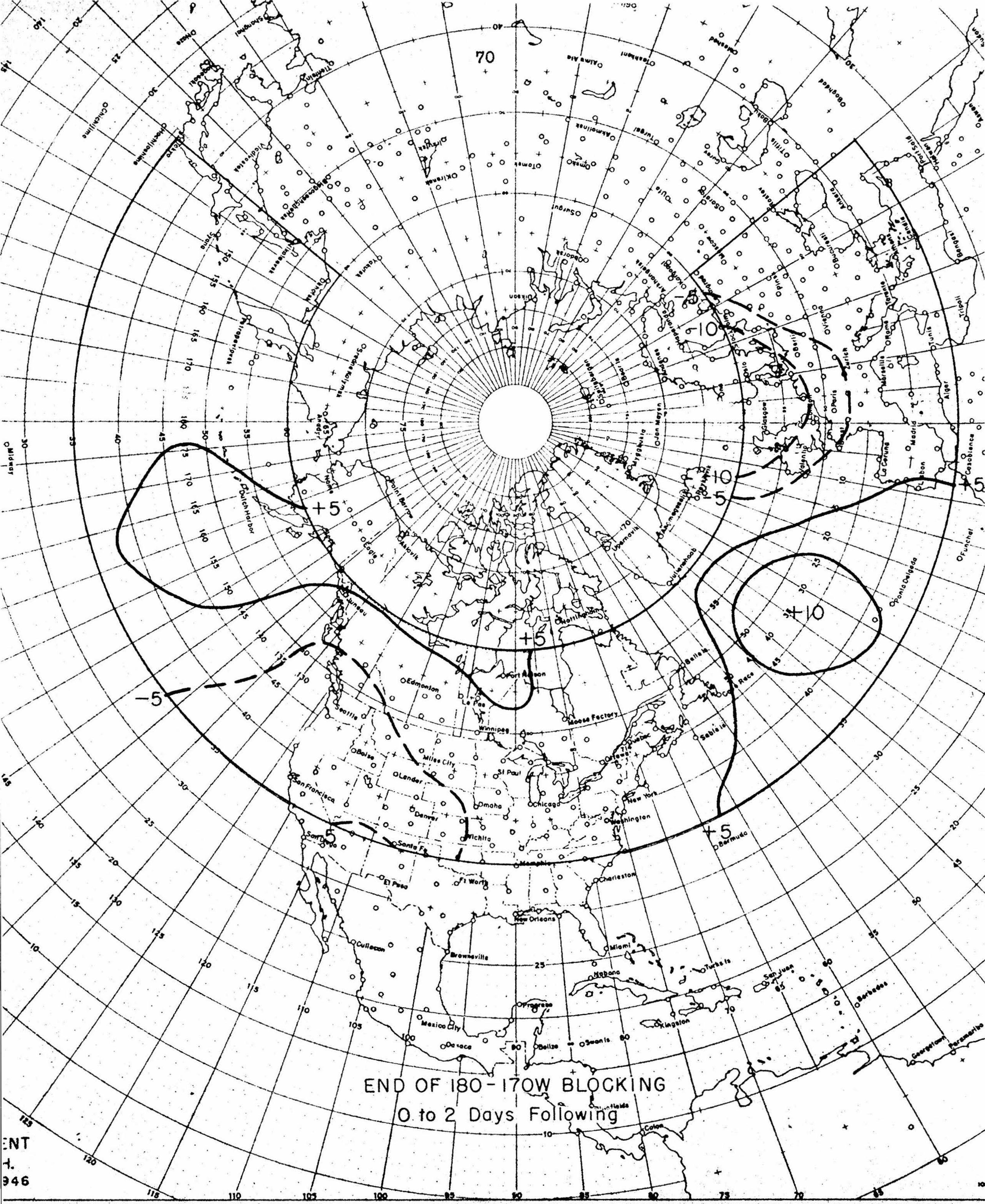


Fig. XLIV

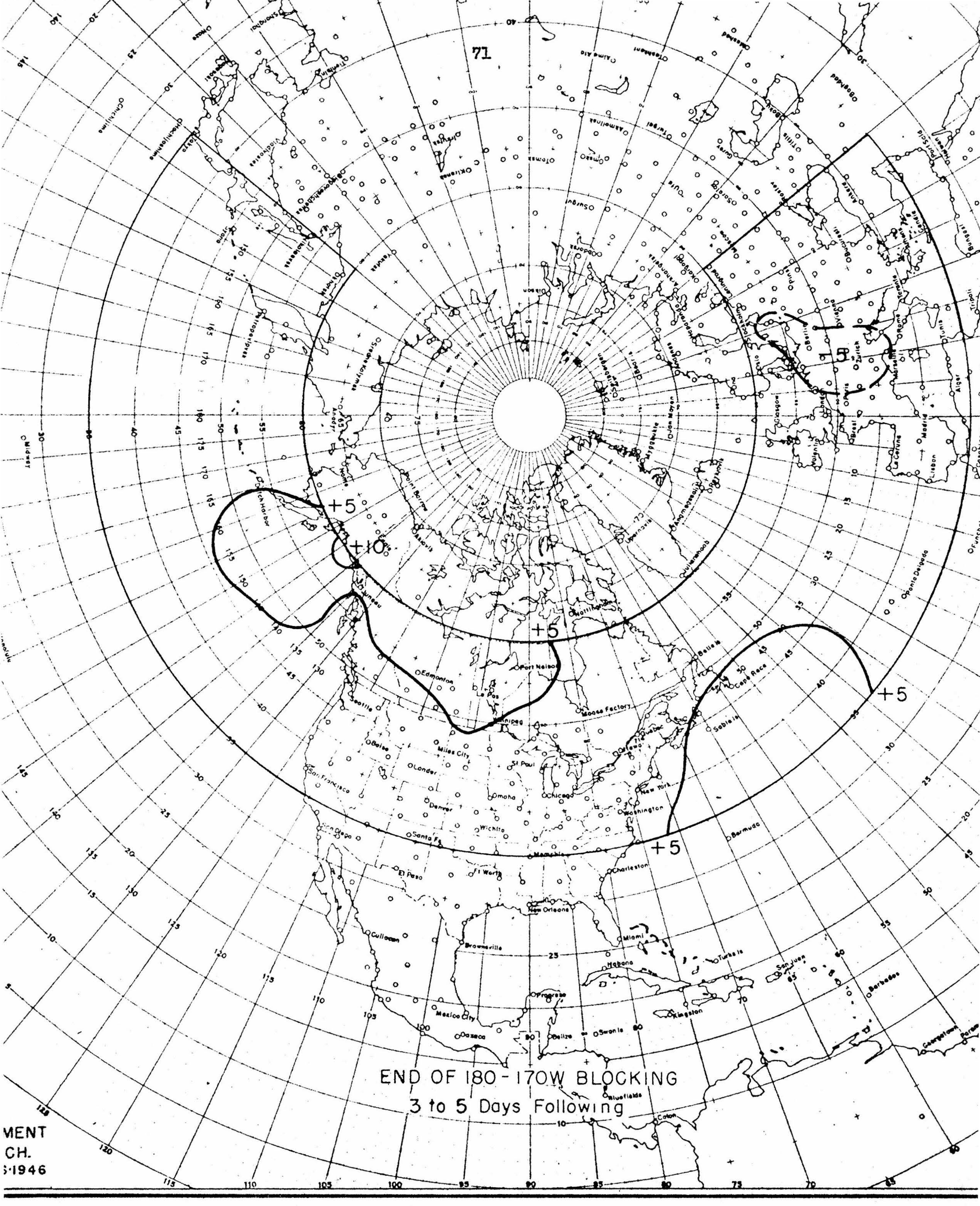

71
END OF 180 - 170W BLOCKING
3 to 5 Days Following
+5
+10
+5
+5
+5
-5
MENT
CH.
-1946

Fig. XLV

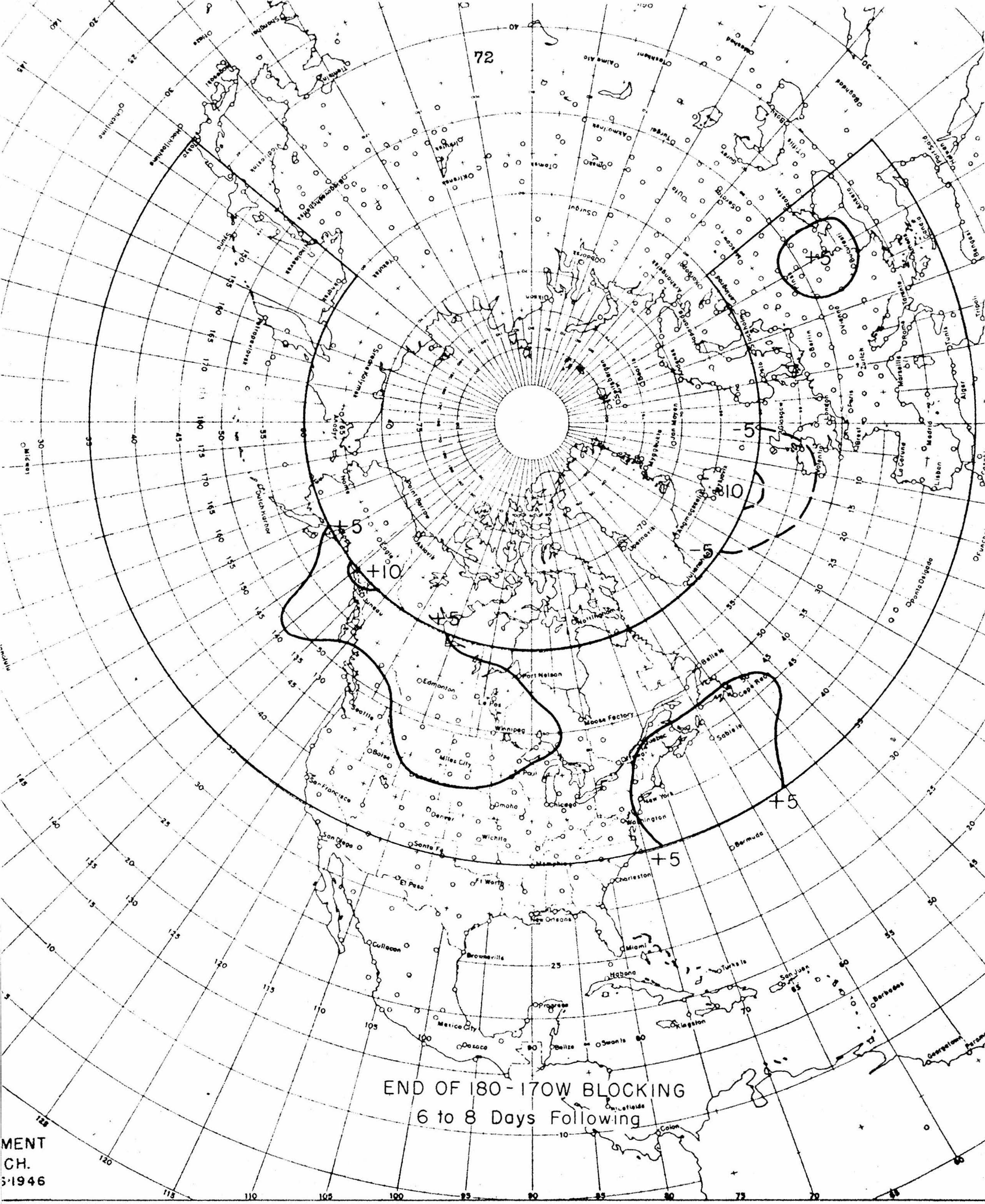

END OF 180 - 170W BLOCKING
6 to 8 Days Following
+5
+10
-5
-10
Edmonton
Winnipeg
Seattle
Boise
Miles City
San Francisco
Omaha
Chicago
Denver
Wichita
Santa Fe
San Diego
El Paso
Ft Worth
Memphis
Charleston
New Orleans
Miami
Brownsville
Habana
San Juan
Barbados
Kingston
Mexico City
Oaxaca
Progreso
Belize
Swan Is
Colon
Bermuda
New York
Washington
Quebec
Sable Is
Cape Race
Belle Is
Moose Factory
Port Nelson
Le Pas
Juneau
Eagle
Aklavik
Point Barrow
Nome
Dutch Harbor
Nottingham
Julianehaab
Angmagssalik
Jan Mayen
Glasgow
London
Paris
Berlin
Zurich
Rome
Marseille
Madrid
Lisbon
La Coruna
Brest
Valentia
Alger
Tunis
Tripoli
Benghazi
Ponta Delgada
Georgetown
Alma Ata
Tashkent
Baghdad
Omsk
Dikson
MENT
CH.
5·1946

Fig. XLVI

from the mid-Pacific blocking High is located in northeastern Canada. Due to the mechanism suggested in Part II a blocking cell develops in the mid-Atlantic region for reasons independent of the action of the Pacific blocking. The position is out of phase with the stable wave pattern formed downstream from the Pacific blocking cell. The mid-Atlantic cell tends to set up its own stable wave pattern independent of that formed by the Pacific cell. If there is greater energy associated with the Atlantic disturbance than with the Pacific, then the Atlantic pattern will dominate in the general circulation and the original wave pattern will be destroyed.

PART IV. THE OPTIMUM USE OF MEAN PRESSURE CHARTS

It has become apparent in the preceding sections that a large number of discrete processes can be considered as taking place in the atmosphere at various times. These processes may be thought of as continuously variable in length beginning with the short term fluctuations caused by the passage of migratory cyclones and anti-cyclones and continuing through the long period Blocking Action processes of a month or more. With the reality of these long period processes established by this and other investigations it would seem that some thought should be given to the problem of the length of period for which a mean pressure chart should be constructed in order to obtain the optimum benefit from it. This problem has been considered at some length and the principal results are given below.

The uses to which mean pressure charts may be put can be classed into two general categories; 1. They may serve as an extrapolation aid such that a series of mean charts may be used in an attempt to foretell the mean pressure distribution during some future period. 2. They may be used to describe, in average terms, a distinct process which has taken place within the atmosphere.

In the first category, neglecting any relationships between individual processes, the best extrapolation procedure would involve short segments of the individual process while the second category would involve a mean chart made up of that portion of the entire process which contributes pressure departures of the same algebraic sign. The results of this study will be discussed in terms of these two categories.

Because of the great number of calculations involved the mean pressure chart in this investigation has been considered as made up of a single point at 60° N and 170° W. All computations have been carried out for that point alone but the results may be generalized to apply to the mean pressure chart as a whole with only slight modifications in the magnitude of the results.

Data used in the study were daily pressure departures from normal at the point 60° N and 170° W for the winter season of November through March and for the twenty even years 1900 through 1938. The study was restricted to the winter season in order to obtain as homogeneous a sample as possible omitting the smaller standard deviations characteristic of the summer pressure field. The individual daily pressure departures were added algebraically in consecutive two day periods, three day periods, four day periods etc. up to and including thirty-nine day periods. These consecutive values form groups of data representing consecutive two day means, three day means, etc. Each group has been treated in two ways, as a group of consecutive mean pressure departures for a given period and as a group of consecutive total pressure departures for the given period. The individual elements of the total pressure departure group are simply the length of the period multiplied by the corresponding individual element of the mean pressure departure group.

Each group of two day values, three day values, etc., has a mean value and a standard deviation about that mean. The standard deviation measures the magnitude of fluctuation of the individual elements in the group. If the individual element of the group is assumed to be representative of the process taking place during that time interval the standard deviation is a measure of the variation between the different processes represented by the individual elements of the group. These standard deviations have been plotted as a function of the length of the period in Figs. XLVII and XLVIII for the two methods of treatment mentioned above. Fig. XLVII represents the standard deviations of the mean pressure departures. The general shape of the curve is determined by the rather obvious fact that means taken over a longer period of time tend to smooth out some of the erratic fluctuations in the pressure curve and consequently the standard deviation of the group of means for the longer period is considerably smaller. In terms of the two uses of mean pressure charts little can be said in regard to the use in the first category, namely, extrapolation, since the standard deviation between the individual elements of the group does not necessarily yield any information about the relation between successive values in the group. For the second category, or the delineation of individual processes, a small standard deviation implies small differences between the individual elements and mean values which are not sufficiently distinct from one another to give good delineation between the individual values. Consequently if mean values are used it would appear that the left hand portion of Fig. XLVII would give the best representation for individual processes.

The standard deviations of the total pressure departures are plotted in Fig. XLVIII. The parabolic form of the curve shows increasingly large differences between individual elements of a given period length as the length increases. If the total pressure departure

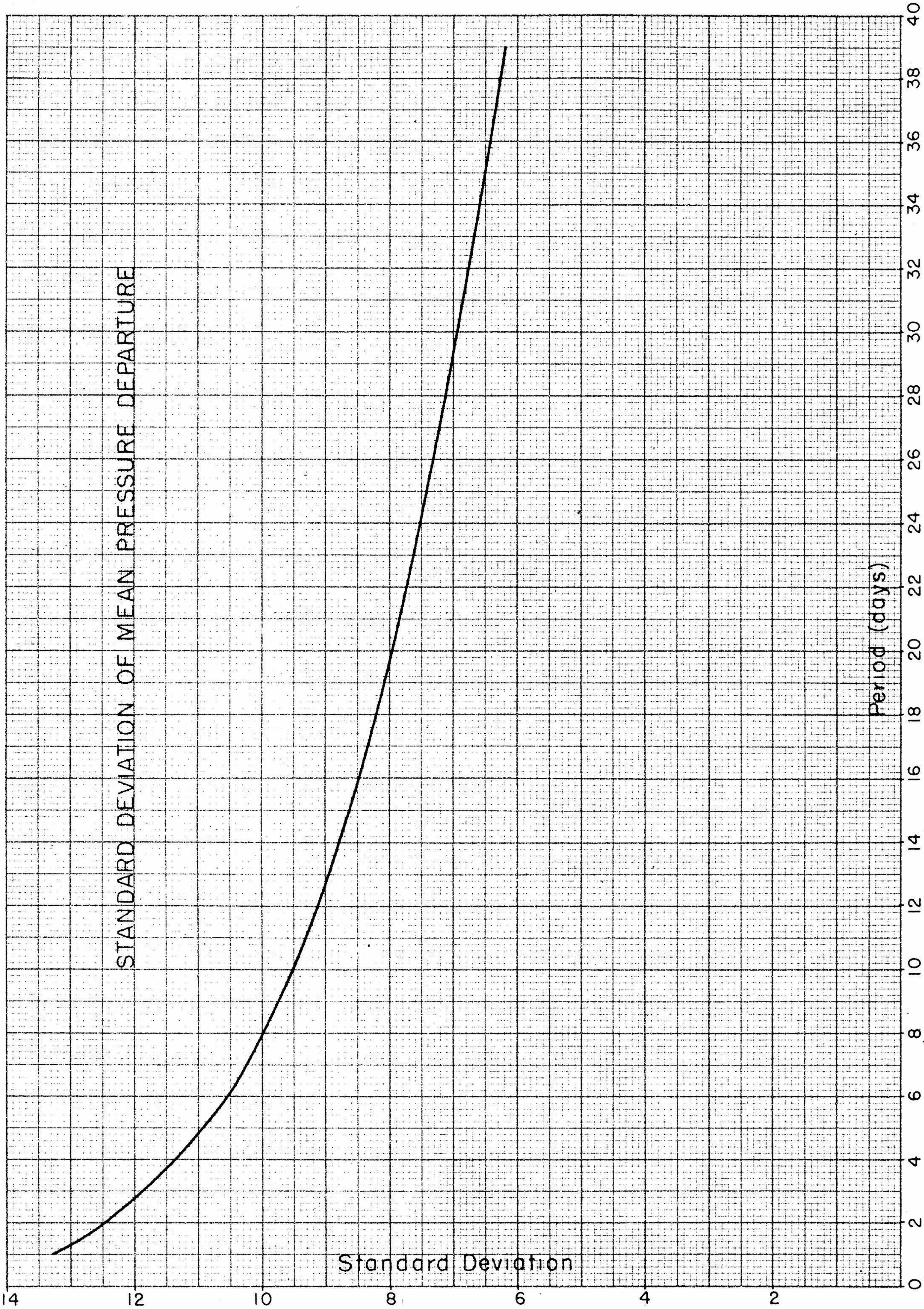

STANDARD DEVIATION OF MEAN PRESSURE DEPARTURE
Period (days)
Standard Deviation
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40
14 12 10 8 6 4 2

Fig. XLVII

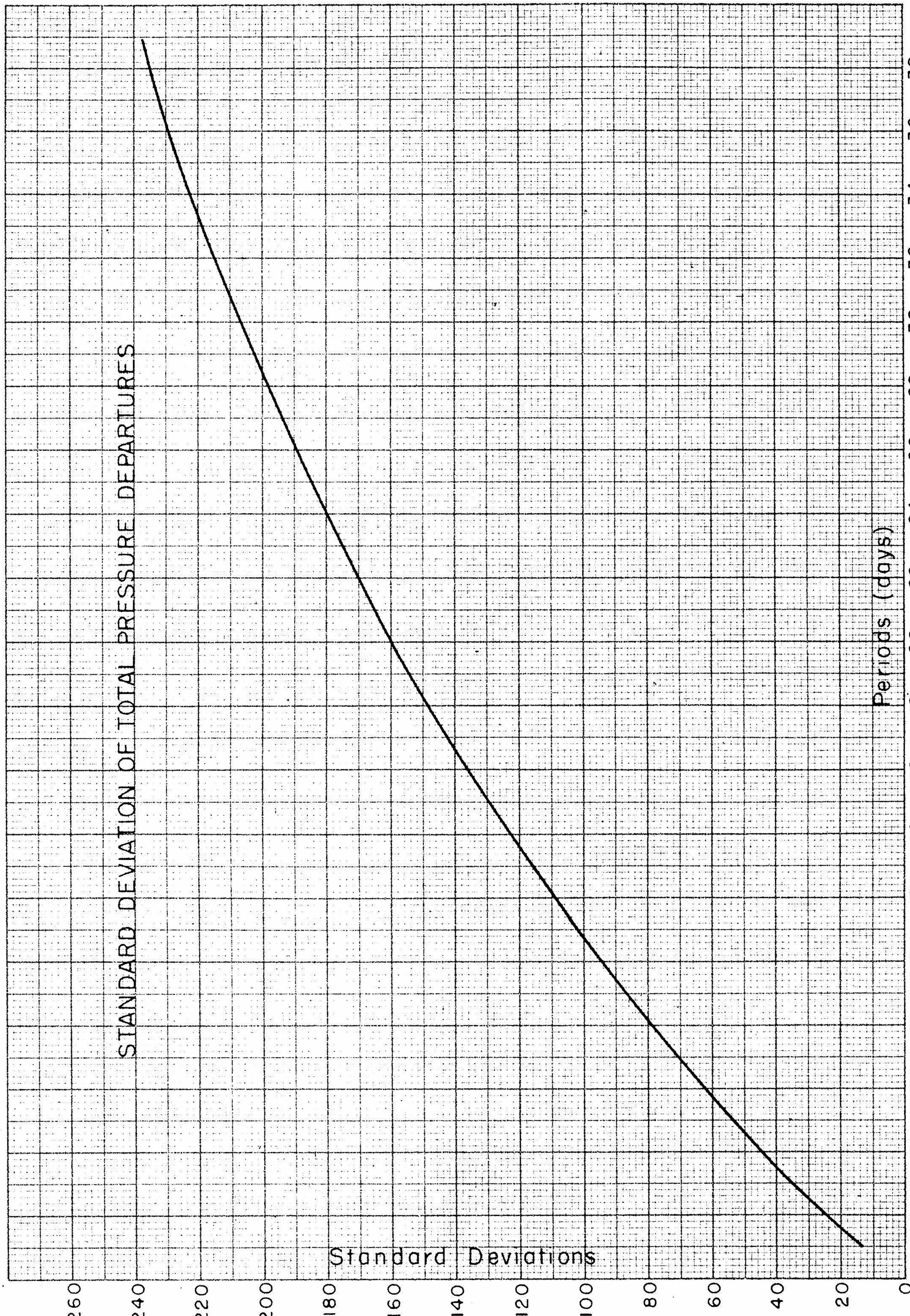

STANDARD DEVIATION OF TOTAL PRESSURE DEPARTURES
Standard Deviations
Periods (days)
260 240 220 200 180 160 140 120 100 80 60 40 20 0
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38

Fig. XLVIII

for a given period is assumed to represent the process taking place within that interval the best delineation between processes occurs for the longer periods. This is more representative of the characteristic features of the individual process than the use of the mean pressure discussed in the preceding paragraph.

It has been assumed that the mean or total pressure departure for a single period is representative of the process taking place within that interval. A check of the standard deviations of the daily pressure departures which are added together to form the mean or total pressure departure shows that these standard deviations have the same shape curve as Fig. XLVIII when plotted against the length of period. This may be visualized as the problem of fitting an erratic curve by mean values taken over varying lengths. The best fit is obtained by means taken over short segments of the curve. The curve is parabolic, however, so that the increase in standard deviation for the longer periods is not great. No great error is introduced, then, by using mean values taken over these longer periods.

More quantitative information can be obtained by considering the correlation coefficients between successive individual elements of each group. These correlation coefficients have been plotted as a function of the length of the period in Fig. XLVIX. For use in extrapolation, mean charts should have as large a correlation as possible with the preceding chart. This is clearly satisfied only for periods of three to four days or shorter. Longer periods where the correlation coefficient has dropped to .5 or lower can hardly be expected to yield much when used consistently for

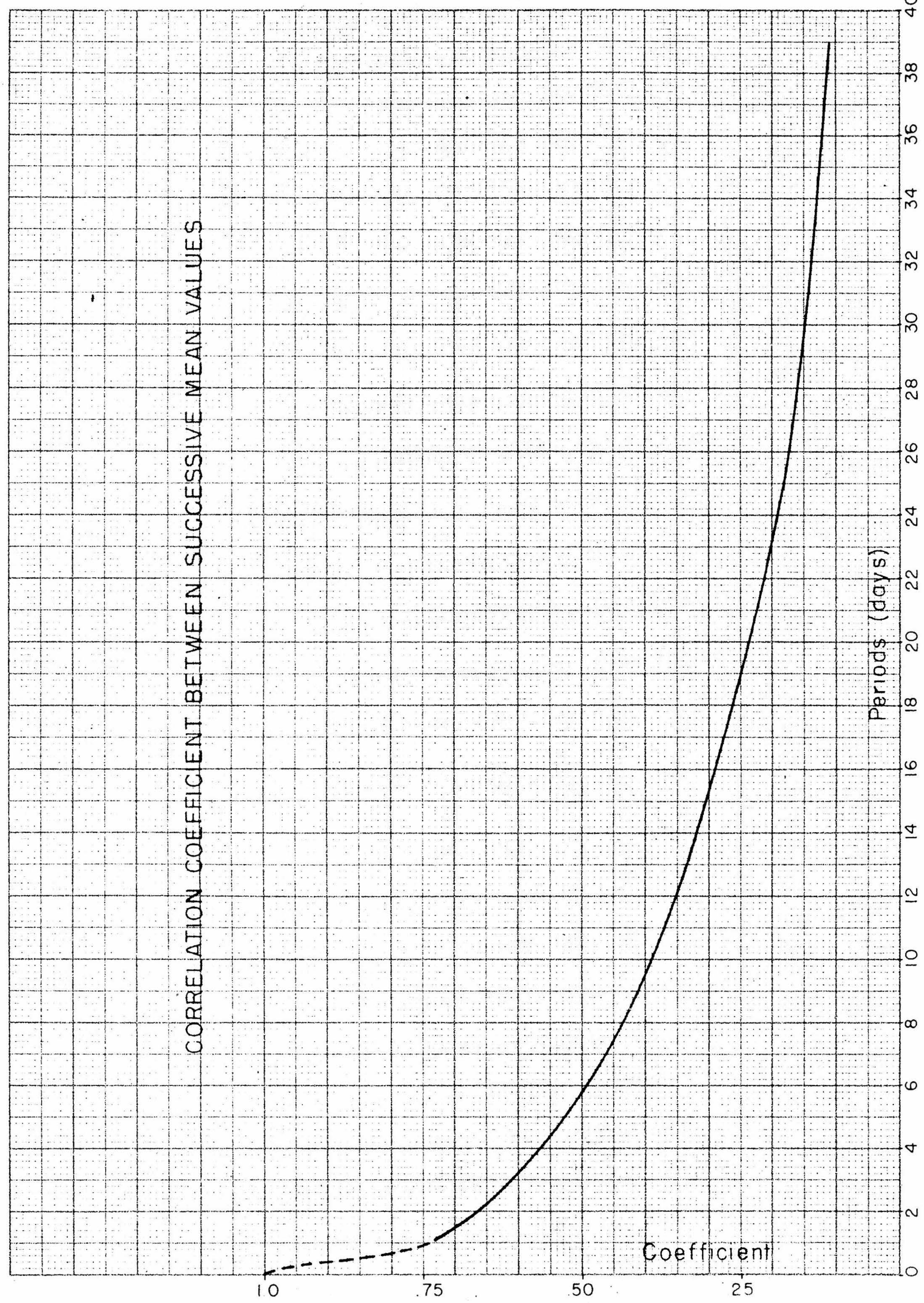

CORRELATION COEFFICIENT BETWEEN SUCCESSIVE MEAN VALUES
Periods (days)
Coefficient
1.0
.75
.50
.25
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40

Fig. XLIX

extrapolation purposes. For use in delineating individual processes, mean charts should have as small a correlation as possible with the preceding chart. This minimum correlation is best satisfied for periods of twenty days or more.

The effect of the migratory cyclones and anticyclones on the form of the pressure departure curve has been considered in Fig. L. This figure gives the frequency distribution of the number of days between peak pressures for the point 60° N - 170° W. The maximum value at three days represents the most frequent interval between successive pressure ridges passing the given point where these ridges are the effects of the alternate passage of the migratory cyclones and anticyclones. Little can be done to represent these short term processes on a mean pressure chart. Maximum delineation would be obtained using one half cycle of the entire process from one nodal point to the next or a chart of about one and one half days in length. For extrapolation even shorter length charts would be needed. Since these periods are of the order of magnitude of the time between daily synoptic weather charts, these daily charts represent the short term fluctuations of the passage of the migratory cyclones and anticyclones without the need for any additional mean charts. The most satisfactory representation of any longer term process will involve the elimination of these short term fluctuations by the use of some multiple of the most frequent period of three days between successive pressure crest passages. This will allow the representation of the longer period process with a minimum of contribution from the pressure changes caused by the migratory cyclones and

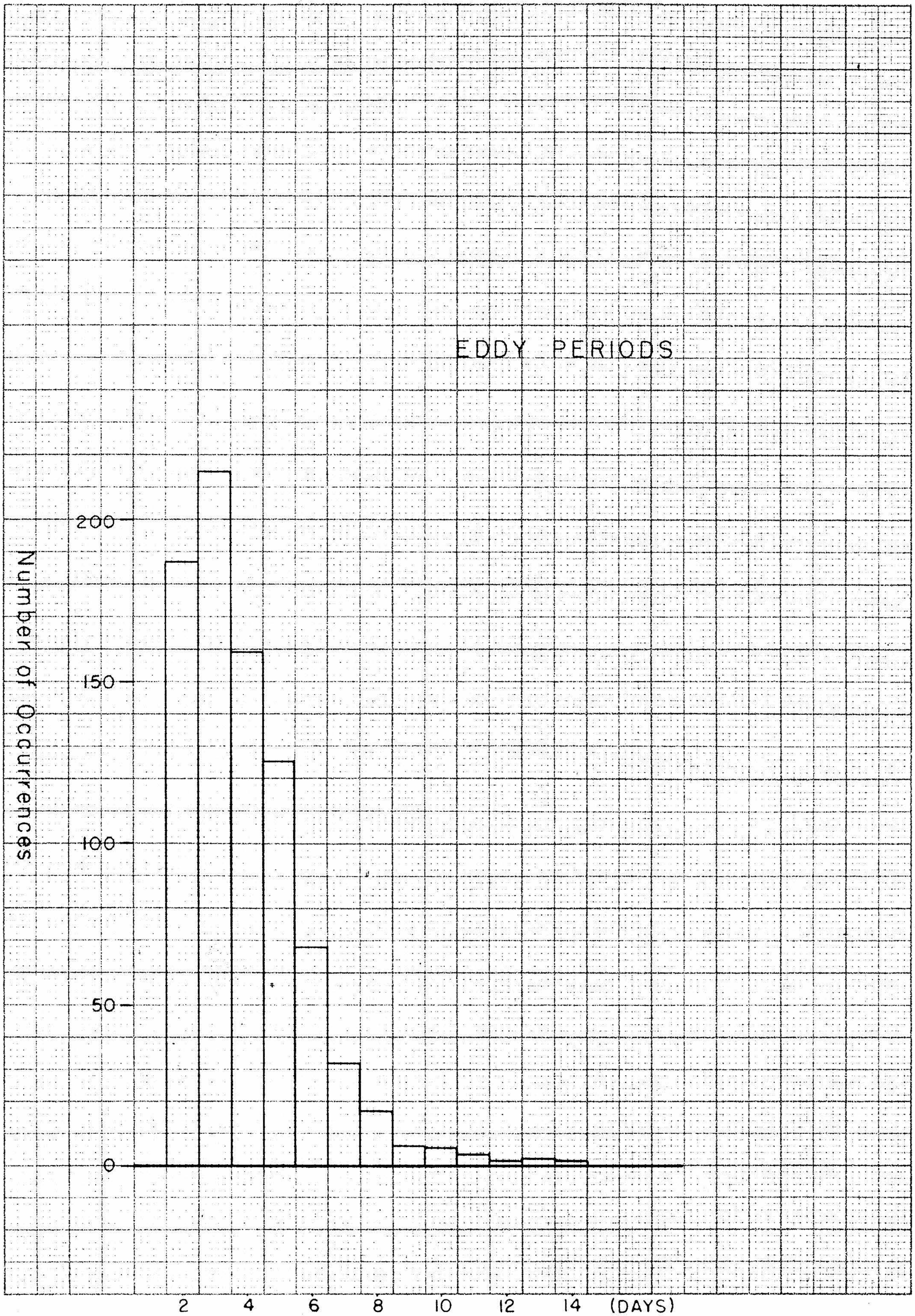

EDDY PERIODS
Number of Occurrences
200
150
100
50
0
2
4
6
8
10
12
14
(DAYS)

Fig. L

anticyclones. The use of three day mean charts in the preceding sections is thus an attempt to eliminate the effects of these migratory cyclones and anticyclones and to present only those pressure changes characteristic of the longer period Blocking Action processes.

It is of interest to compare the shape of Figs. XLVIII and XLIX with curves obtained in the statistical theory of turbulence as discussed by G. I. Taylor (7). Taylor has treated the problem of turbulent flow by considering the standard deviation of the distance traveled by a particle as a function of the time of travel and by considering the correlation between the velocity of the particle and its velocity at some later time. In a later work (8) he has extended this idea to the correlation between the velocity at a fixed point and the velocity at the same point at some later time. The standard deviation curve and the correlation curves which he obtains are of exactly the form of Figs. XLVIII and XLIX. In terms of turbulent flow Taylor has used the velocity of the flow as the characteristic function describing the character of the turbulent motion. Since the mean pressure over some interval is also a characteristic function of the turbulent flow one may choose to represent the motion in terms of this characteristic function. Interpreting Fig. XLVIII and XLIX in the light of Taylor's results one may assume that they represent the passage of turbulent eddies of varying sizes past the fixed point. In terms of the processes discussed in the preceding sections the turbulent eddies begin with the small scale eddies associated with the passage of migratory cyclones and anticyclones and increase in size through the Blocking Action processes of varying length.

To summarize the preceding paragraphs, the most satisfactory short period mean pressure chart to use consistently will be that covering a three day interval. This will give the smoothest representation of short segments of a longer period process with a minimum of contribution from the small scale cyclones and anticyclones. For the best delineation of the long period processes, a mean pressure chart over a period of twenty or more days will consistently give the best results with due consideration being given to the elimination of the short term pressure fluctuations associated with migratory cyclones and anticyclones.

CONCLUSION

Various experimentally observed facts in regard to the Blocking Action process have been presented in this study and some attempt has been made to offer tentative explanations for these facts. An adequate theory is not yet available but the observations presented here must be taken into account in the formation of any future theory. It is hoped that enough information has been presented to demonstrate the extreme importance of these processes in the anticipation of weather trends covering periods of a few days to three to four weeks and that this information will serve to stimulate further research in this field.

APPENDIX A

The statistical significance of an average pressure departure of plus five mbs. for a three day period has been checked by adding the daily pressure departures at the point 60° N - 140° W in overlapping three day periods for the January-February months of the twenty even years 1900-1938. This gives all possible consecutive three day total pressure departures for the January-February interval of these years. The characteristics of this set of data are the population characteristics and are given by:

Mean	2.21 mbs.
Standard deviation	37.6 mbs.
Total number	1149

From this data it is assumed that a sample of ten three day periods is drawn and it is to be determined whether this sample may be considered as a random sample drawn from the original population. The characteristics of the sample data are:

Mean	The mean value is to be sufficiently high to allow one chance in twenty for the sample to be a random sample of the original population.
Total Number	10

From the concept of a pressure departure from normal, the pressure departures may be considered as normally distributed about the mean value of 2.21 mbs.

The usual statistical test for deviations from a normal distribution is:

$$t = \frac{(\bar{x} - \tilde{x})\sqrt{N}}{\sigma}$$

where t is distributed normally with a mean of zero and a standard deviation of one. $\bar{x}$ is the mean of the sample, $\tilde{x}$ is the mean of the population, N is the total number in the sample and σ is the standard deviation of the population.

$t = 1.64$ corresponds to a probability of less than or equal to .05 that the sample is a random sample drawn from the population.

For this case:

$$\bar{x} \geq 7.2 \text{ mbs.}$$

An average of 7.2 mbs. over a period of three days is therefore statistically significant at the five percent level.

A similar check at the point 60° N - 170° W shows that an average departure of 5.3 mbs. for a sample of ten is statistically significant at the five percent level.

APPENDIX B

The correlation coefficient between the North American sector and the Atlantic sector is computed from standard correlation formulae found in any standard statistics reference. In its simplest computational form the correlation coefficient is given by:

$$r = \frac{n\Sigma xy - (\Sigma x)(\Sigma y)}{\left[(n\Sigma x^2 - (\Sigma x)^2)(n\Sigma y^2 - (\Sigma y)^2\right]^{\frac{1}{2}}}$$

For the 1914 case of one day lag:

$n = 58$

$\Sigma x = 535.81$ mbs.

$\Sigma y = 625.70$ mbs.

$\Sigma x^2 = 5121.50$ mbs.^{2}

$\Sigma y^2 = 6979.71$ mbs.^{2}

$\Sigma xy = 5772.54$ mbs.^{2}

From these data:

$r = .485$

REFERENCES

(1) Elliott, R. D. Progress Report No. 3 on Blocking Action Project submitted to Office of Naval Research February 10, 1948

(2) Defant, A. Die Zirkulation der Atmosphare in den Gemassigten Breiten der Erde-Geografiska Annaler (1921) 3, p. 209

(3) Lettau, H. "Atmospharische Turbulenz," Akademische Verlagsgesellschaft, Leipzig (1939) Chap. 12

(4) Rossby, C. G. J. Marine Research (1939) 2, p. 38

(5) Cressman, G. P. J. Meteorology (1948) 5, p. 58

(6) Rossby, C. G. J. Meteorology (1945) 2, p. 187

(7) Taylor, G. I. Proc. London Math. Soc. (1922) 20, p. 196

(8) Taylor, G. I. Proc. Roy. Soc. A (1935) 151, p. 421