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THE STRATOSPHERIC MONSOON

Part I

An Atlas of Prevailing Monthly Zonal Winds in the Stratosphere over the Northern Hemisphere

by
A. D. Belmont

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2003 East Hennepin Avenue
Minneapolis 13, Minnesota

THE STRATOSPHERIC MONSOON

I. PURPOSE

The seasonal reversal of stratospheric winds is one of the major features of the general circulation. Previous studies have described the "normal" progress of this reversal along the east and west coasts of North America (1, 2) and the individual yearly events of 1957, 1958, and 1959 (3). Some interesting and irregular features of this process led us to see how it occurs on a larger scale, and with respect to longitude. Stratospheric circulation is usually too asymmetric to allow generalization from a single meridian. We thus present here the same parameters used earlier, on a hemispheric scale at four levels (100, 50, 30, and 10 mb), to demonstrate how the reversal is propagated by month with respect to longitude, latitude, and altitude.

This text is intended mainly to explain how the atlas was prepared, and to give a preliminary description of the main features of the monsoon. A full discussion of the reversal process and a comparision with earlier results is under preparation as a separate paper.

II. PARAMETERS USED

There are two usual methods for describing the winds at a given station. One is to present a frequency distribution of direction and speed for the period which may be shown graphically as a wind rose. A second method is to give the resultant wind vector for the period, and perhaps to reduce this vector into its zonal and meridional components.

Since our purpose here is to describe the change of easterly flow to westerly flow, the net resultant zonal component is not completely satisfactory. The change is gradual, because each month contains both components. We present here the total frequency of occurrence and the mean zonal magnitude, separately for consolidated easterlies and for westerlies. That is, all easterly directions on a 16 point compass are considered east, with north, south, and calm excluded.

In this way it should be possible to evaluate, in more detail than has previously been attempted, (1) which zonal direction is the relatively prevailing one and by how much, and (2) the mean zonal component of the prevailing direction.

The frequency values are simply the sums of all easterly (or westerly) directions, omitting north, south, and calm. The zonal components of the mean scalar wind speed were found for each observed direction, then weighted by the corresponding frequency for each direction, and averaged over all easterly (or westerly) directions.

"Prevailing" wind is defined as the zonal direction with the larger frequency. The dashed line on atlas charts depicts the boundary between prevailing easterlies and westerlies. Rather than prepare two charts, one of east and one of west, we have used a combined chart which shows only the prevailing portions of each. The average zonal component maps give the speed in knots for the same prevailing direction shown on the corresponding frequency sections.

The centers of maximum west (or east) frequency are indicated by a capital W (or E), and those minor centers where winds only prevail to a minimum degree (about 60%) are marked by a script "w" (or "e"). The frequency charts use the intervals of 60%, 80%, and 95%. Wind speeds are shown at 10-knot intervals.

There is the question of whether relative frequencies of east and west winds should not be used rather than their absolute frequencies because the primary purpose of the study is to show how the change from one to the other occurs, without consideration of north, south, or calm winds. During the analysis, it was found that blind adherence to absolute frequencies often resulted in complicated minor patterns which would have been greatly simplified had relative frequencies been used. This occurs because when there is an appreciable frequency of N + S + C wind, the frequencies E + W are not really comparable to those frequencies of E + W which occur when there are no N + S + C. If it is the relative frequency of E or W with which we are concerned, all E + W frequencies should be "normalized" to a base of 100% in order to be comparable and to avoid peculiarities in the analysis. After the frequencies are so normalized, the corresponding isolines will not usually represent absolute frequency of E or W (since N, S, and C are excluded). However, as many users would like to have absolute frequency values, and as it was impractical to make both analyses, it was decided to use absolute frequencies.

III. DATA

The stations used on these maps were limited to those for which summaries of upper wind observations, by month, were already available from the National Weather Records Center for levels at and higher than 100 mb. The length of record at each station varies greatly. Some of the data extend back to 1949, although the highest levels are generally available only for the years since 1957 because of the encouragement of the IGY program to attain highest possible rawinsonde ascents. Although no pilot balloon data is included, the rawins were observed with many different types of equipment, using the various procedures of each country; and thus the accuracy of the data is equally variable.

The only practical way to evaluate such heterogeneous material is to rely on the maxim of consistency of independent data. Where all data are in agreement there is excellent confidence; and this decreases in proportion to the difficulty of fitting isolines to the data. Because the number of observations decreased rapidly above 50 mb, there were large areas of no data and for which no analysis was reproduced (although tentative analyses were estimated on the working charts). We wish to present the best estimate possible with the available data, but experience has shown it to be undesirable to extend preconceived ideas to unknown areas. The general seasonal pattern is already known; the exceptions and variations by longitude are precisely what we wish to determine, and these should not be extrapolated without some evidence.

All analysts are aware how easy it is to analyze over areas of sparse coverage, and how difficult it is when there is much, but inconsistent, data. The data were first analyzed quite literally and the analyses examined for continuity. Consistent, large perturbations were usually retained; temporary and minor complications were smoothed out. Hence, areas of little data always have a smooth pattern, and complicated analysis generally reflects the presence of data too consistent to be ignored. Although analyses have been scrutinized carefully, and an effort was made to smoothen consistently, the charts may still contain some variations in interpretation.

The climatological bias of rawinsonde observations should be kept in mind:

1. There is a strong bias in favor of weak winds at high levels which permit a balloon to remain within observation range longer.

2. For the same reason, a reversal of flow at higher levels may be reported with greater proportional frequency than ascents without reversals.

3. Winds taken with radio direction or other methods which utilize radiosonde data to determine height, suffer from all the errors inherent in stratospheric radiosonde measurements due to aneroid and thermistor errors and resultant errors in height computations. Hence, winds may be ascribed to incorrect levels, in a not always systematic fashion, as the instrumental errors may be random.

4. The number of balloons reaching highest levels is frequently a function of air temperature; hence ascents in warmest conditions are more likely to reach highest levels (10 mb for example) than those taken during coldest air temperature.

The reader should also recall that reported direction has little significance near the pole. A broad current passing directly over the pole can be reported from all directions depending only on the relative location of the observer, although the flow is from a single direction.

The same flow at mid-latitudes, however, would be reported from the same direction regardless of the relative location of the observer to the flow pattern. Similarly, a small closed low positioned symmetrically around the pole gives westerly flow at all longitudes, but if slightly displaced so that the pattern is entirely to one side of the pole, half of the flow is called easterly although the circulation pattern has really not changed. Because of this polar singularity of direction, direction data of the farthest north stations may lose much of their significance.

IV. MAIN FEATURES OF THE STRATOSPHERIC MONSOON

A. 100 MB

Frequency

The stratospheric monsoon does not properly reach down to 100 mb, yet its influence is still felt at this level by the presence of weak polar easterlies in summer.

The almost constant winter westerlies have their maximum frequency over the entire hemisphere at mid-latitudes. They decrease in frequency toward the pole where small areas of prevailing easterlies are found in almost all months. Judging from the 95% W isolines, the westerlies reach farthest north in October.

The tropical easterlies remain south of about 15° until May when they start their northward migration from the Asian side; in June they migrate northward from the American sector. The E-W border apparently moves northward last over the oceans. In July the border is near 30° except over the Pacific where it stretches between 20° and 50°. Large weak easterly areas are found near the pole. In August the border starts its retreat southward; and from September to June westerlies again prevail over most of the tropical Atlantic and Pacific. The easterlies are always most prevalent over Southern Asia, with their summer peak extending from the Western Pacific, across southern Asia to the eastern Atlantic.

Speed

The main feature of the average speed distribution is the persistent location of westerly maxima in the areas of Japan, the Himalayans, northeast Africa, and eastern America. This pattern starts with 40 knots in September over Asia and increases rapidly in intensity to 80 knots in November over Japan. Its peak occurs about February, when the Japanese winds are shown with an average zonal speed of 100 knots. The tropical easterlies of about 20 knots in the winter increase to 70 knots in July over India, while over Central America for the same month they are less than 20 knots. The prevailing polar summer easterlies are always weak (less than 10 knots) although occasional centers of prevailing polar easterlies in the winter may have average speeds which exceed 30 knots.

Two main characteristics of the 100 mb prevailing wind pattern are evident:

1. The large belts of prevailing winter westerlies and summer easterlies appear to be located over the main land masses and to occur least frequently over the oceans.

2. Much stronger winter westerlies and summer easterlies are found over Asia than over the Americas.

At this level, with relatively good coverage, there still appears to be an influence of surface land and sea distribution and topography on the atmosphere. Station coverage for the oceans is very sparse, which may partly account for this effect. Nevertheless, there can be little doubt that the Eurasian land mass has far stronger and more extensive seasonal wind systems than occur over North America. The fact that in the tropics the 100 mb surface lies near or even below the tropical tropopause can help explain the stronger winds of the eastern hemisphere only to the extent that we are willing to ascribe a land-sea influence to tropopause height. The 100 mb tropopause intersection is more a function of latitude than longitude, so this intersection does not appear to be a primary contributory cause. As the surface-caused radiational monsoon of Southern Asia may be considered to be below 500 mb, it could be concluded that the 100 mb monsoon reflects the upper stratospheric meridional reversal of thermal gradient. Yet its stronger development over Asia is unlike the pattern at higher levels. The full explanation of these features is complex and probably includes many other factors in addition to those mentioned.

B. 50 MB

Frequency

The areas of prevailing easterlies in the South Pacific and Caribbean are smallest in January and gradually extend east and west so that by April they almost encircle the latitudes south of 20° except over Africa and the eastern Pacific. In May, prevailing easterlies are suddenly found over most of the hemisphere. Small areas of slightly prevailing westerlies are shown over Africa, Western Siberia and between about 40-50° over North America. By June there are no important westerly areas. Until June the easterlies appear to extend farther north on the Pacific sector than in the American or Eurasian sectors. The center of maximum frequency of easterlies is in the tropics and moves northward, reaching its strongest development in July when the entire hemisphere is essentially easterly. In August the region north of 50° has large areas of 60% westerlies indicating the beginning of the fall reversal at this level. The autumn reversal is more clearly established in September as the east-west border moves south to near 40°, with a sharply defined frequency gradient of strongly prevailing westerlies to the north and with easterlies to the south. In the fall (September and October) these westerlies again (as in the spring) appear to extend farther south over Eurasia than over the Pacific or American sectors. In November prevailing westerlies reach south over Africa to the equator while other sectors are still easterly up to 30° in America and almost 40° in the Central Pacific. December and January show prevailing easterlies only in the Pacific from 10-40° and a weak narrow belt along 10-20° over Central America.

Speed

In fall and winter the zonal component of the westerlies has a primary maximum of at least 70 knots in Asia and a secondary one in the north Atlantic. Although the present data do not indicate any important centers of maximum winds over southern Asia in January and March, it is most likely that this region also has the strongest winds of the hemisphere throughout the winter at this level, just as it does at 100 mb. The tropical easterlies are strongest near the equator and increase from 10 knots in April to 50 knots in July and August along the southern Asian coast. They then weaken again as they recede southward from September through November.

There is a difference between 100 mb and higher level reversal patterns. At 50 mb there appears to be a definite preference for the tropical easterlies to be situated over the oceans, especially the southwest Pacific, and for the mid- or high-latitude winter westerlies to be over land. However, at 100 mb both east and west wind regimes preferred the regions of the largest land masses.

C. 30 MB

Frequency

At 30 mb the prevailing easterlies are more extensive than at 50 mb, even in January. Although data over Asia and Eastern Europe are lacking, it again appears that the westerlies are more persistent there than at comparable latitudes in the western hemisphere. The main areas of prevailing easterlies are in the South Pacific and South Atlantic in January, and they gradually move northward in their sectors so that in April the oceanic circulations are easterly, while the continents still appear to be mainly westerly. Suddenly in May, all latitudes become easterly and remain so through August. The autumn reversal is seen in September with westerlies occurring from the pole to about 45°.

One interesting feature is the persistent northward extension of easterlies in the Eastern Pacific from November to April, which reaches 55° in December and almost 70° in April.

Speed

In January maximum mean zonal westerly speeds of at least 60 knots are found in four regions: eastern Asia, the Alaskan sector of the Arctic, northeast Canada and the north Atlantic. Tropical easterlies increase from about 30 knots near the equator in January to 40 knots in March, April and May and 50 knots in June; then the easterlies apparently decrease to 40 knots from July through November and to 30 in December.

D. 10 MB

Frequency

Because this level is near the limit of the rawinsonde, data are of course very sparse; yet some large features seem definite. The most frequent easterlies are centered over the southern ocean regions and move progressively northward as they do at 30 mb. Possibly the polar easterlies, shown already in April, indicate that the reversal occurs first at this altitude. Westerlies over the continents remain through April and again appear last of the group to change to easterlies. Easterlies prevail everywhere during May, June, and July. The westerly center over the Aleutians in August shows that the fall reversal is beginning. However, to the extent that the limited data can be interpreted, the westerly area is less developed at 10 mb than at 50 mb, and we thus conclude that the fall reversal starts first at lower levels and proceeds upward.

Speed

Judging from the small sample, westerlies reach an average of 110 knots over the north Atlantic (Keflavik) in January, and then decrease. The easterly components are also more intense, ranging from 40 knots in January to 60 in February, to a maximum of 80 in June, and decreasing to 70 in July. In November and December they are down to 30 knots.

V. SUMMARY

The spring reversal of polar westerlies to polar easterlies starts at highest levels and proceeds downward and southward from the arctic. In April it is well started at 10 mb, but hardly recognizable at 50 mb. Yet the mean charts show that the process is completed in May at all levels from 50 mb to 10 mb, and that it possibly influences even the 100 mb level. In May, June, and July only easterlies prevail at levels above 100 mb. In August, the fall reversal to westerlies is far more pronounced at 50 mb than at 10 mb or 30 mb. It starts at polar regions and progresses upward and southward. Both reversals occur so rapidly, however, that monthly mean charts can only show that they are completed in May and September. From earlier studies, we learn that the onset of the spring reversal is variable from year to year; but the end of the summer monsoon appears to be fairly constant, occurring between late August and early September. It is of interest to note that the first meteorological rocket data (4) suggest that both reversals proceed downward to 30 km. It is possible that the fall reversal may move upward from 15 to 30 km at the same time that it comes downward from 60 to 30 km, but further data will be needed to clarify this point.

VI. ACKNOWLEDGEMENTS

This type of meteorological data processing and analysis can only be done with the painstaking help of others. Our thanks are extended to T. Bauman, D. Dartt, E. Fritze, H. Jensen, and O. Sondergaard who have all participated in some stage of the preparation of this atlas from reduction of raw data to final drafting. The encouraging support of the Office of Naval Research and the Bureau of Naval Weapons is sincerely appreciated.

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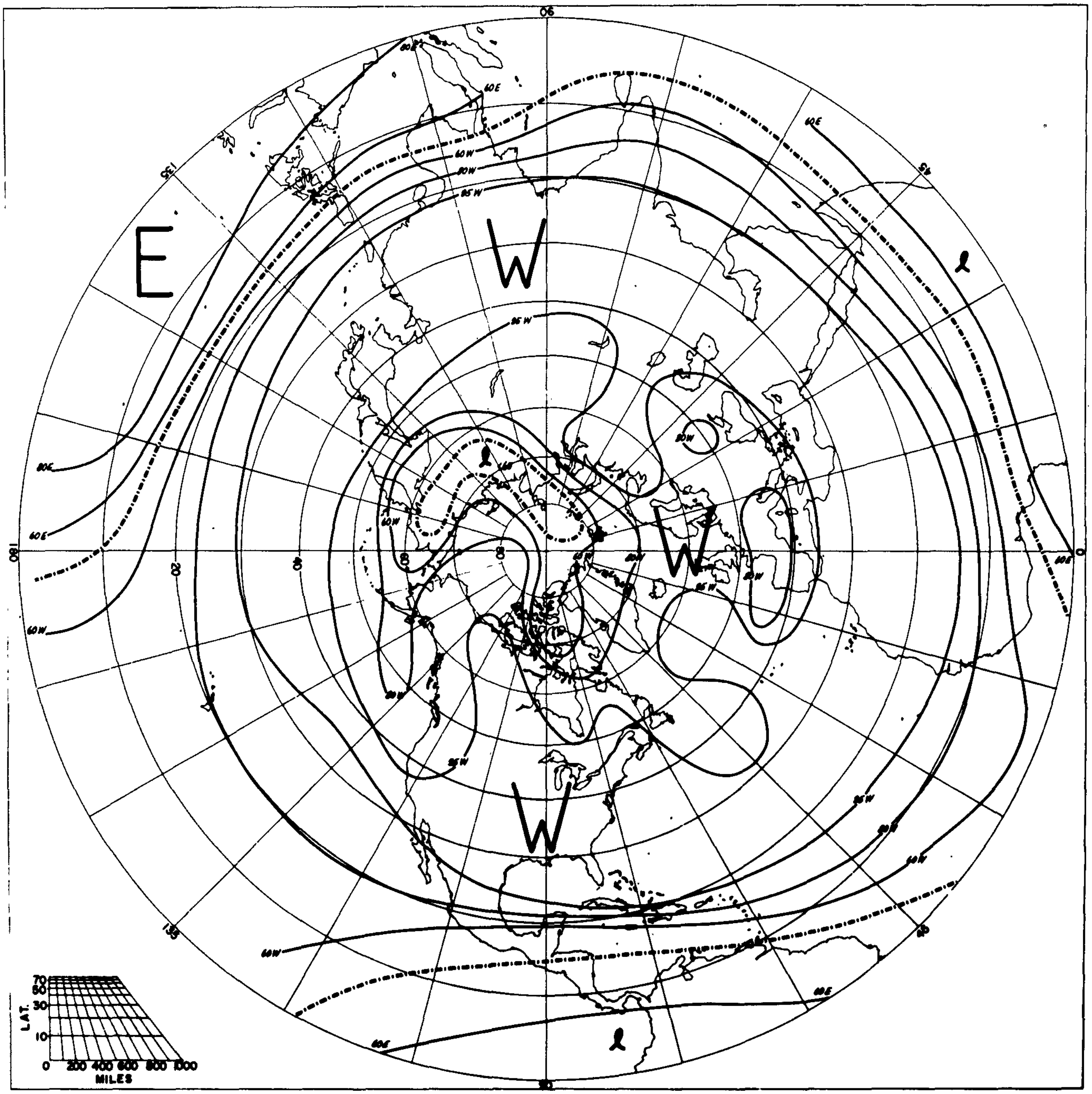

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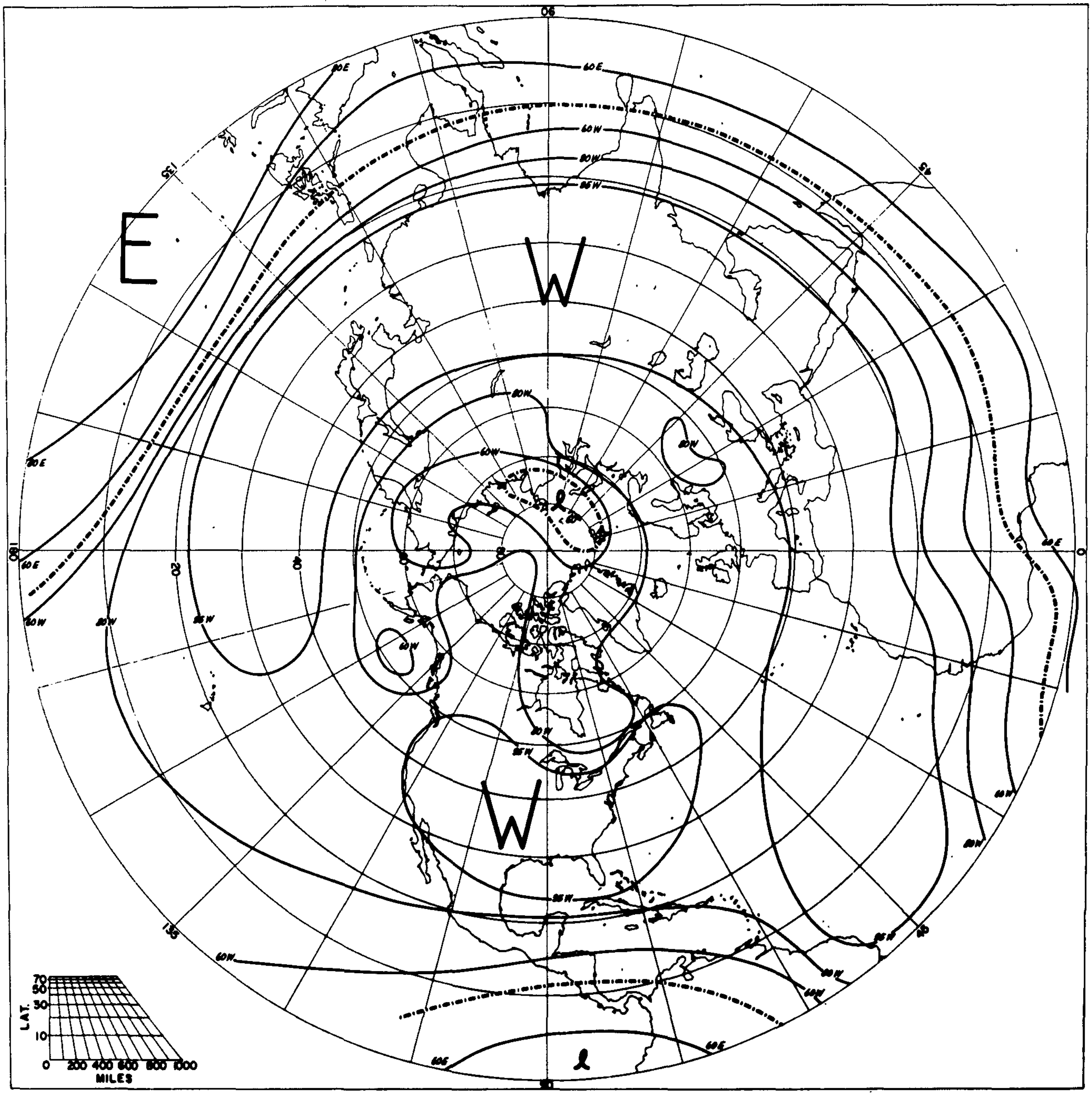

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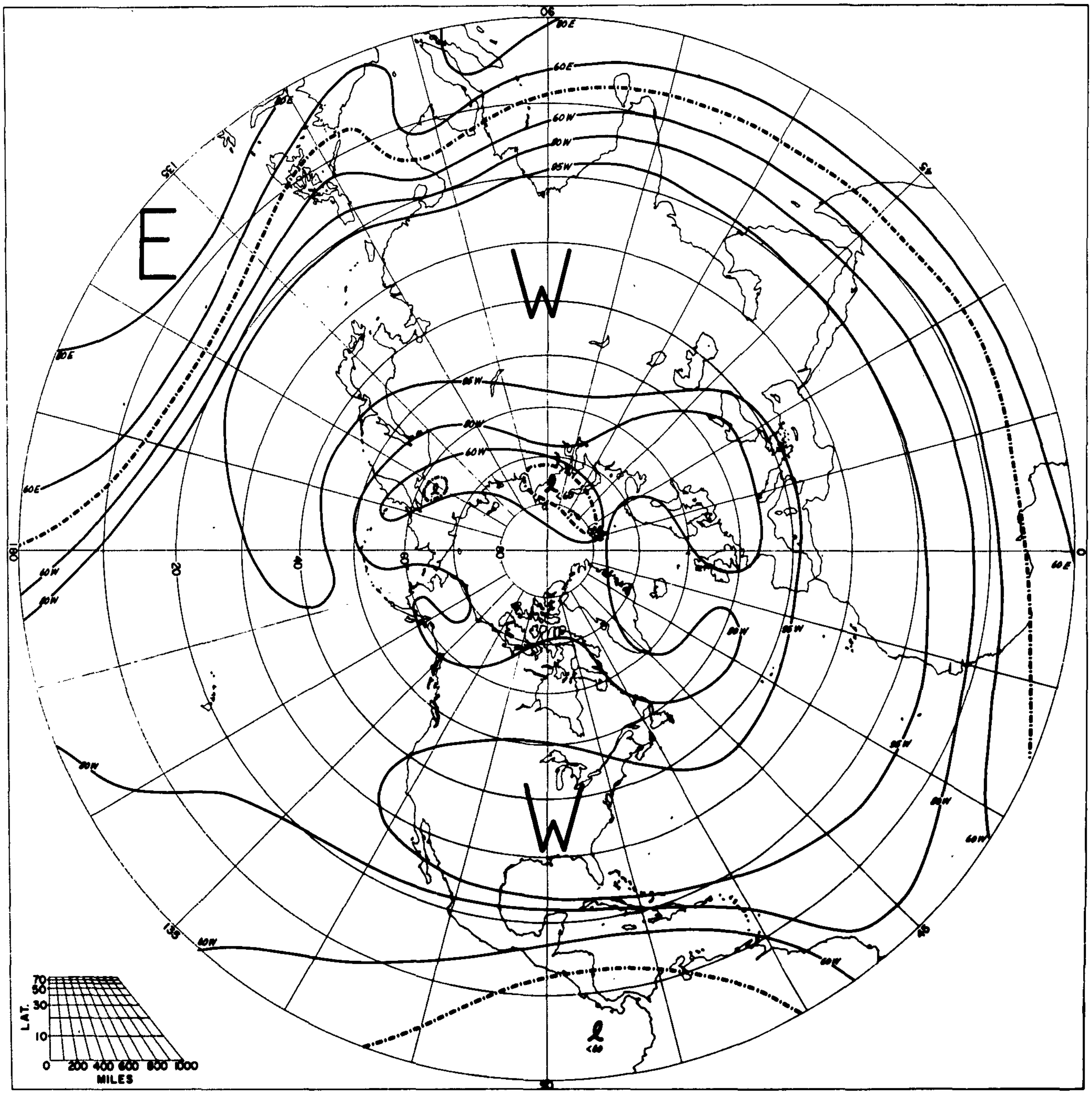

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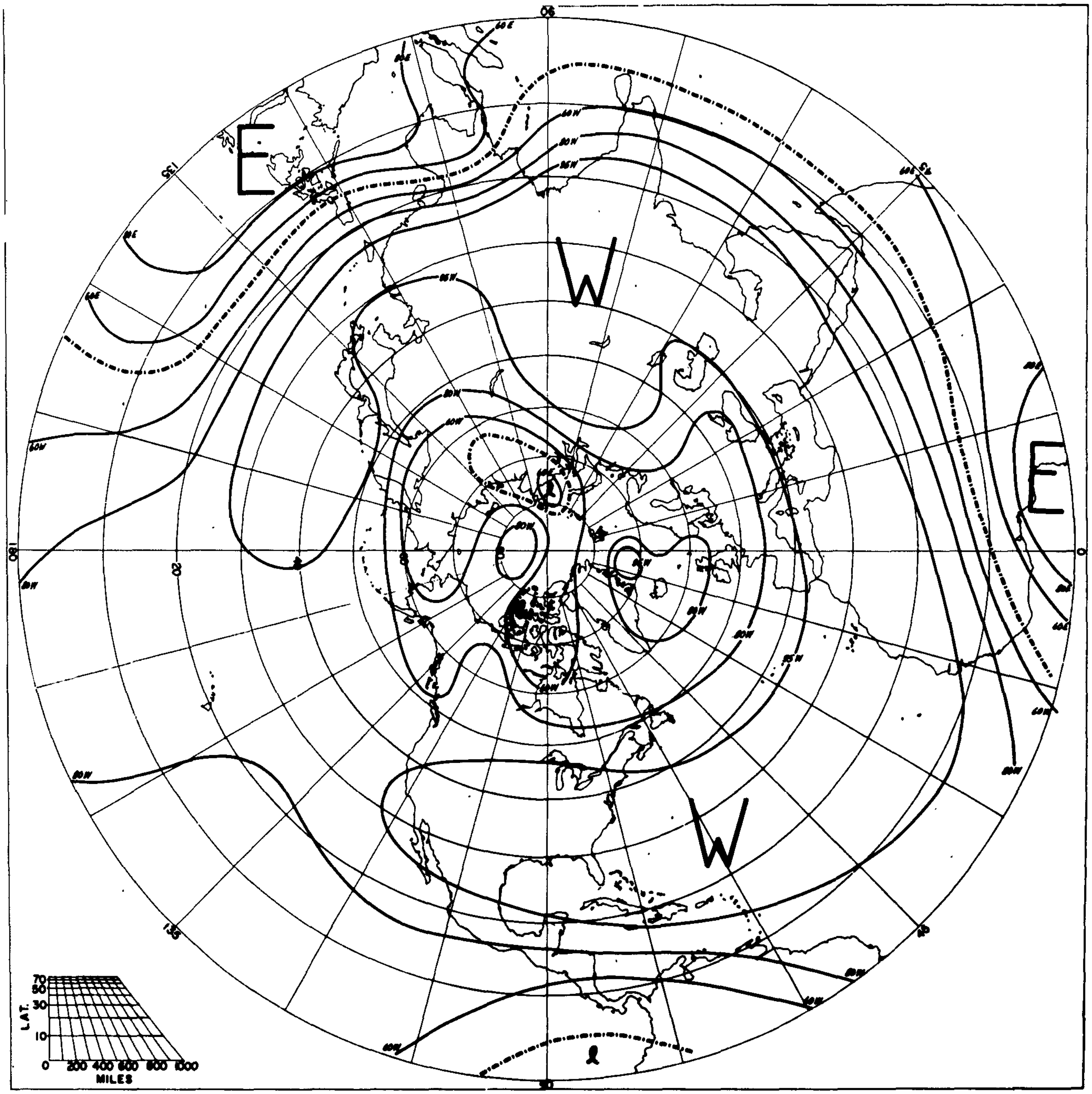

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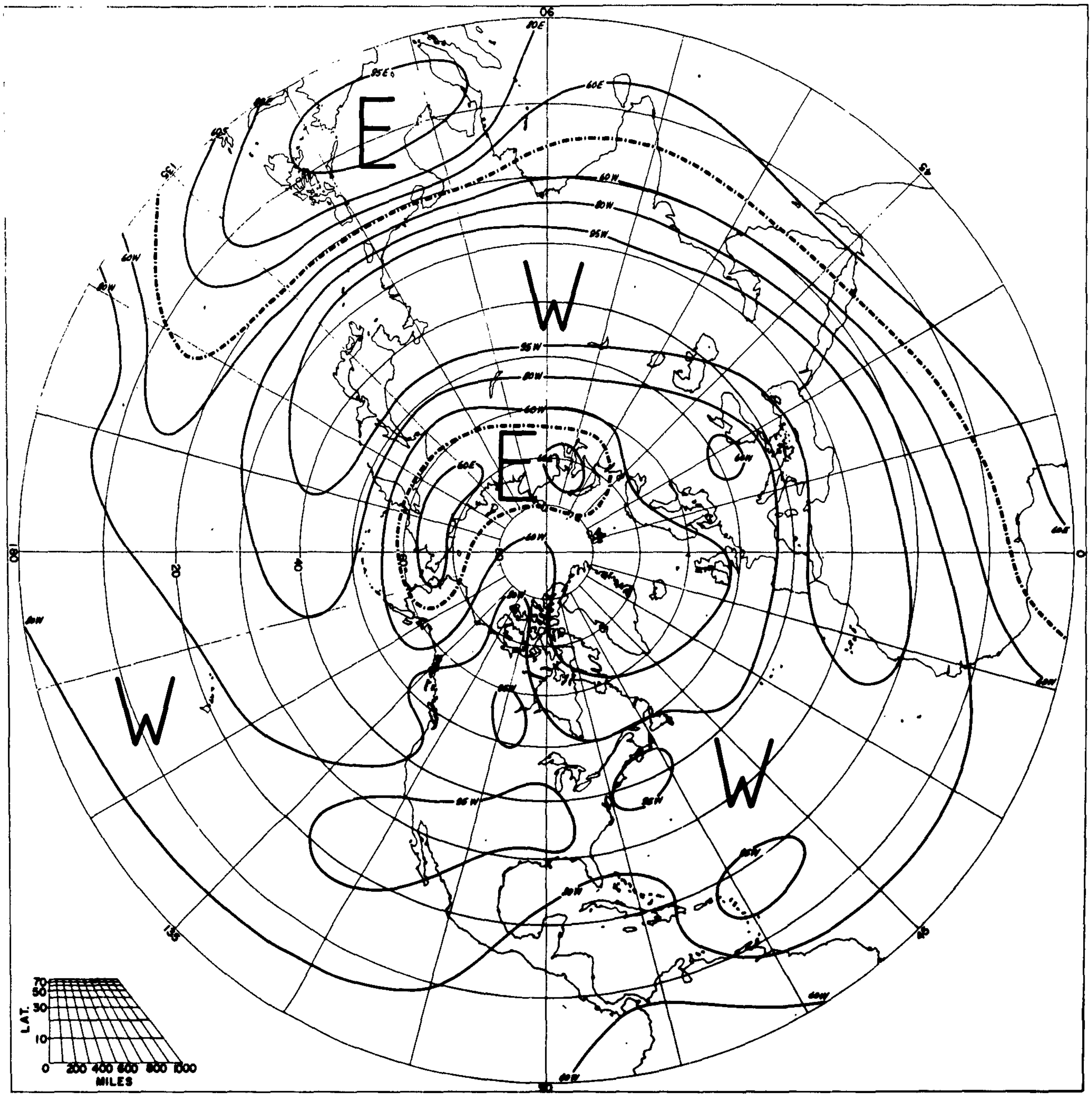

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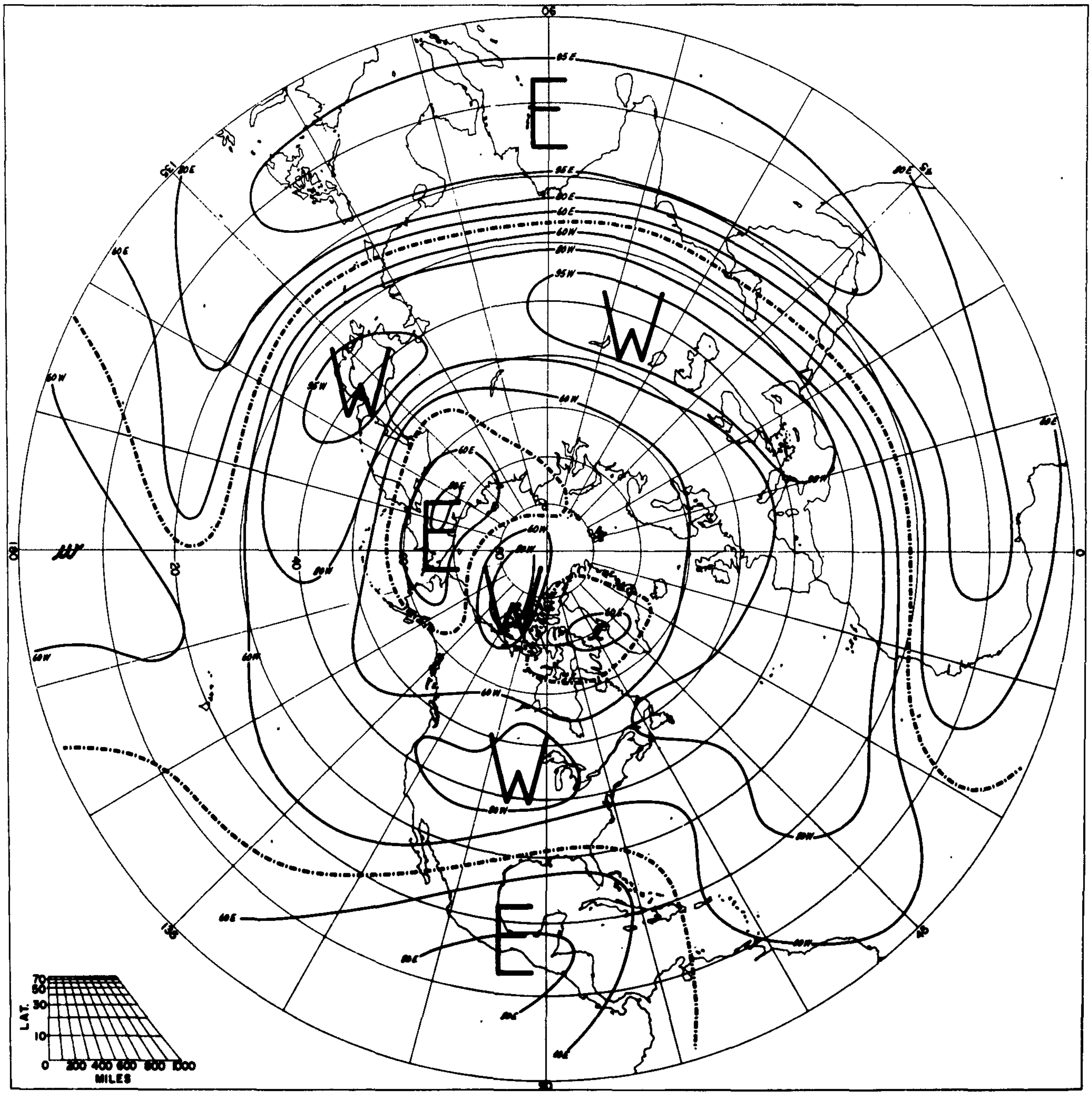

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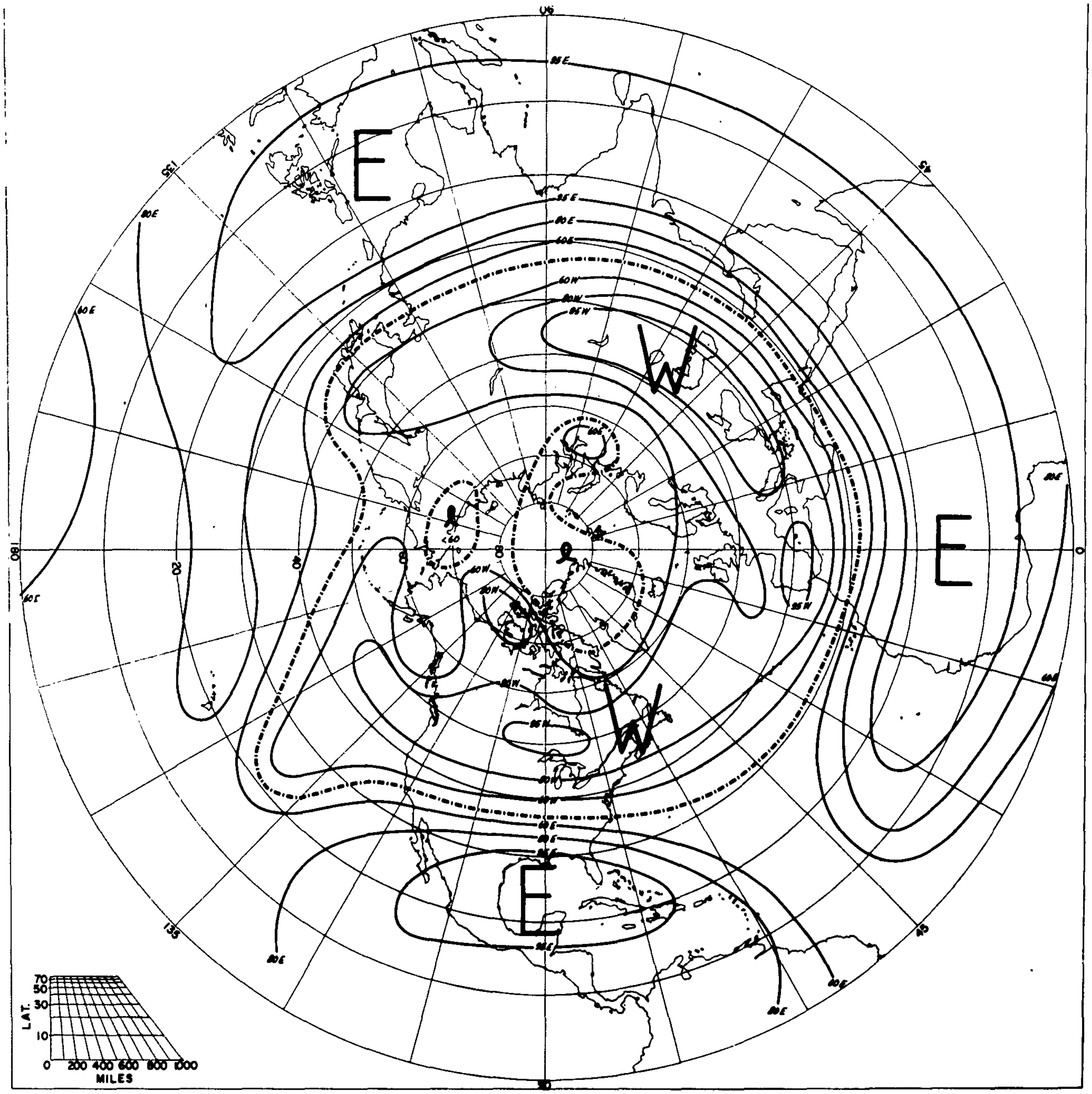

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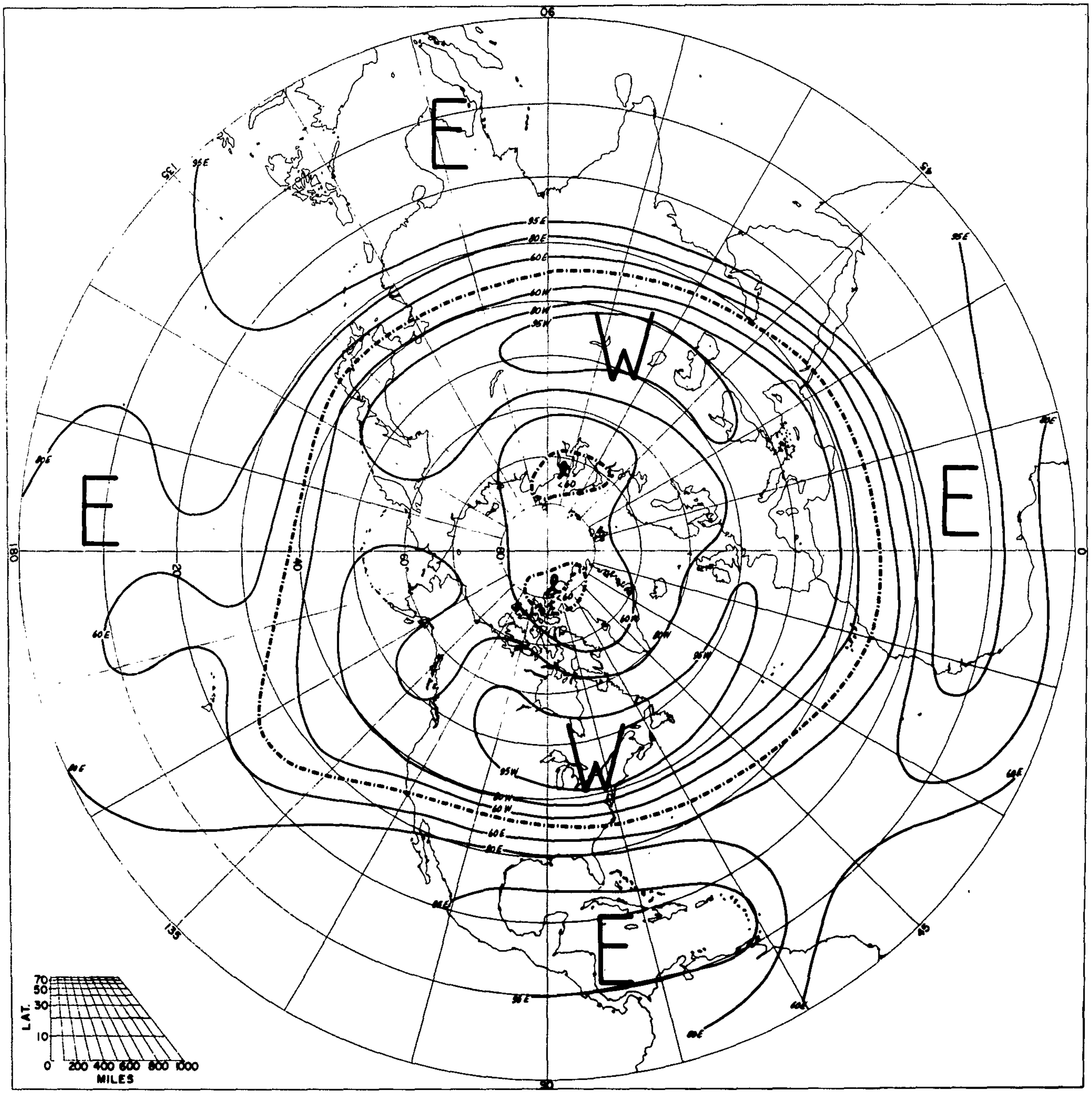

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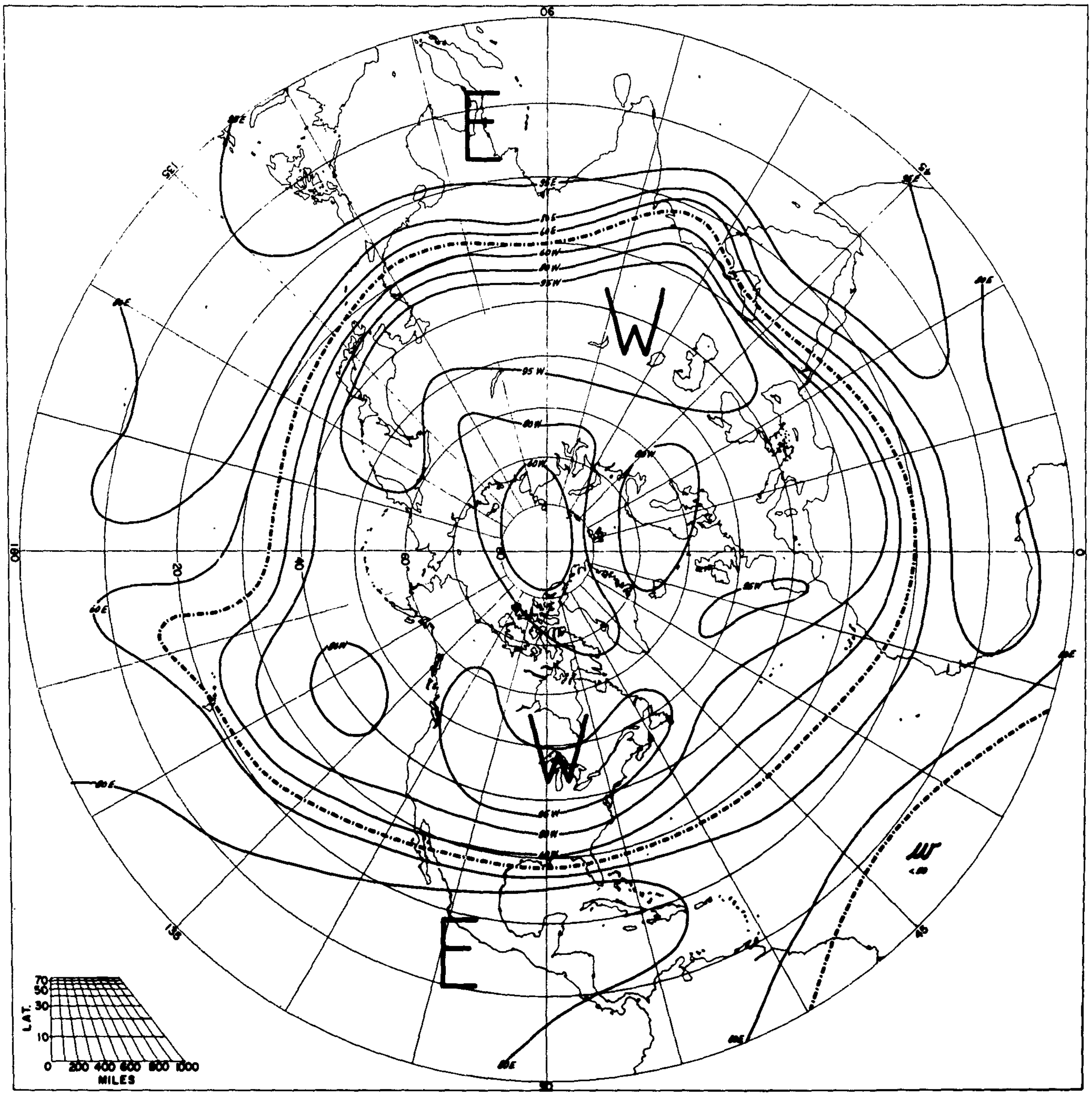

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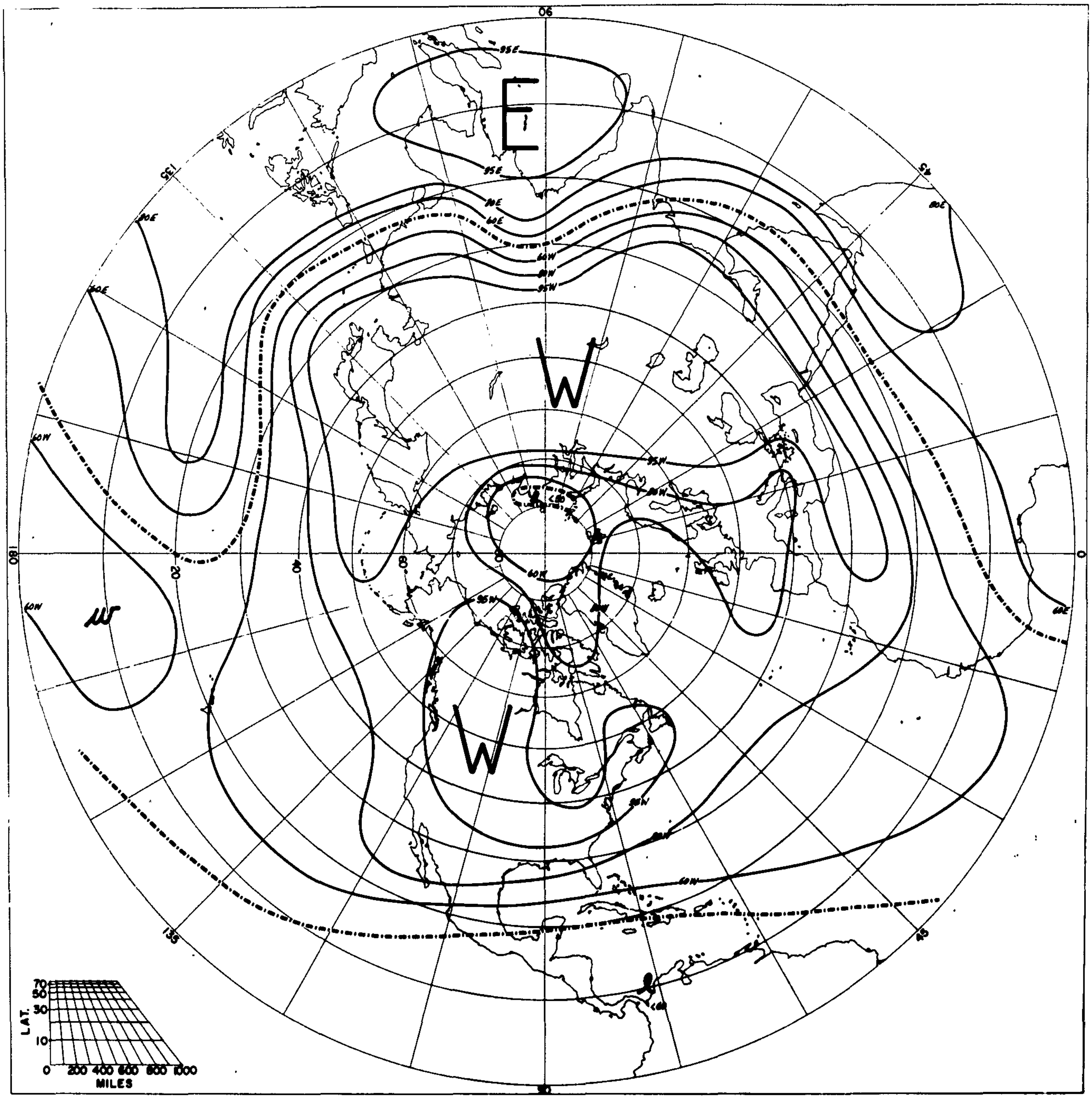

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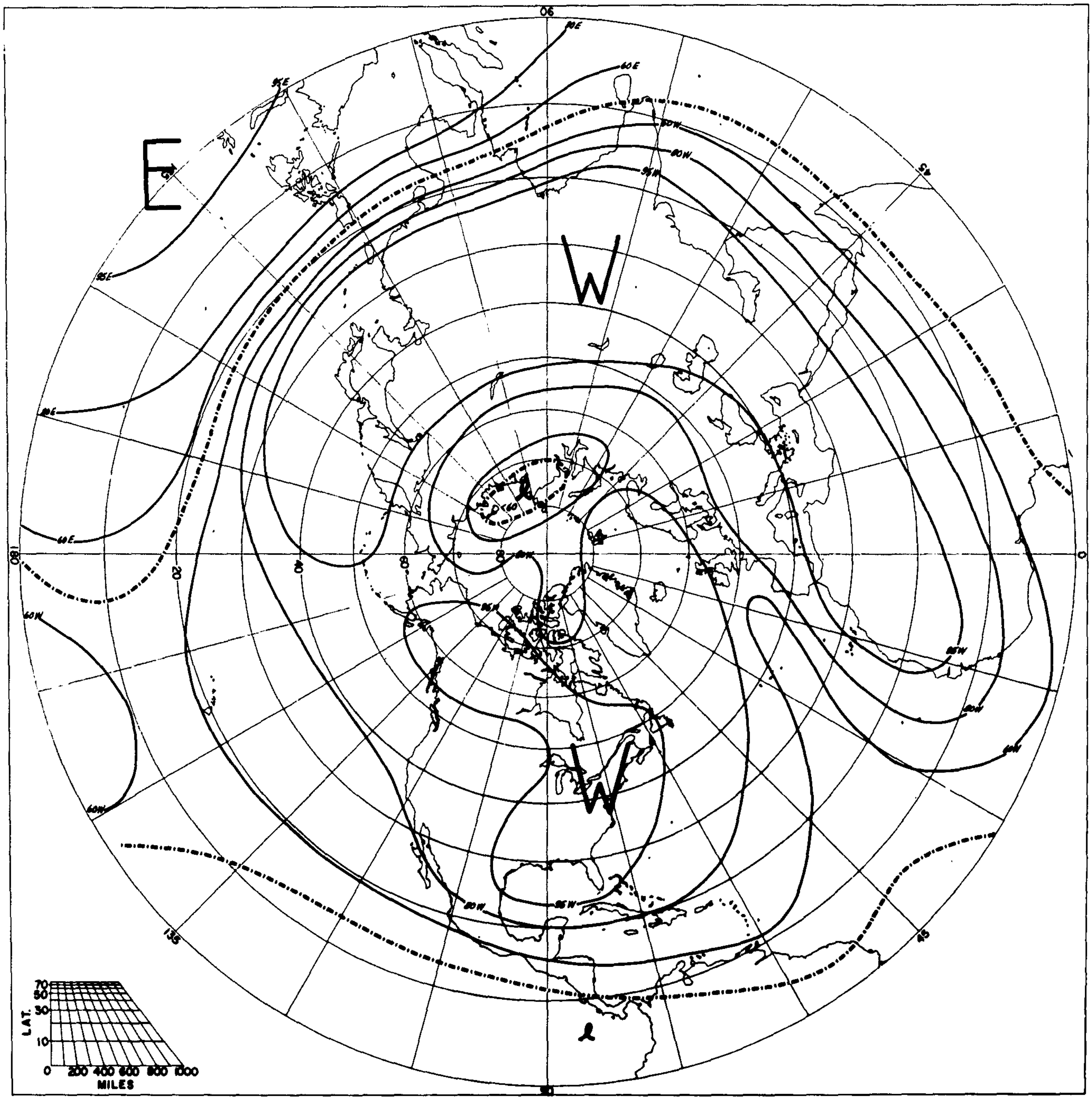

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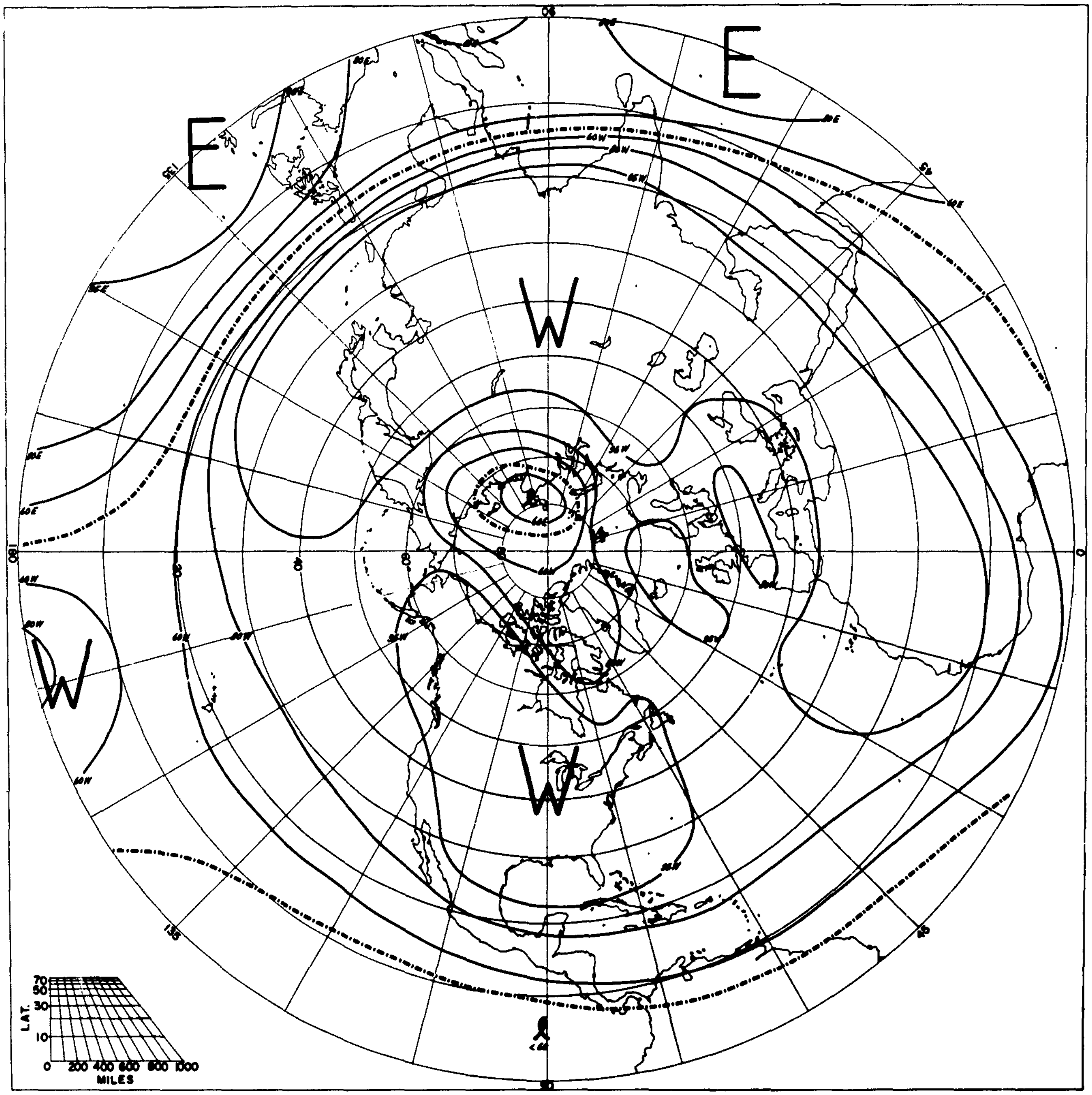

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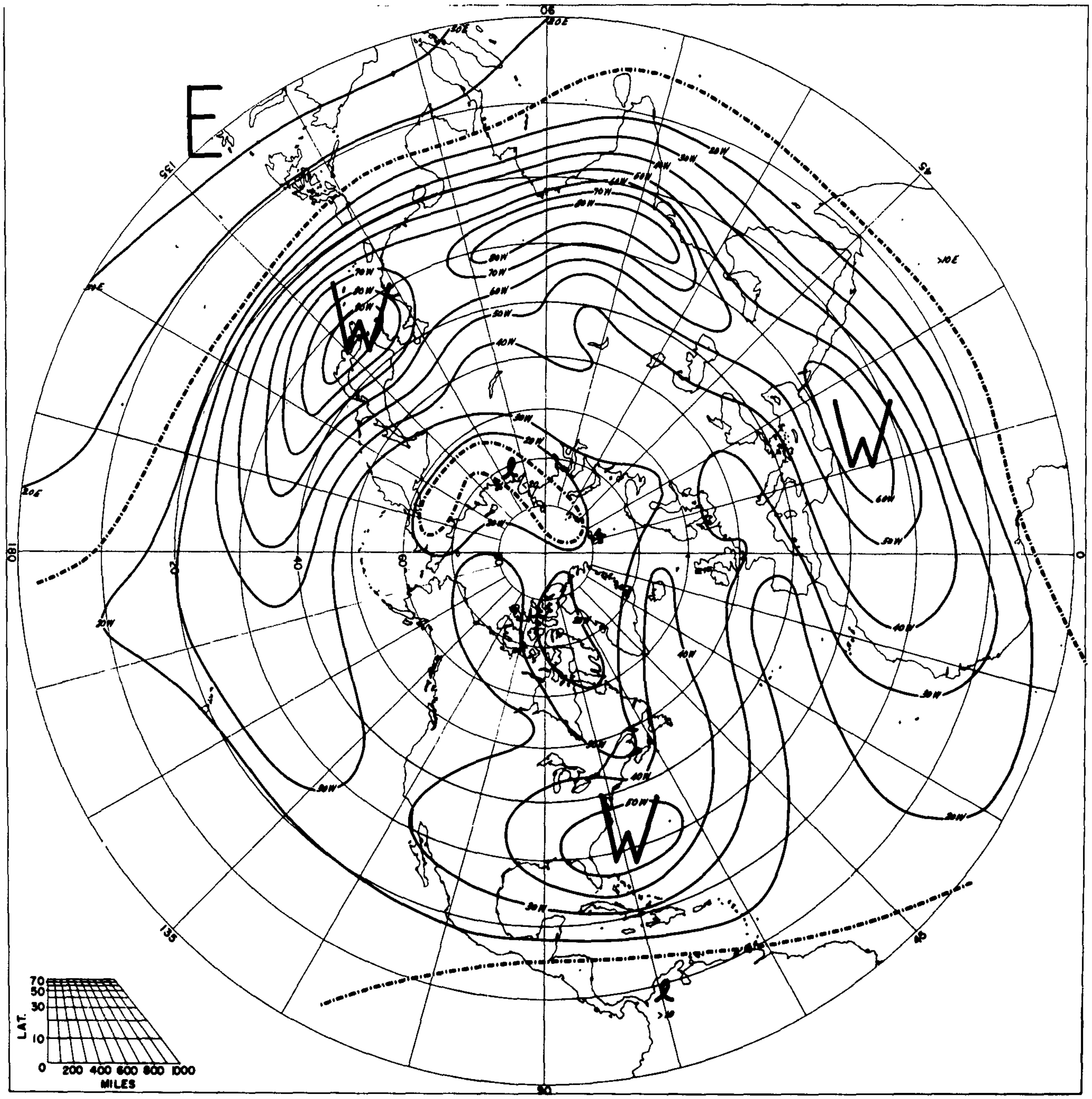

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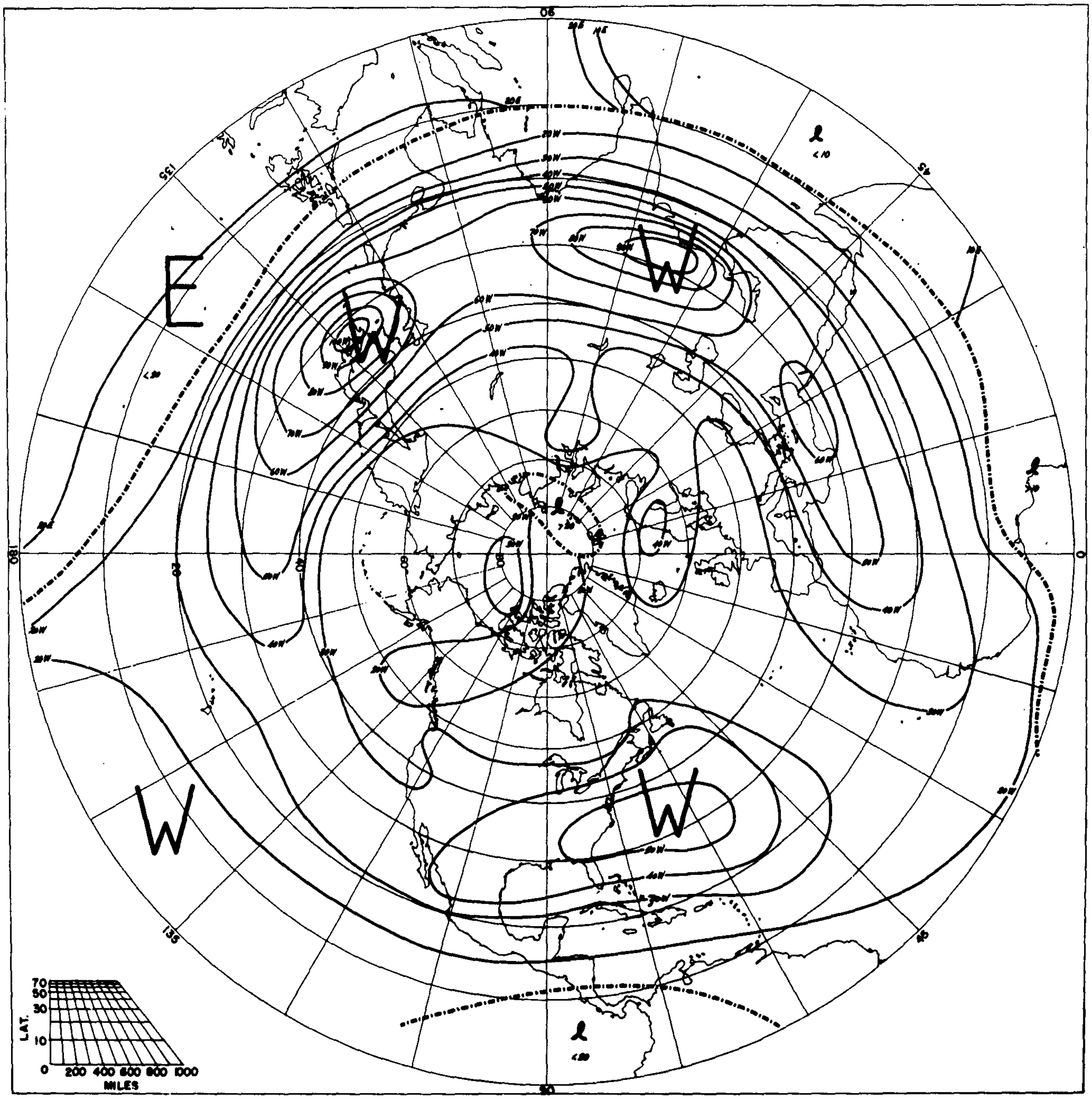

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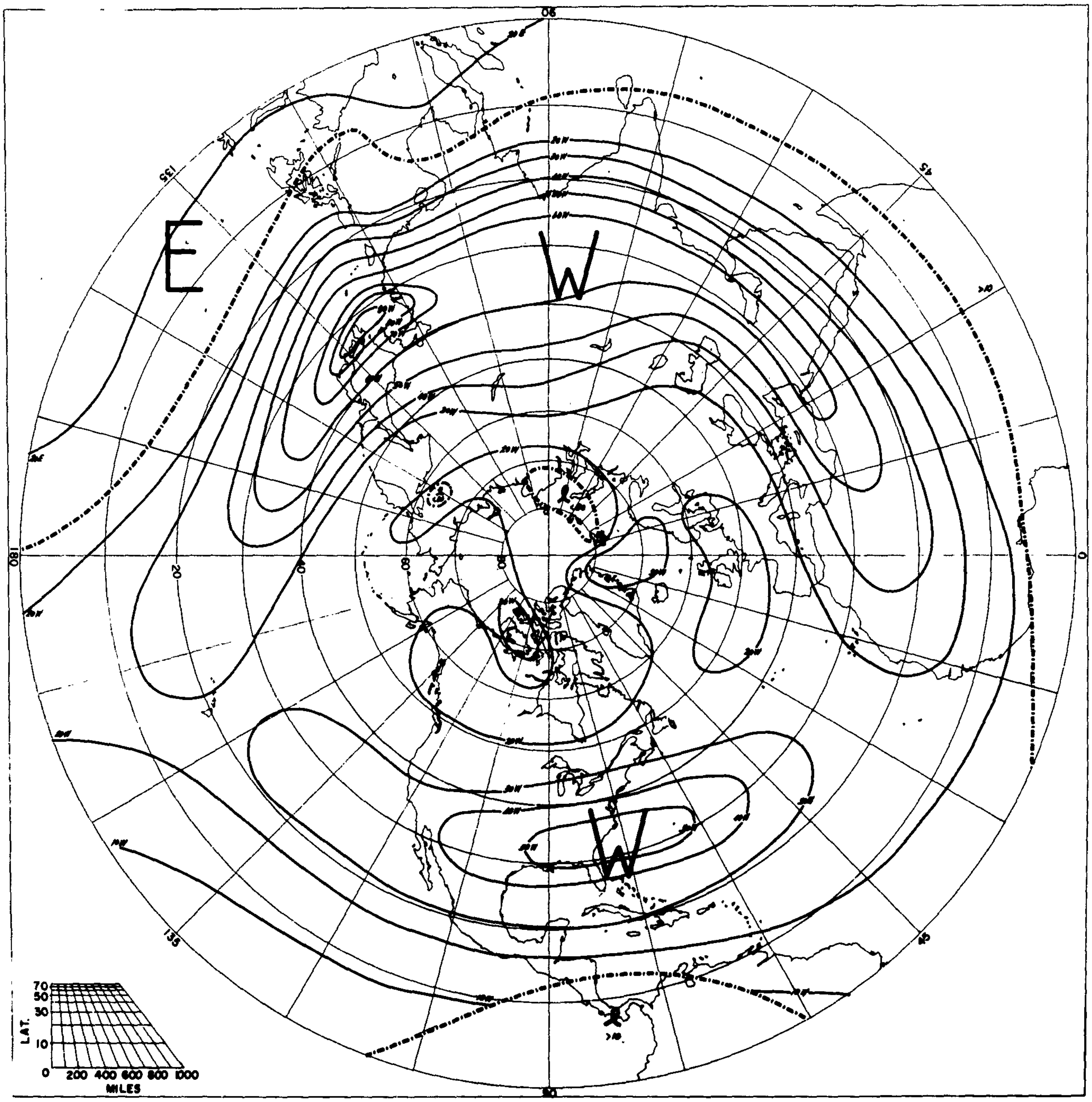

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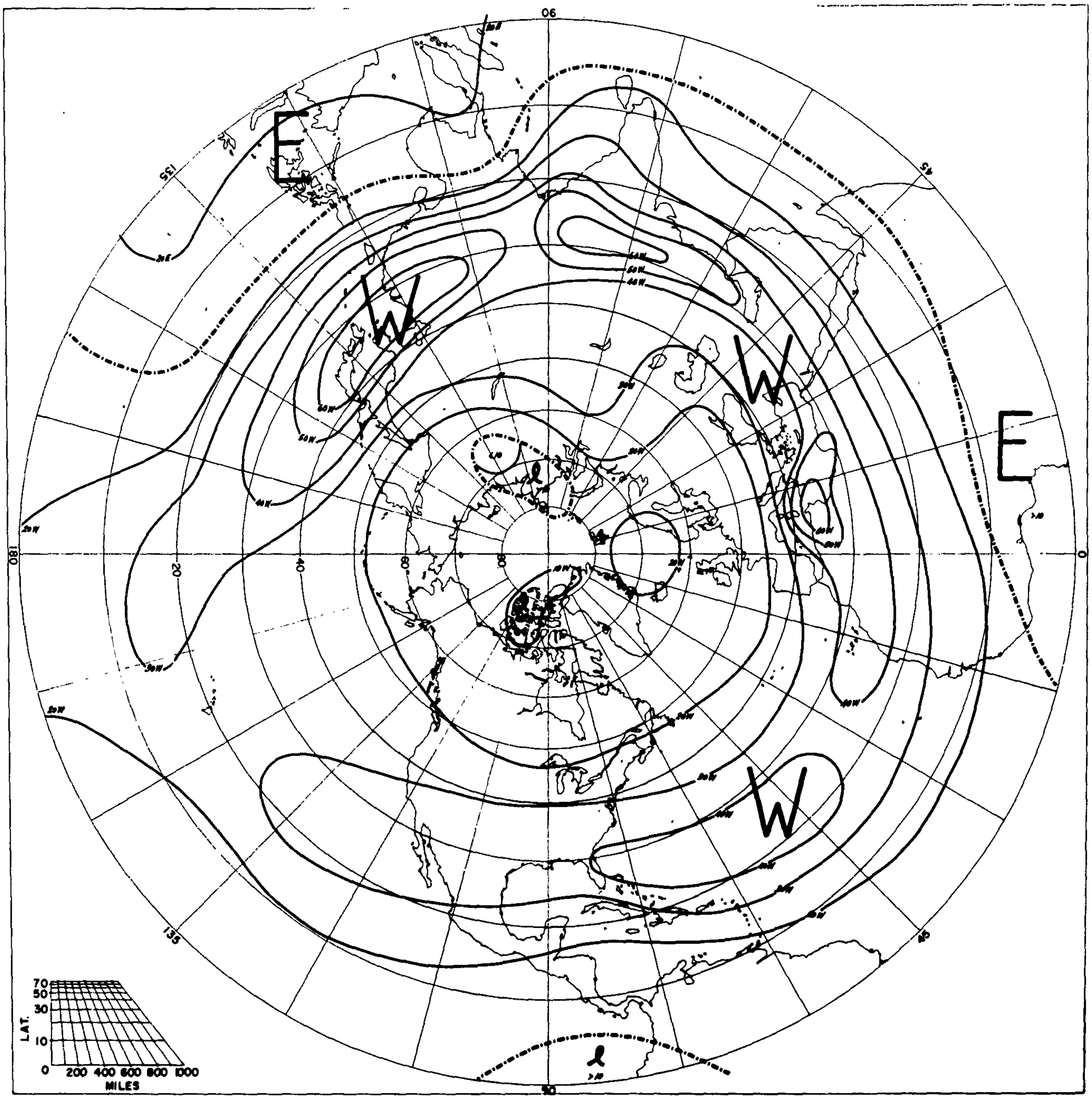

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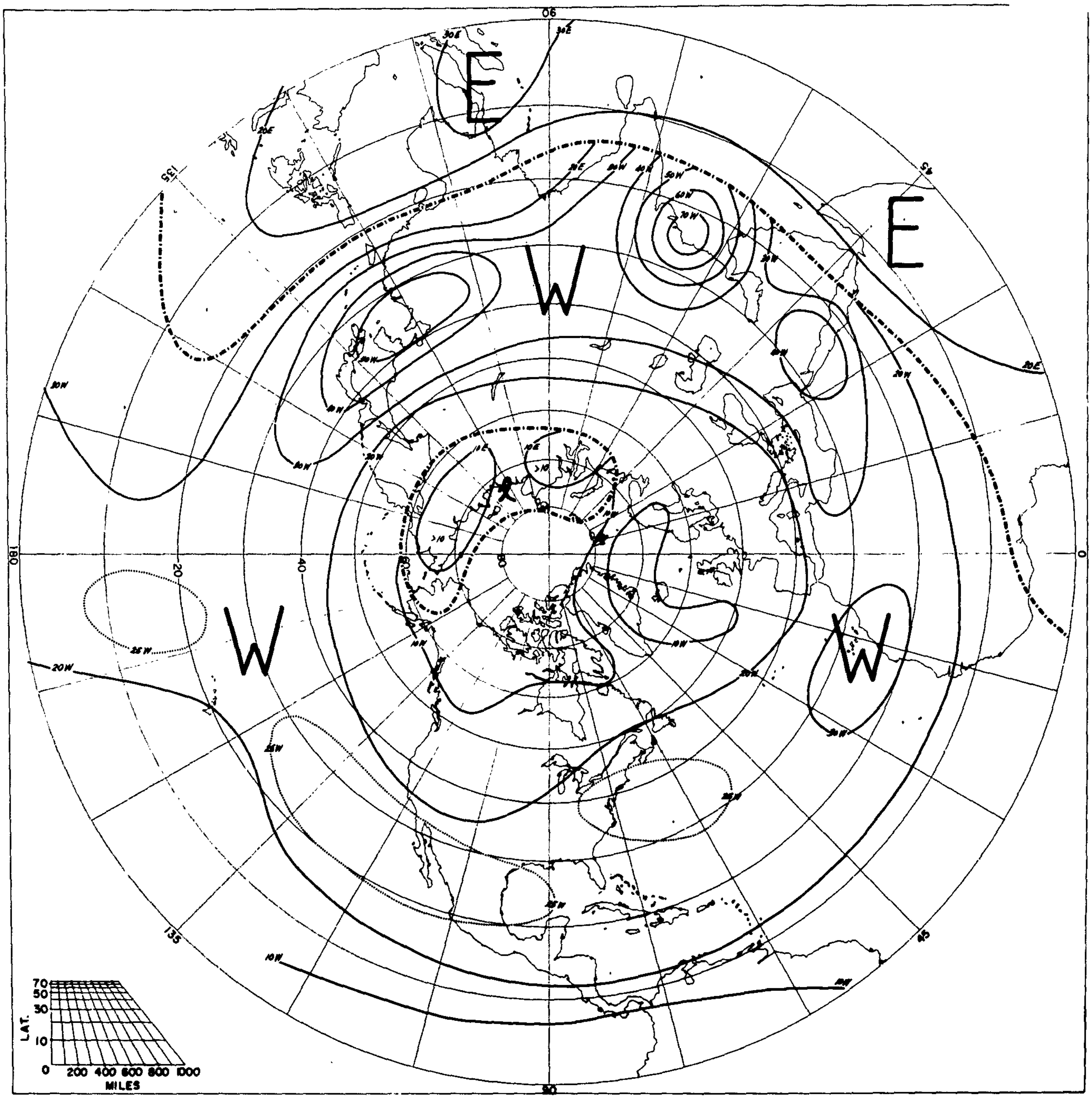

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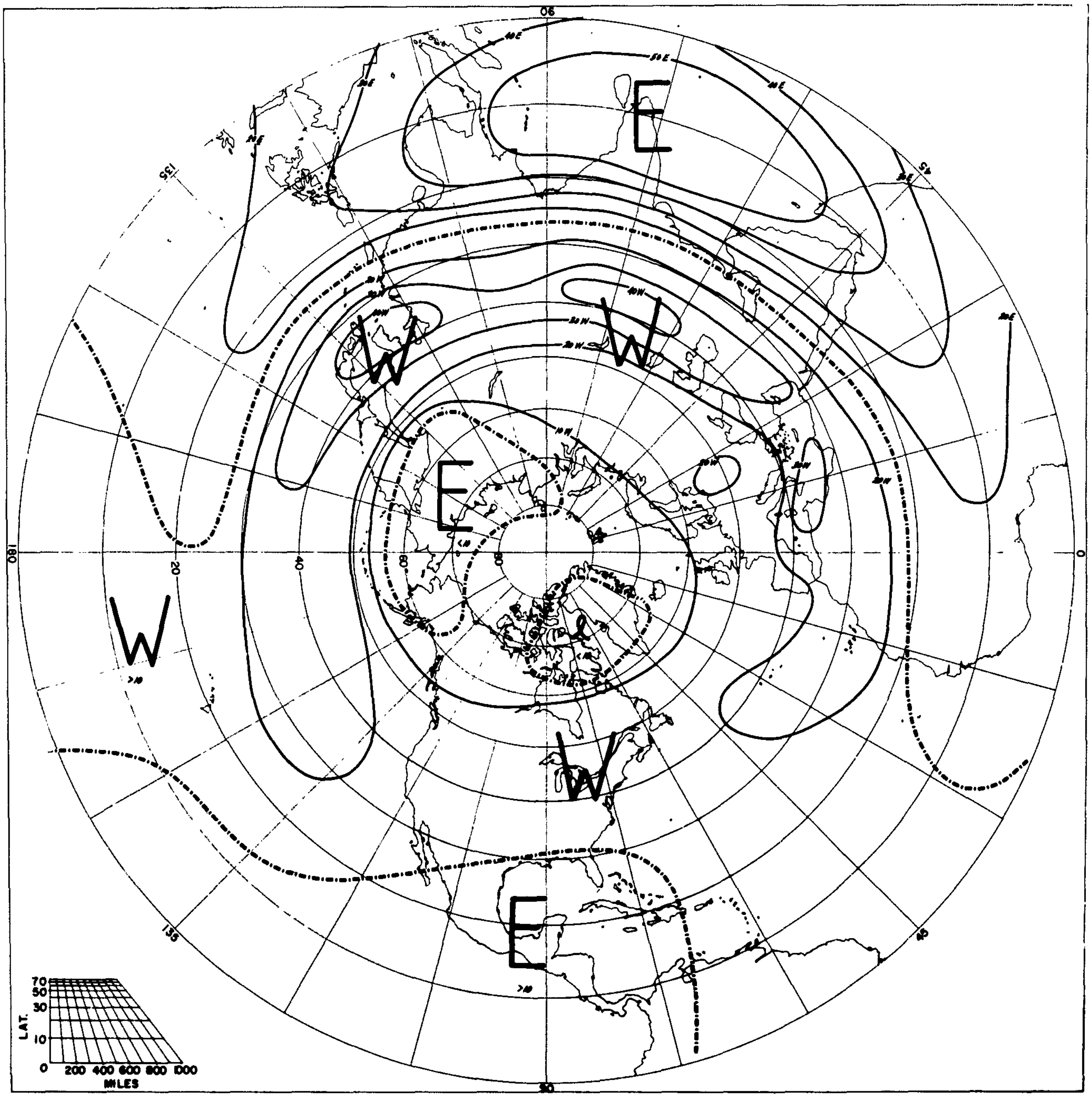

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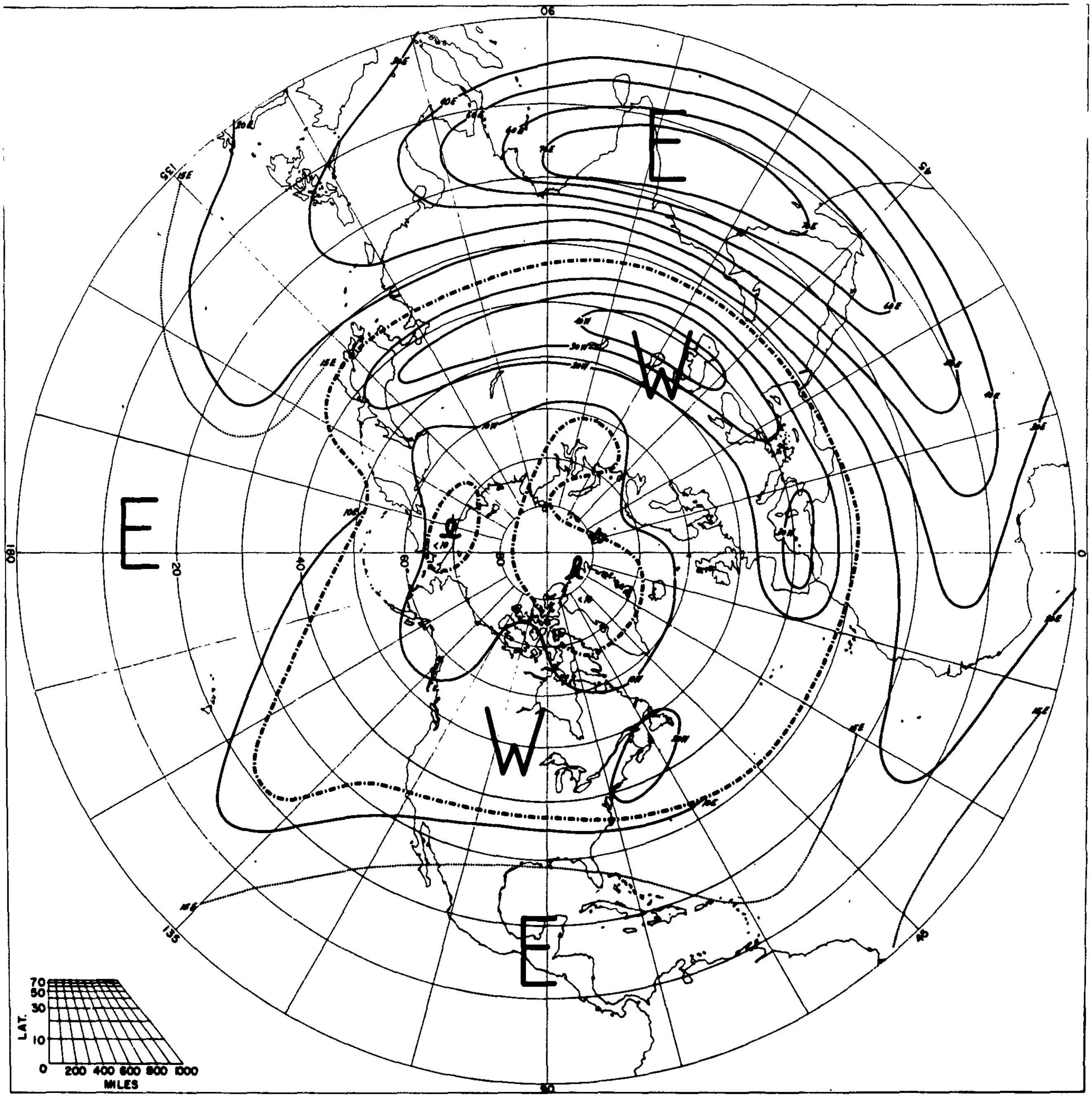

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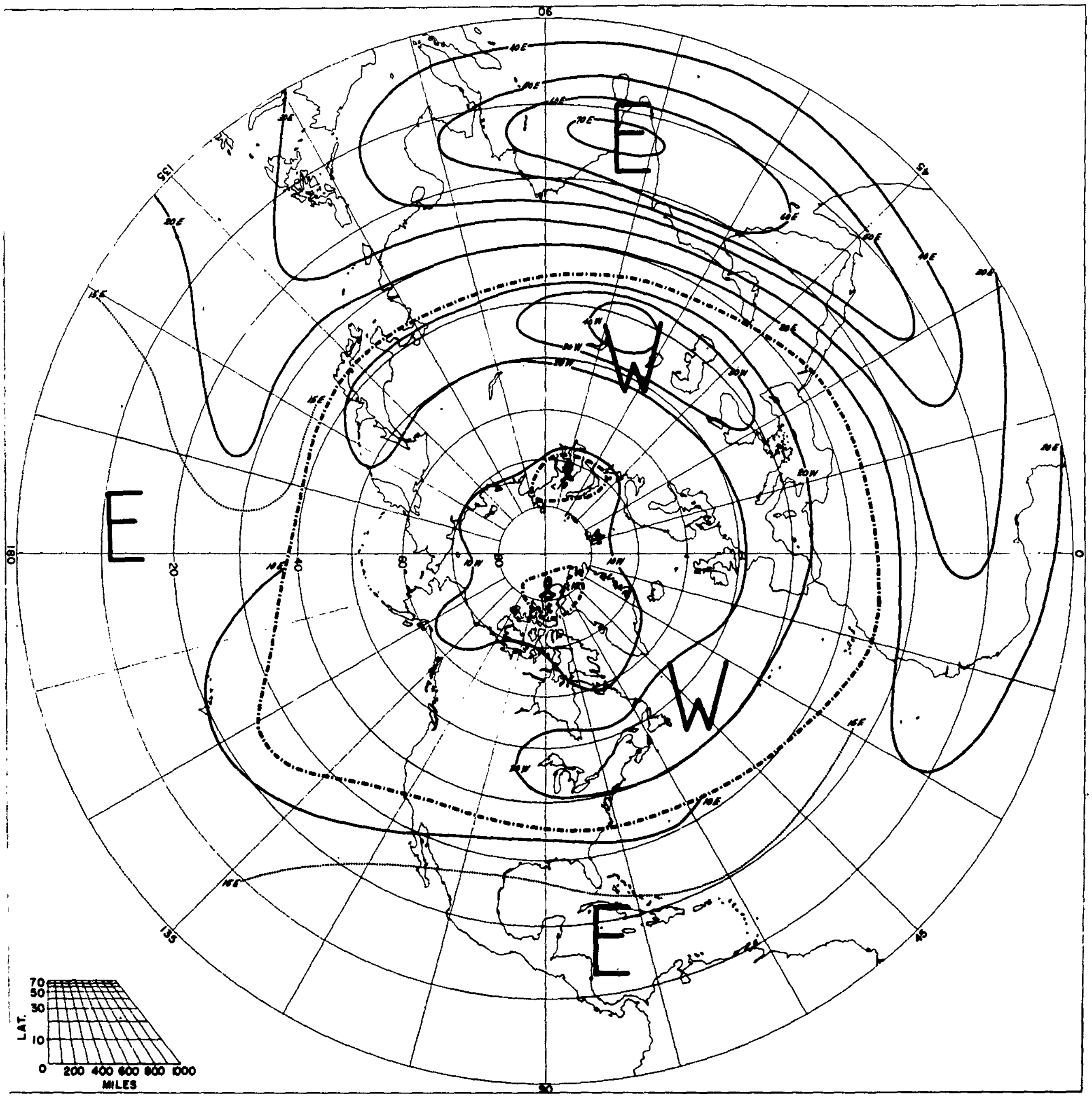

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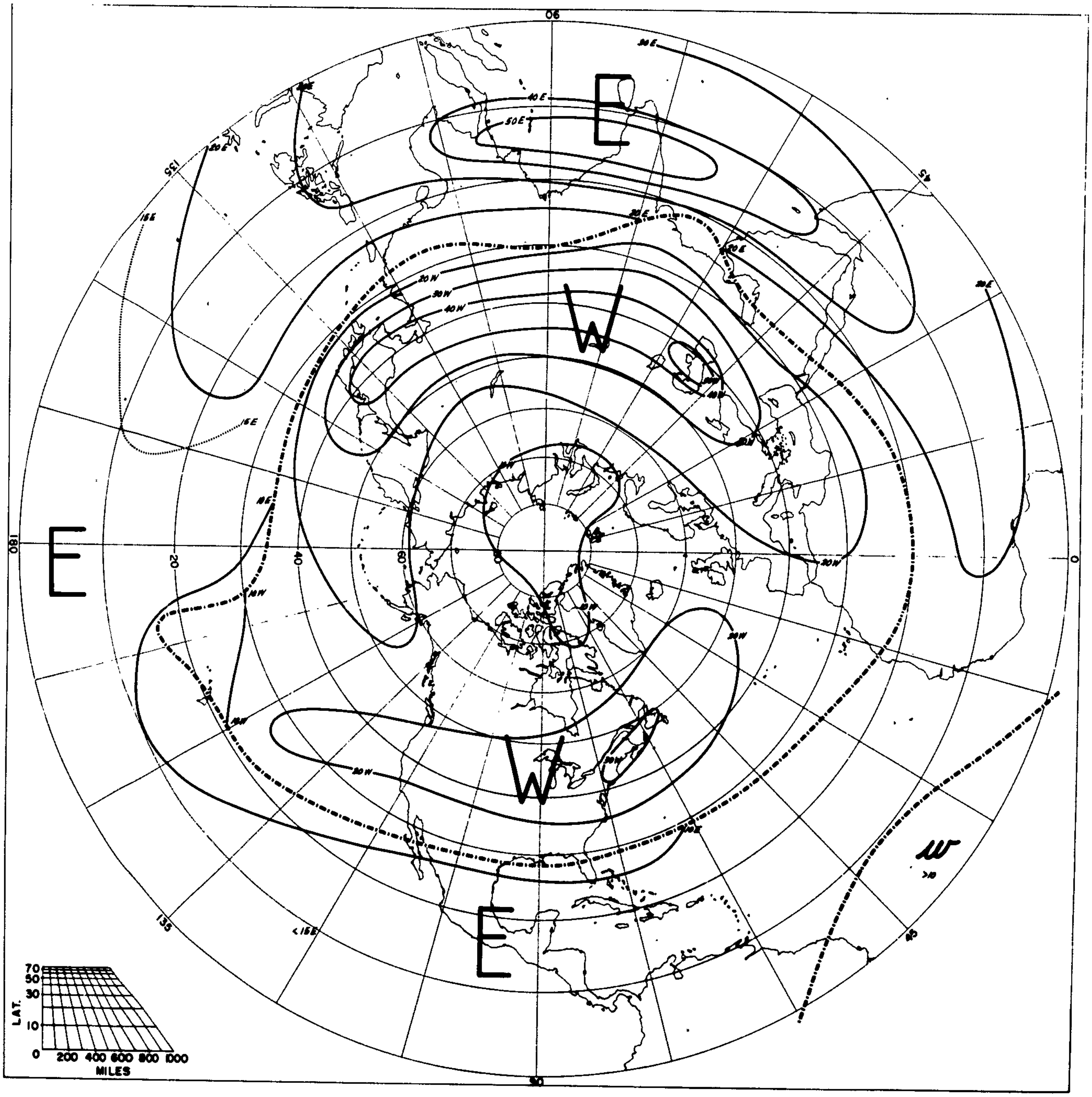

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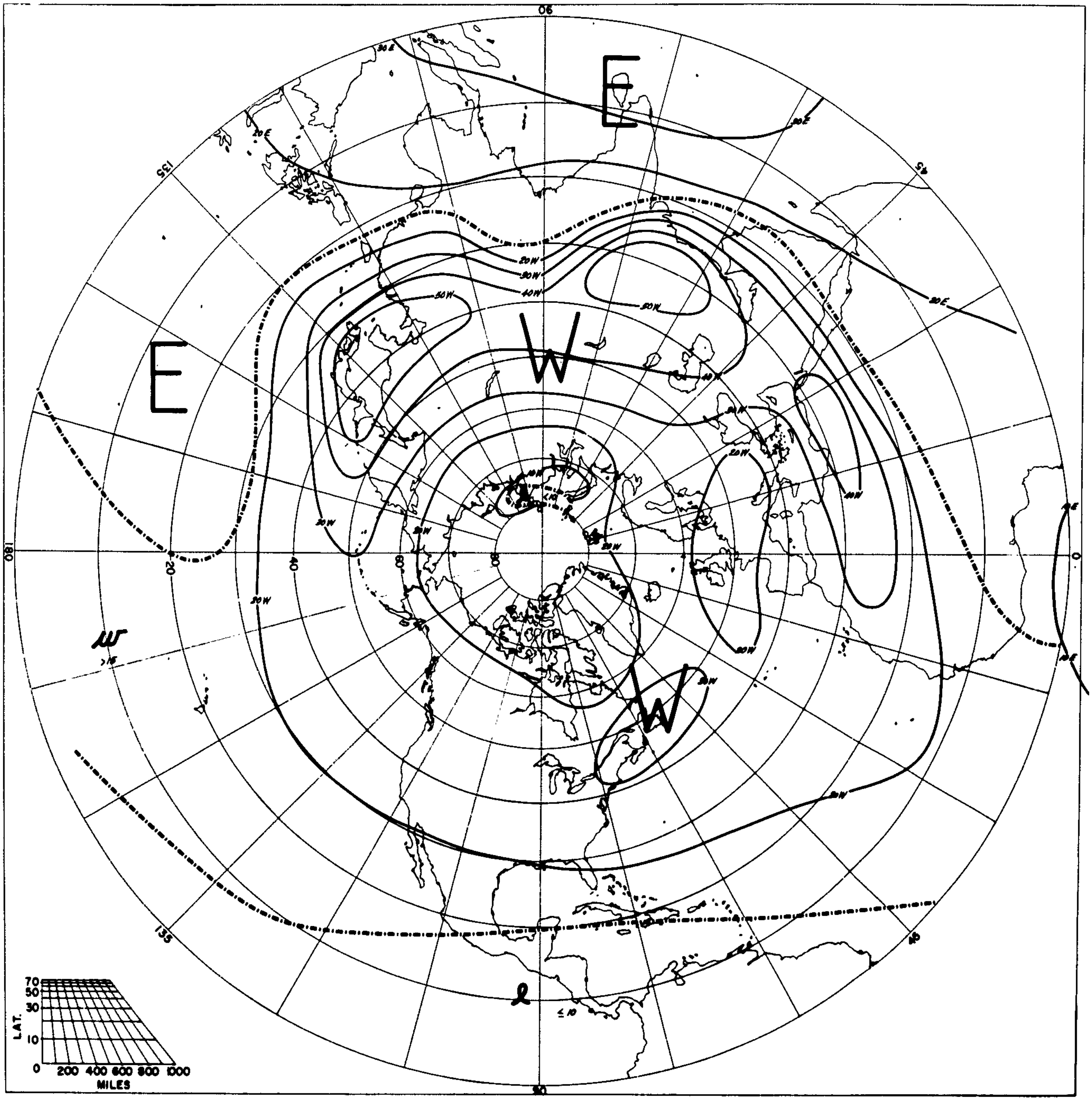

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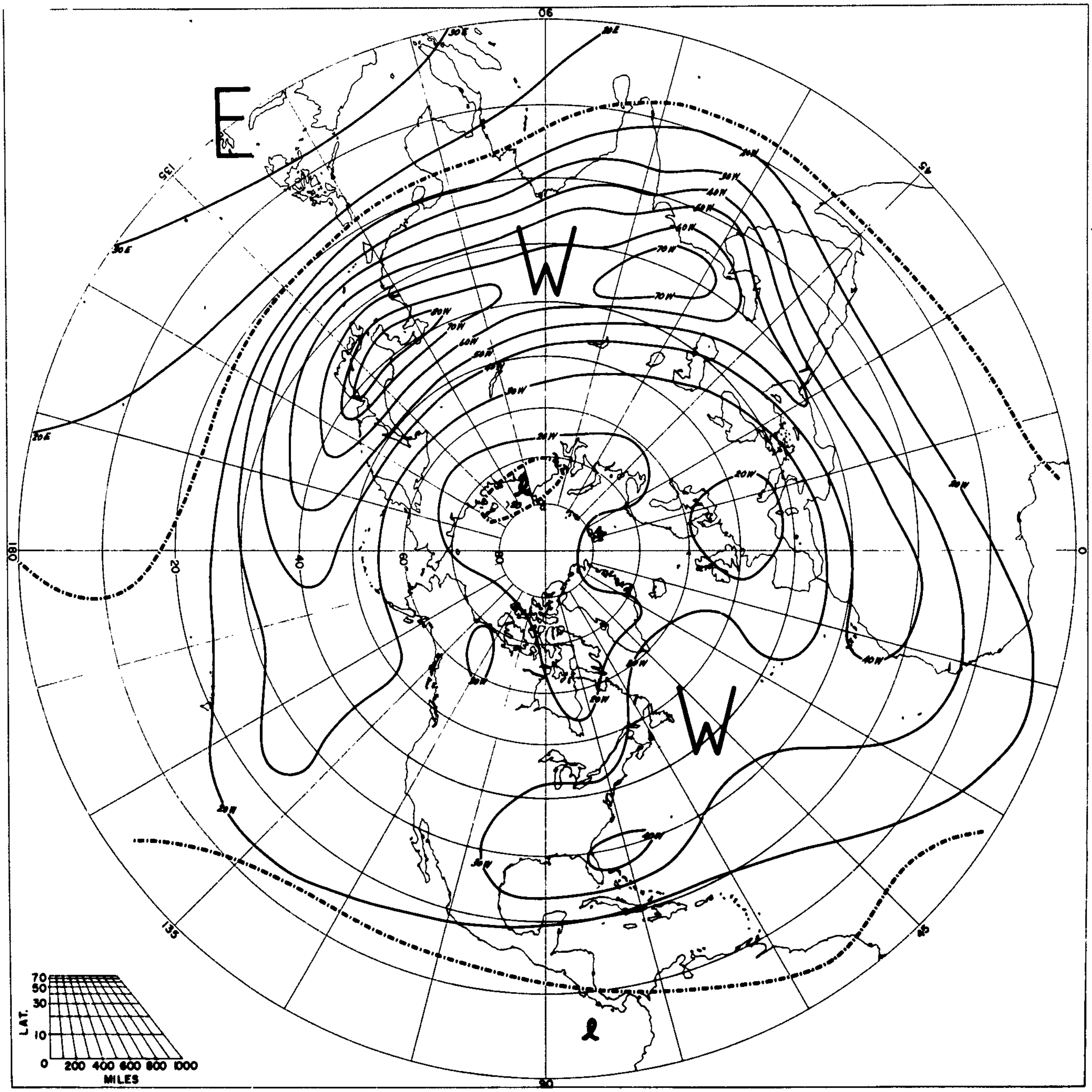

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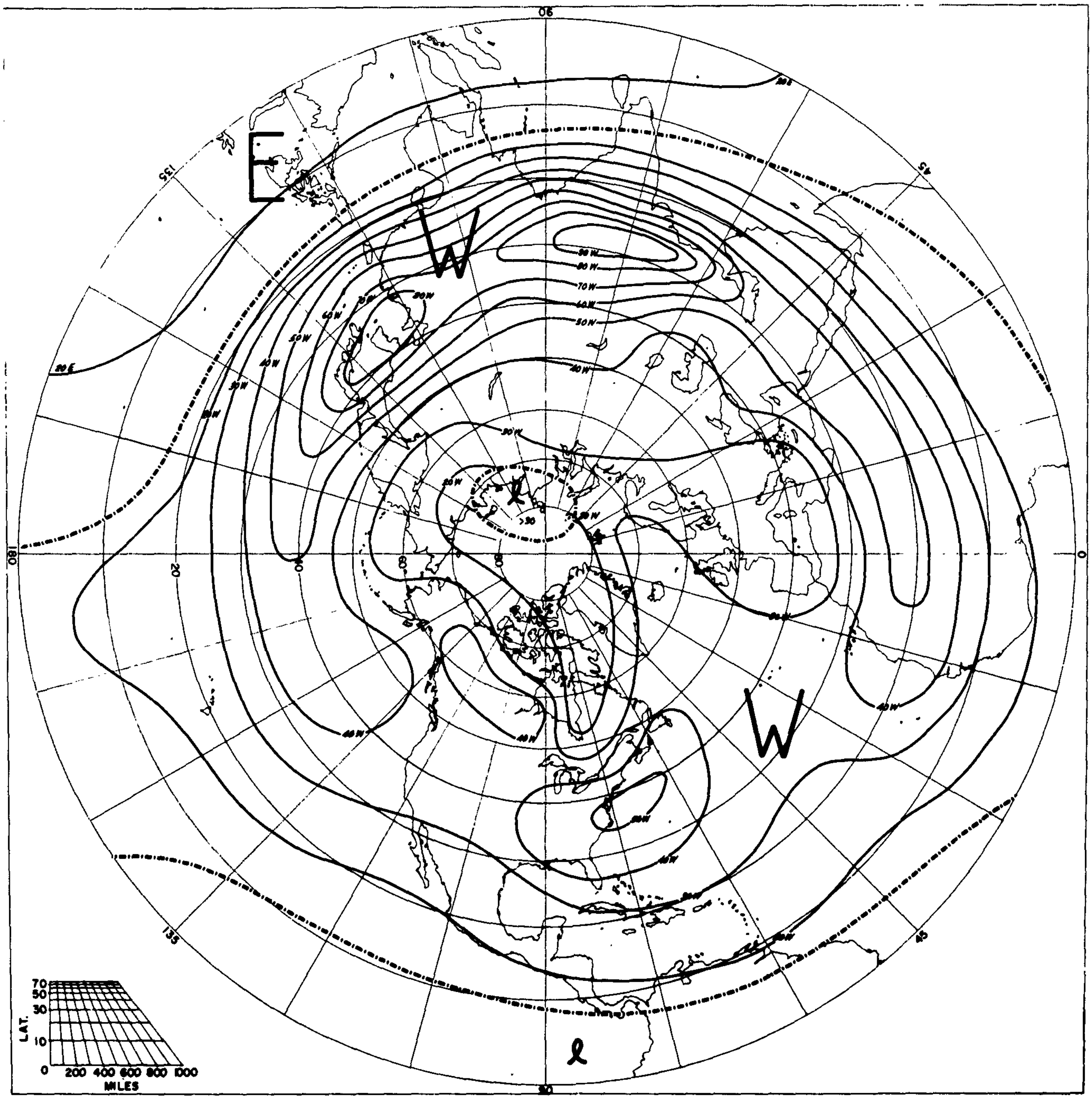

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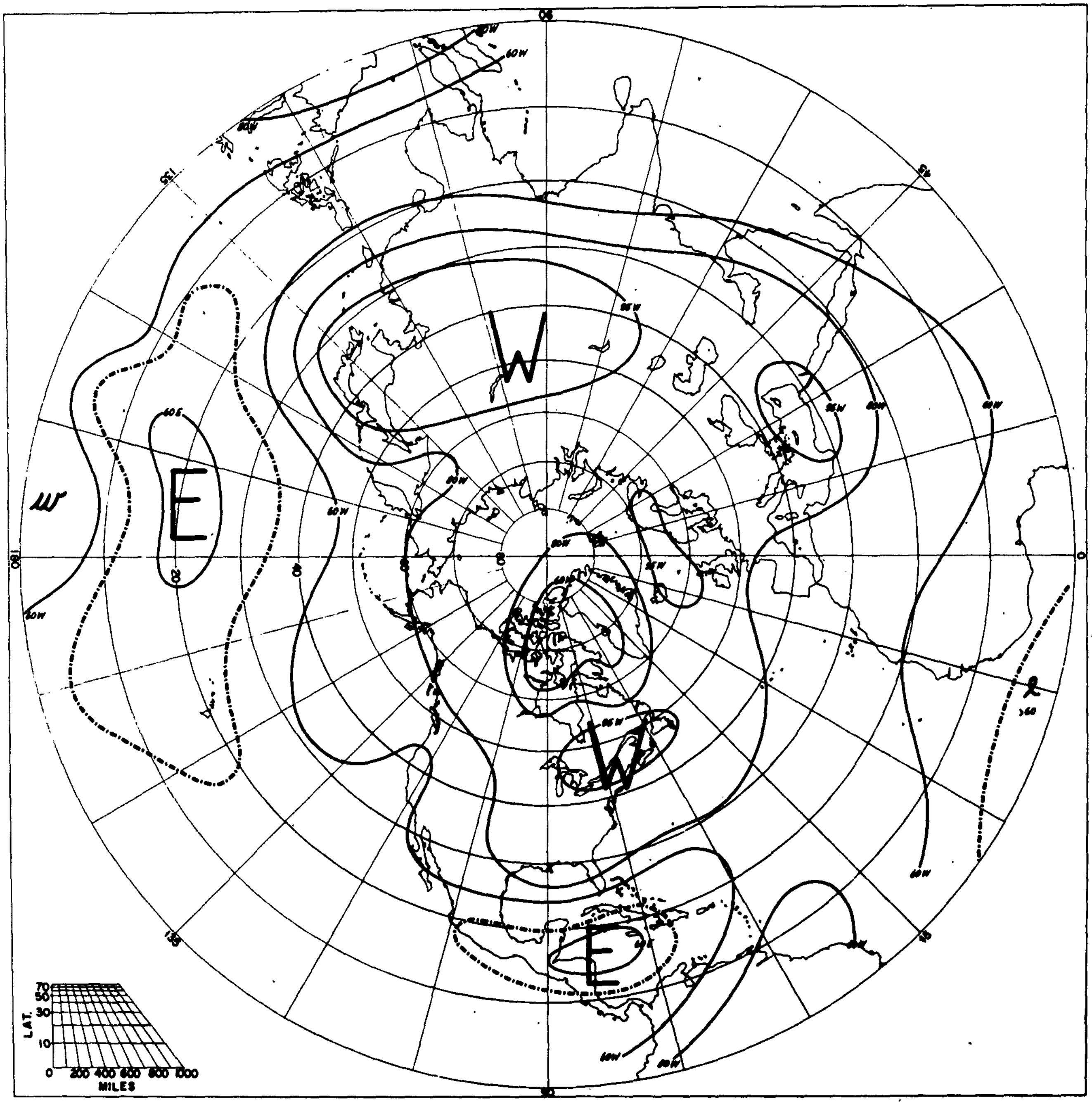

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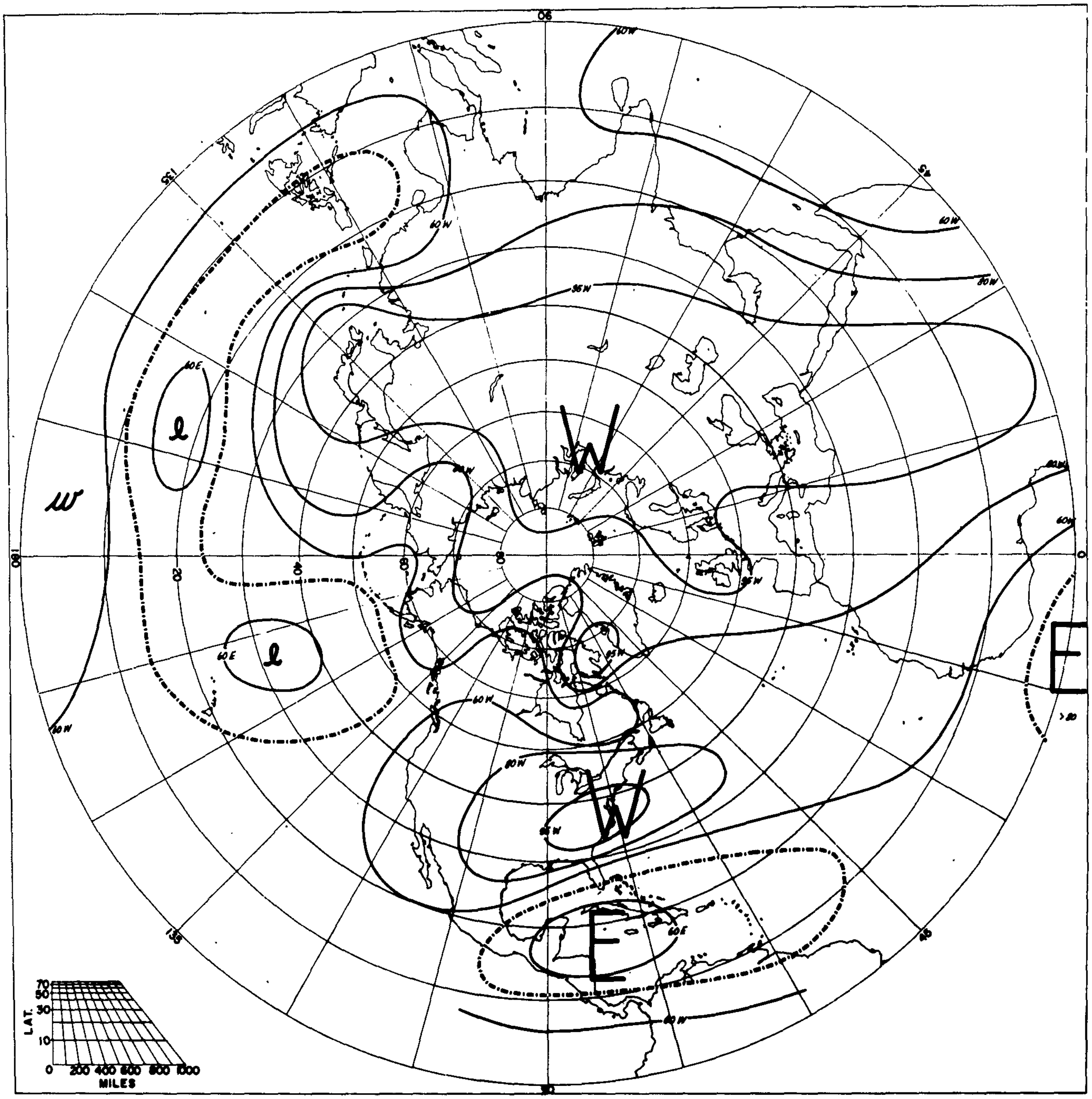

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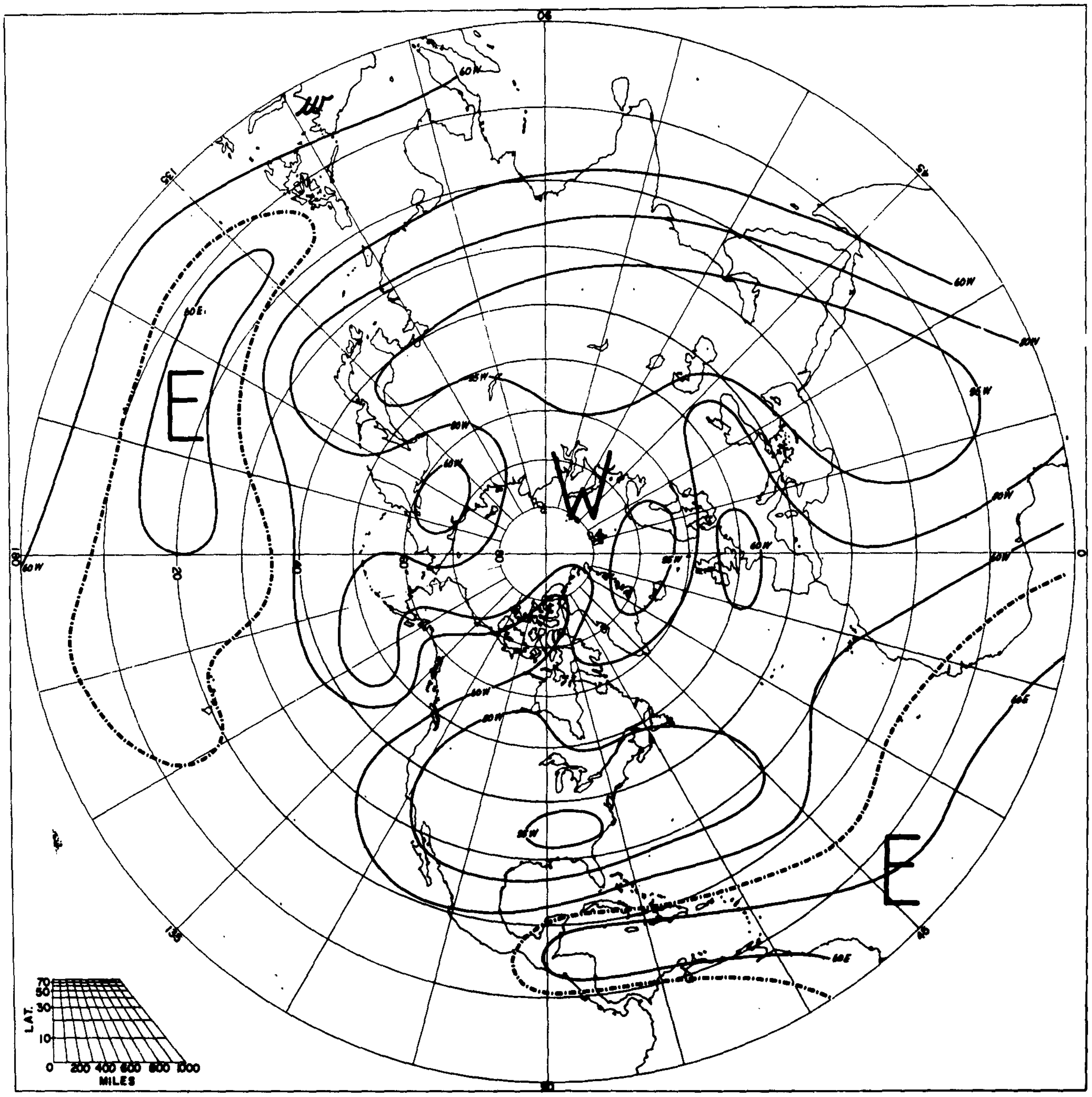

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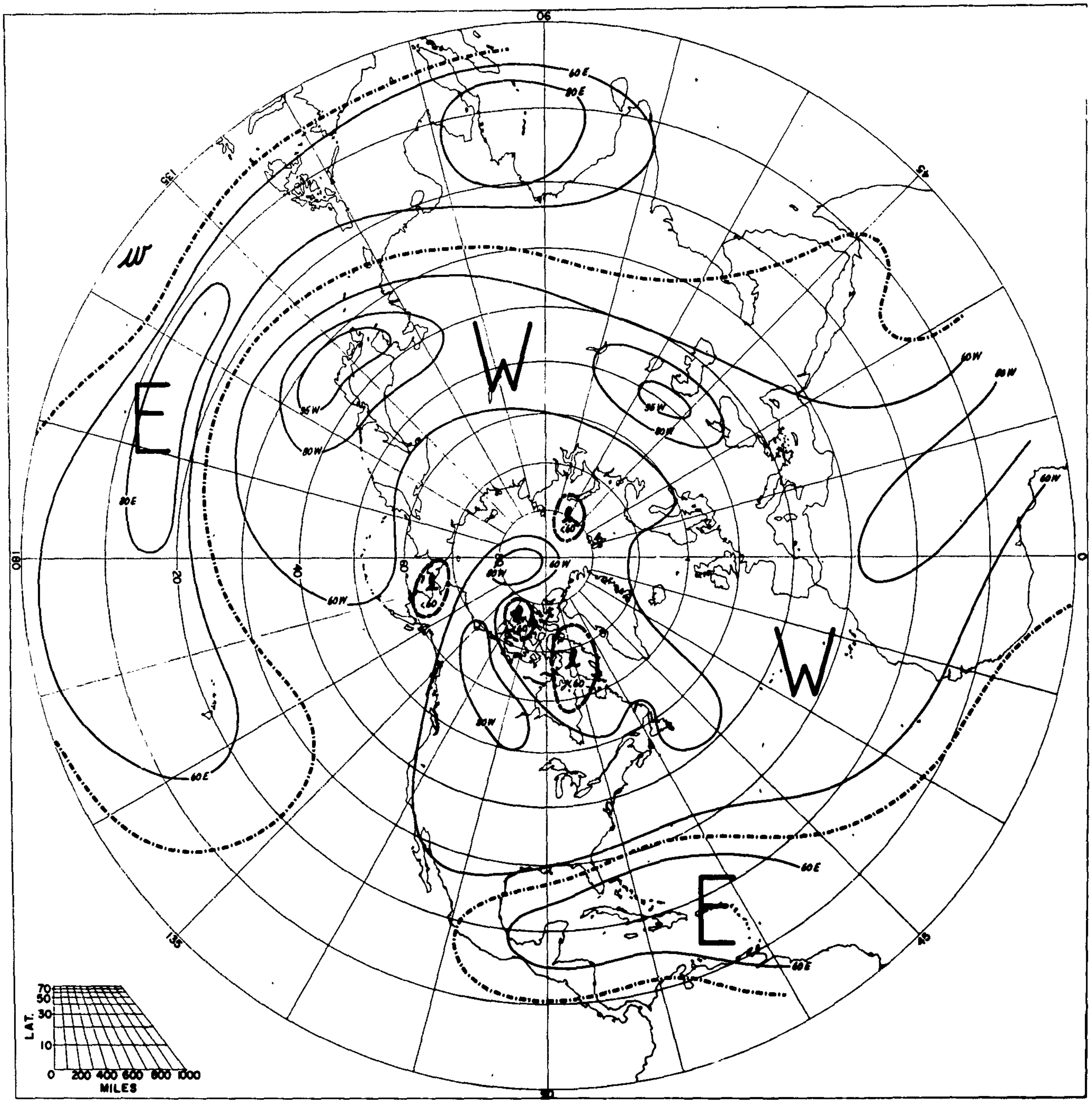

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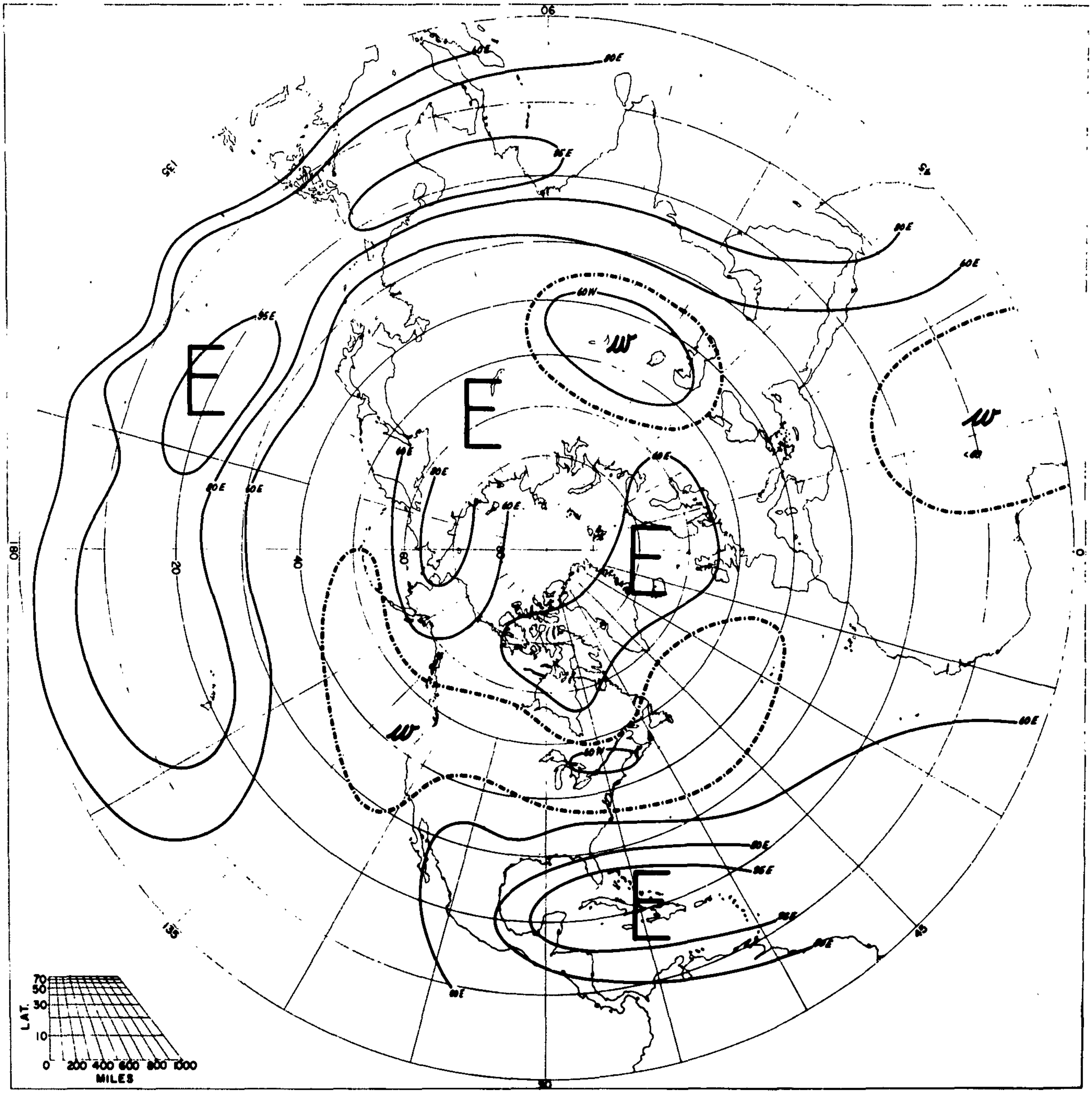

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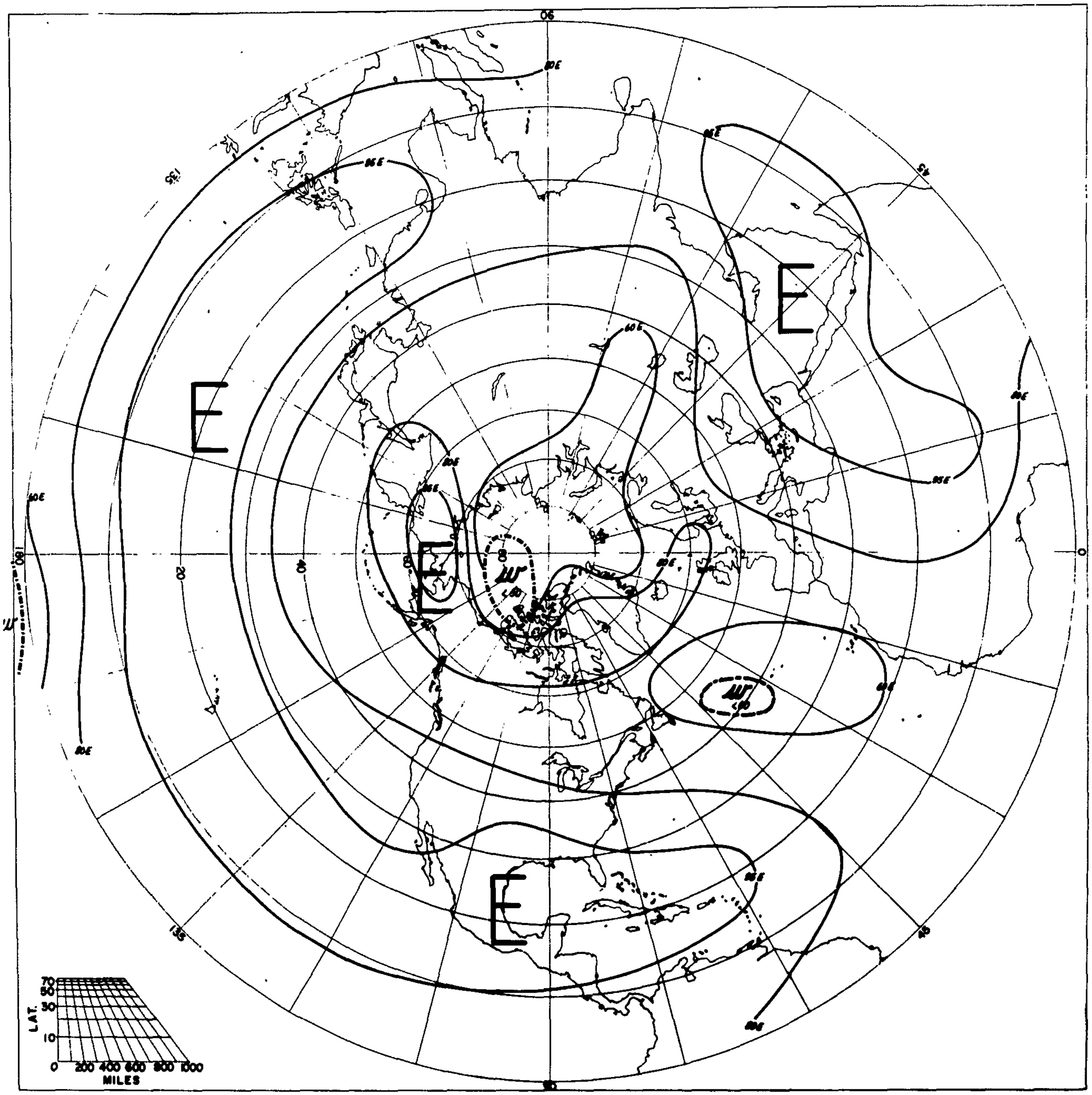

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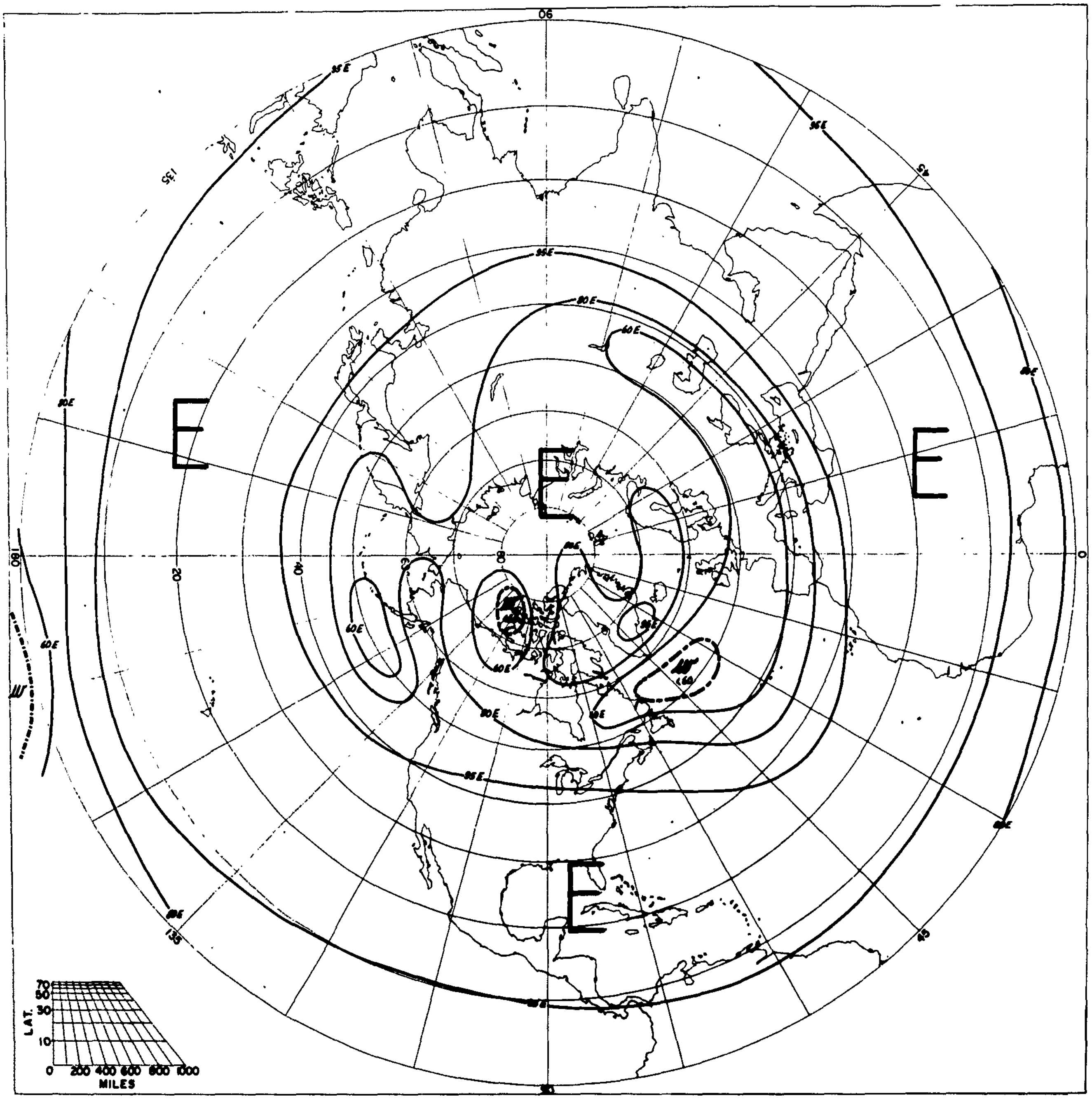

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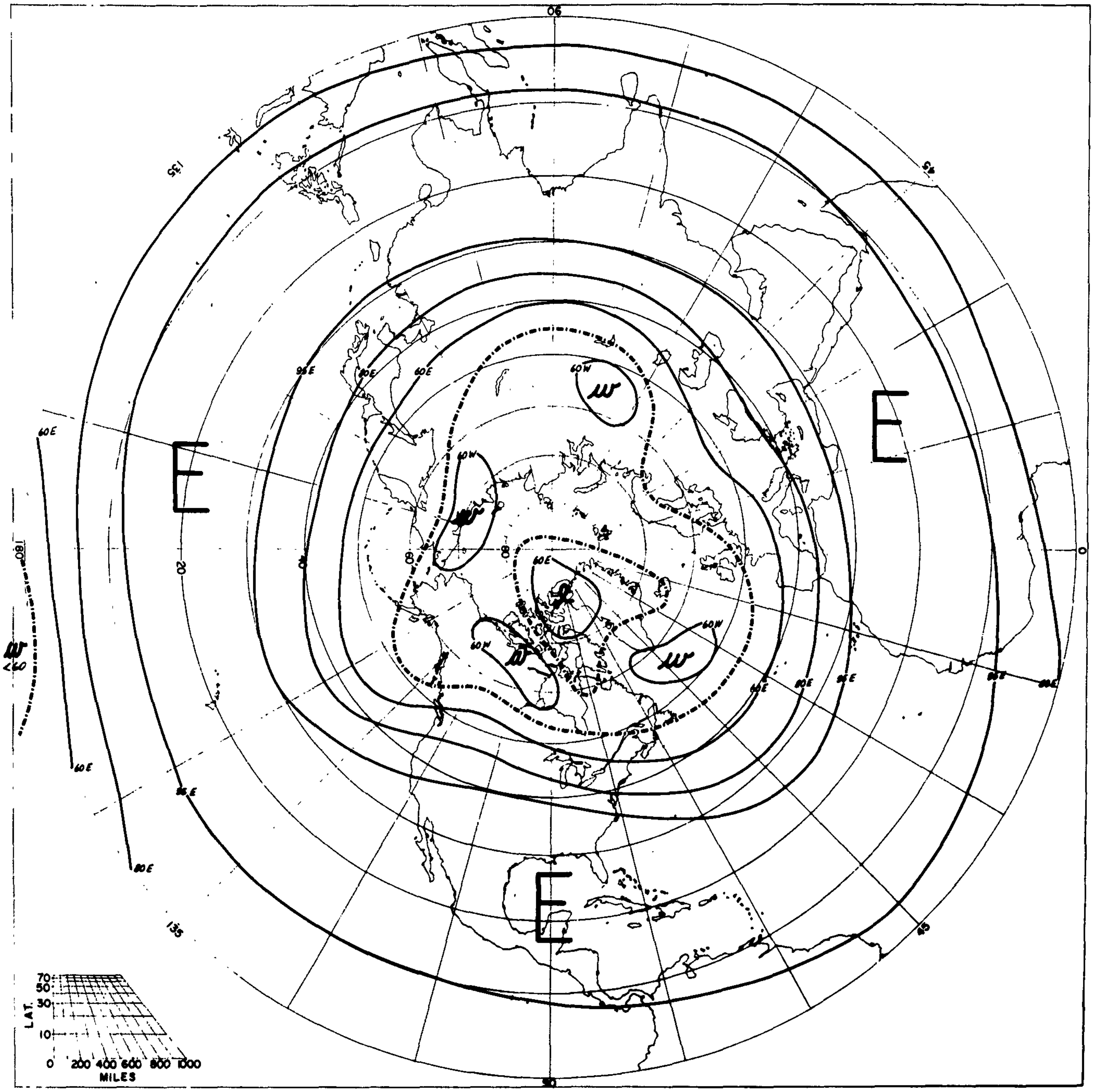

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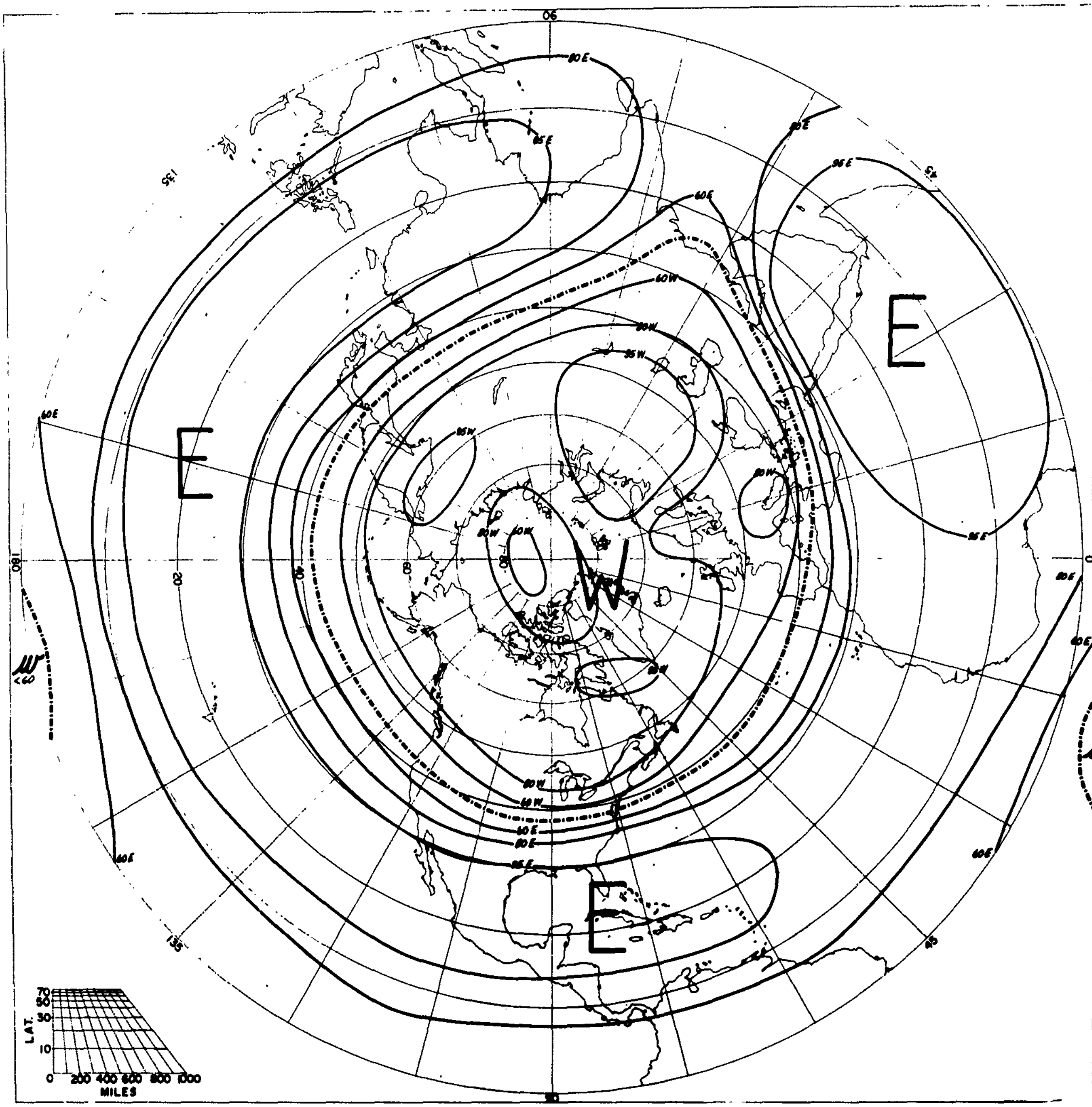

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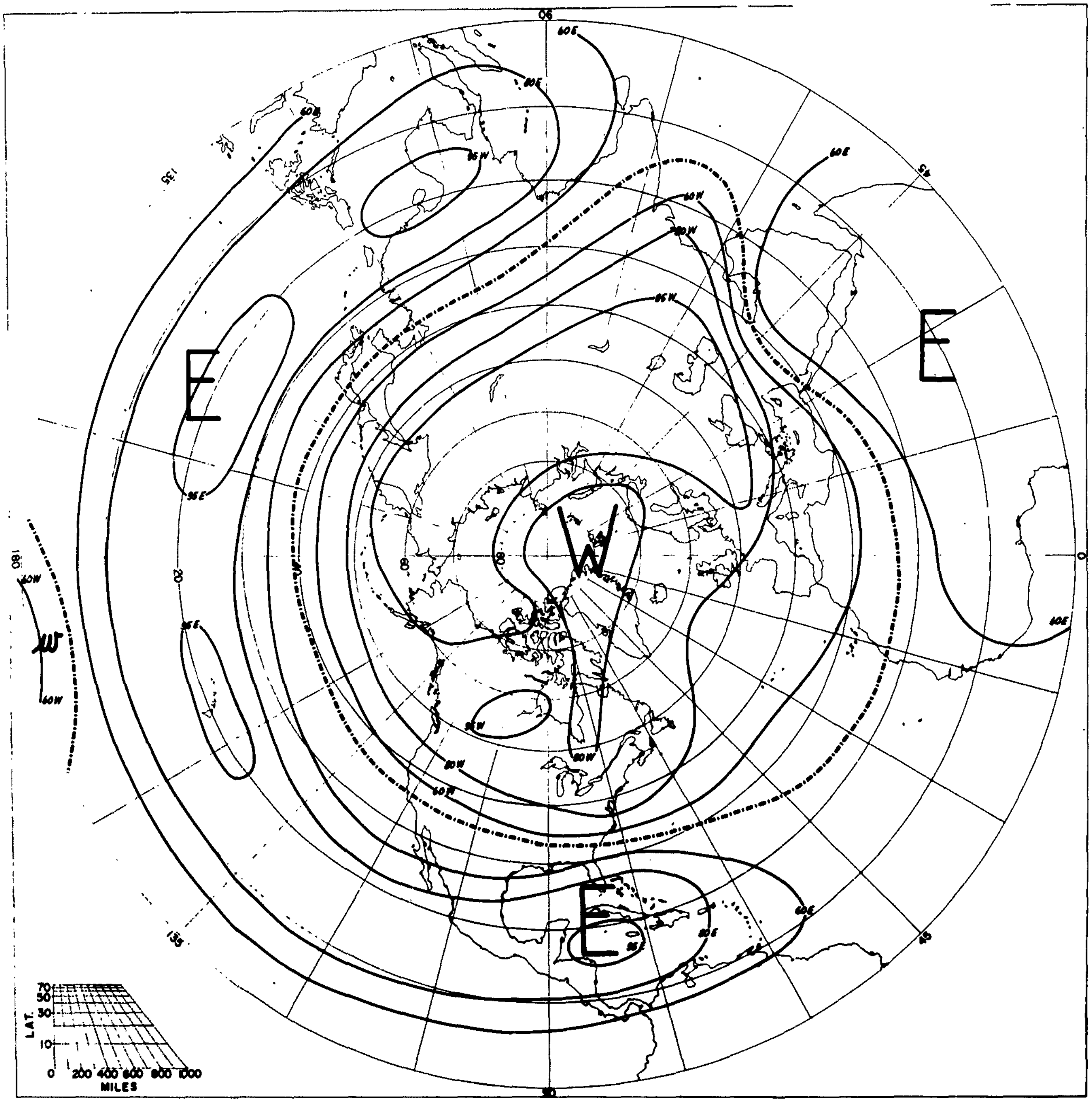

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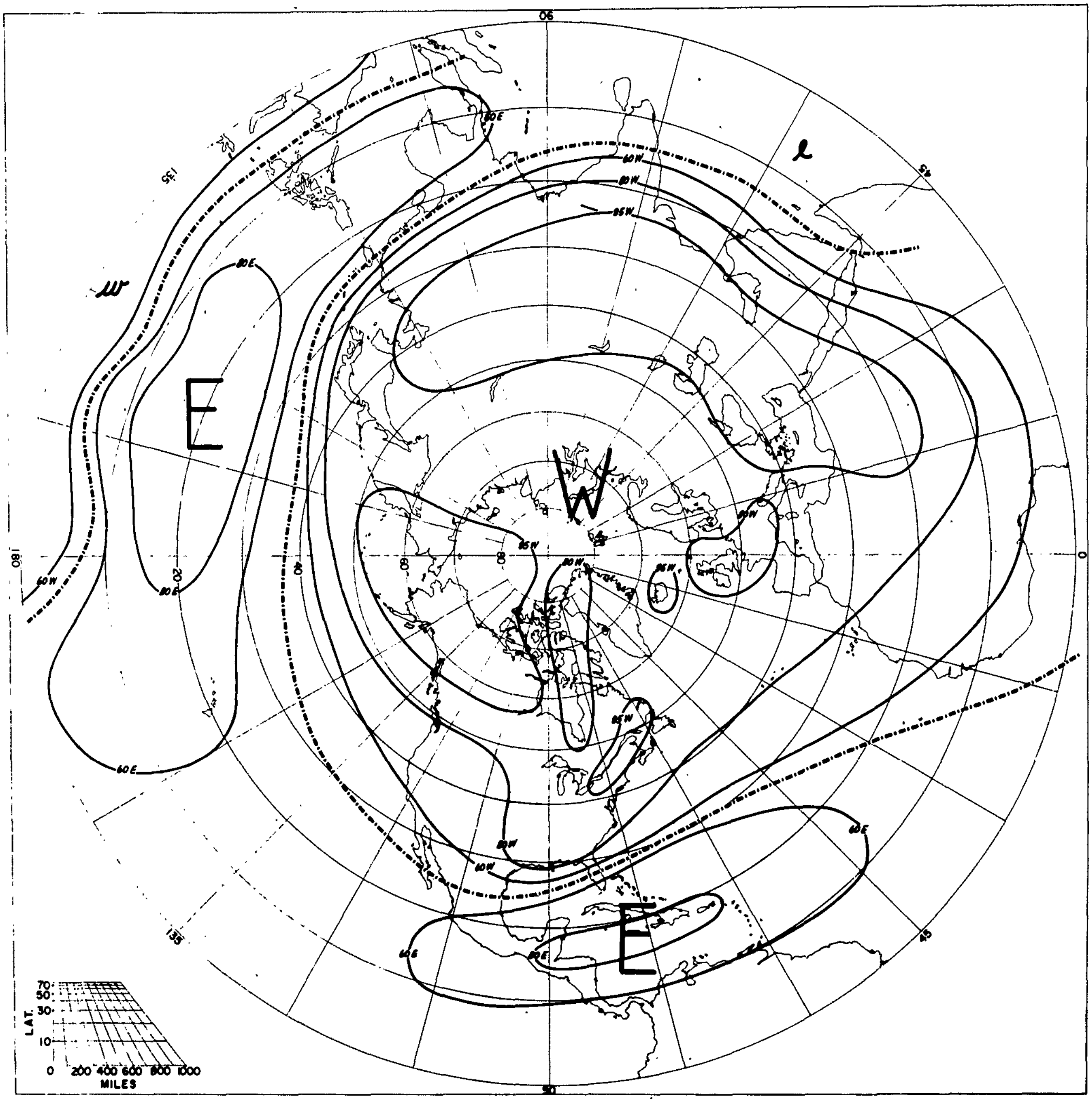

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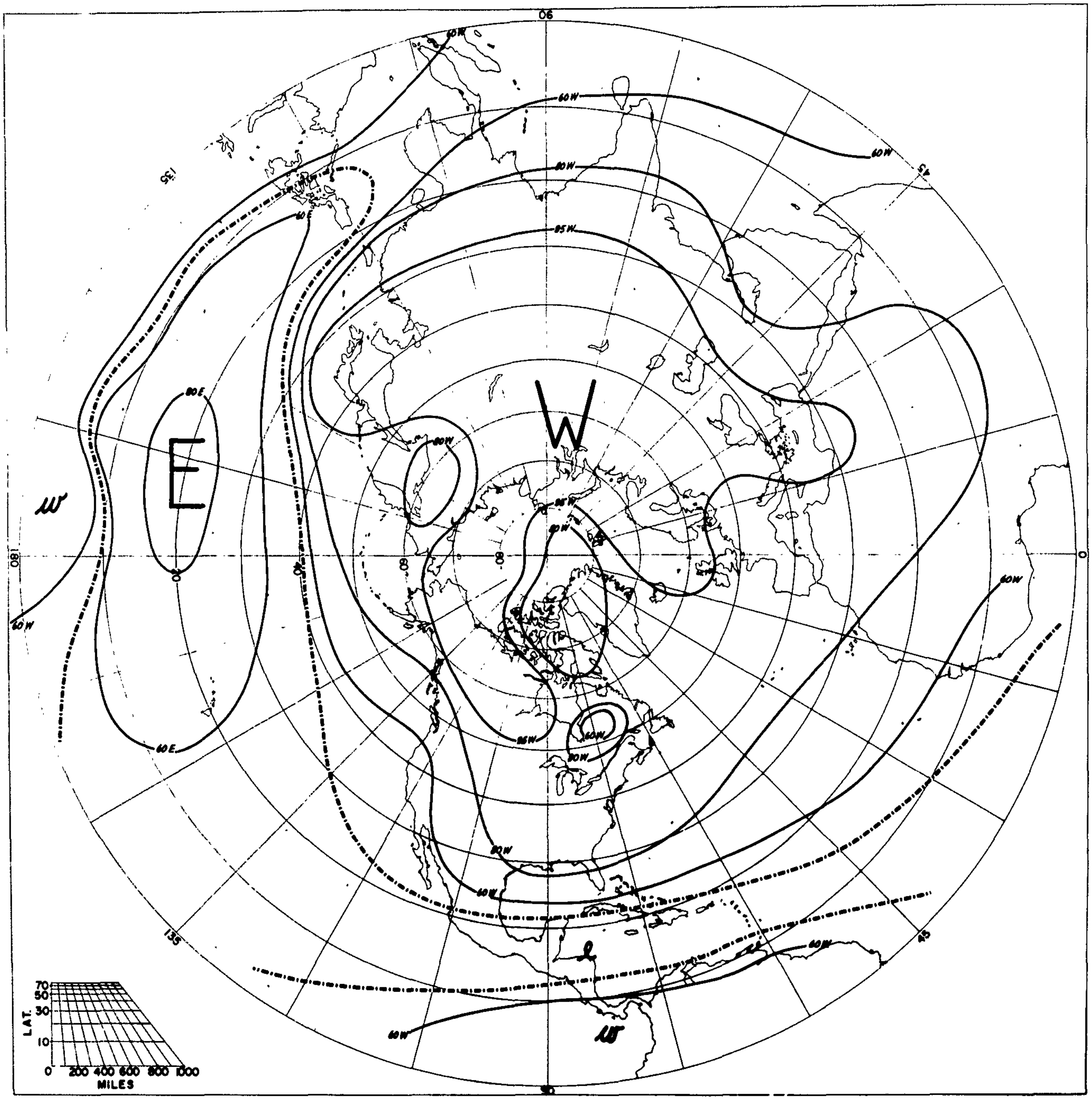

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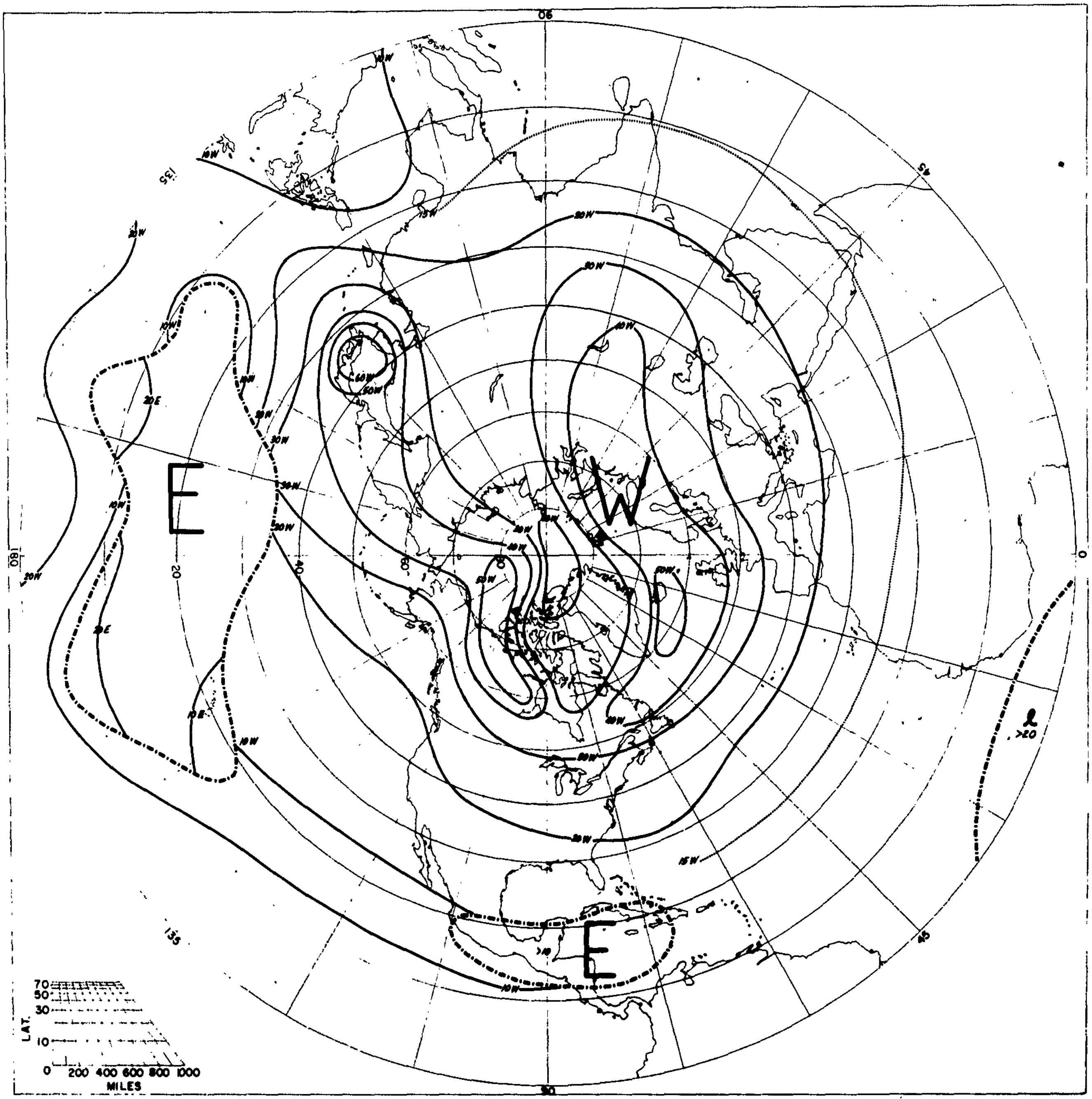

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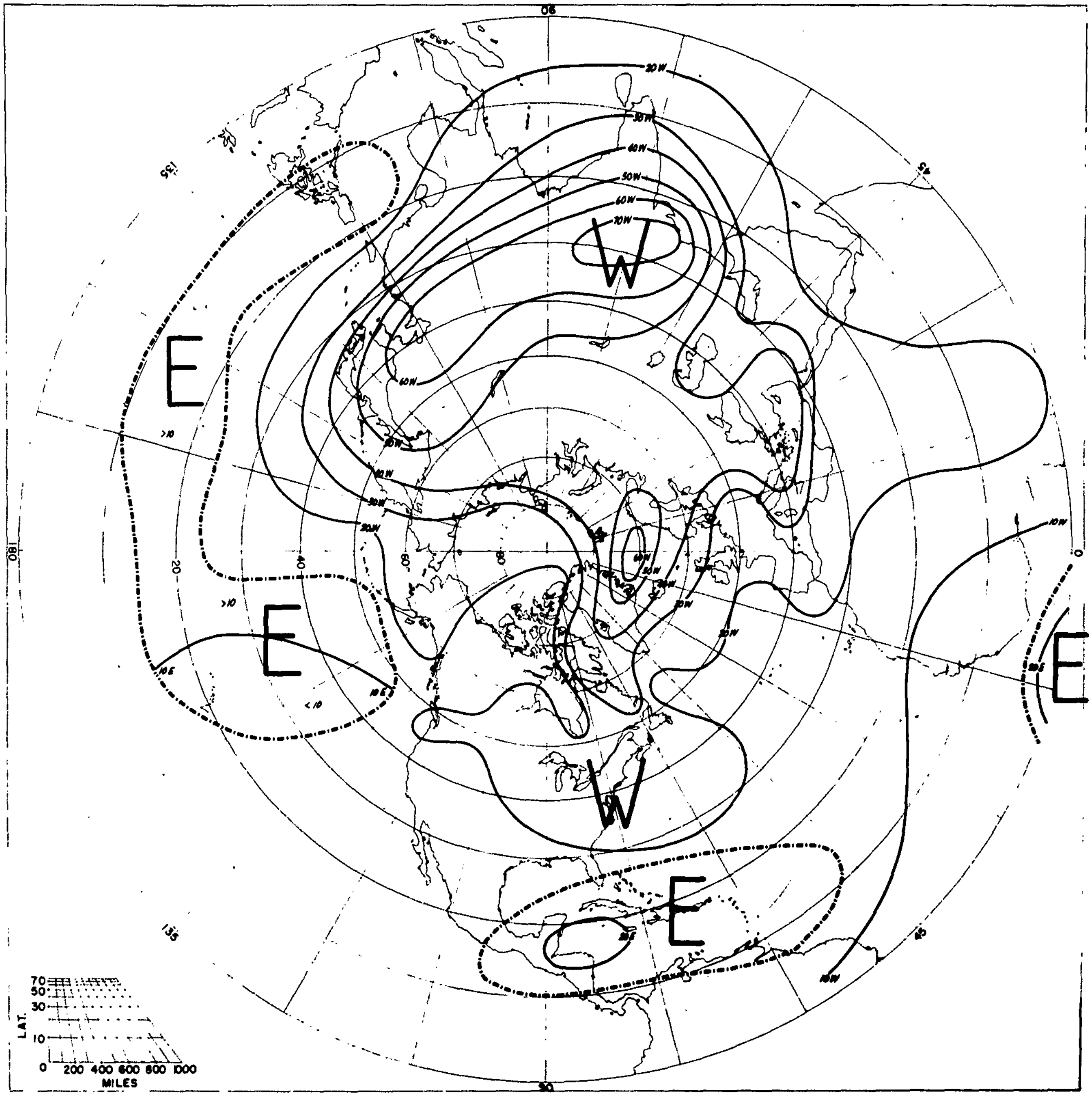

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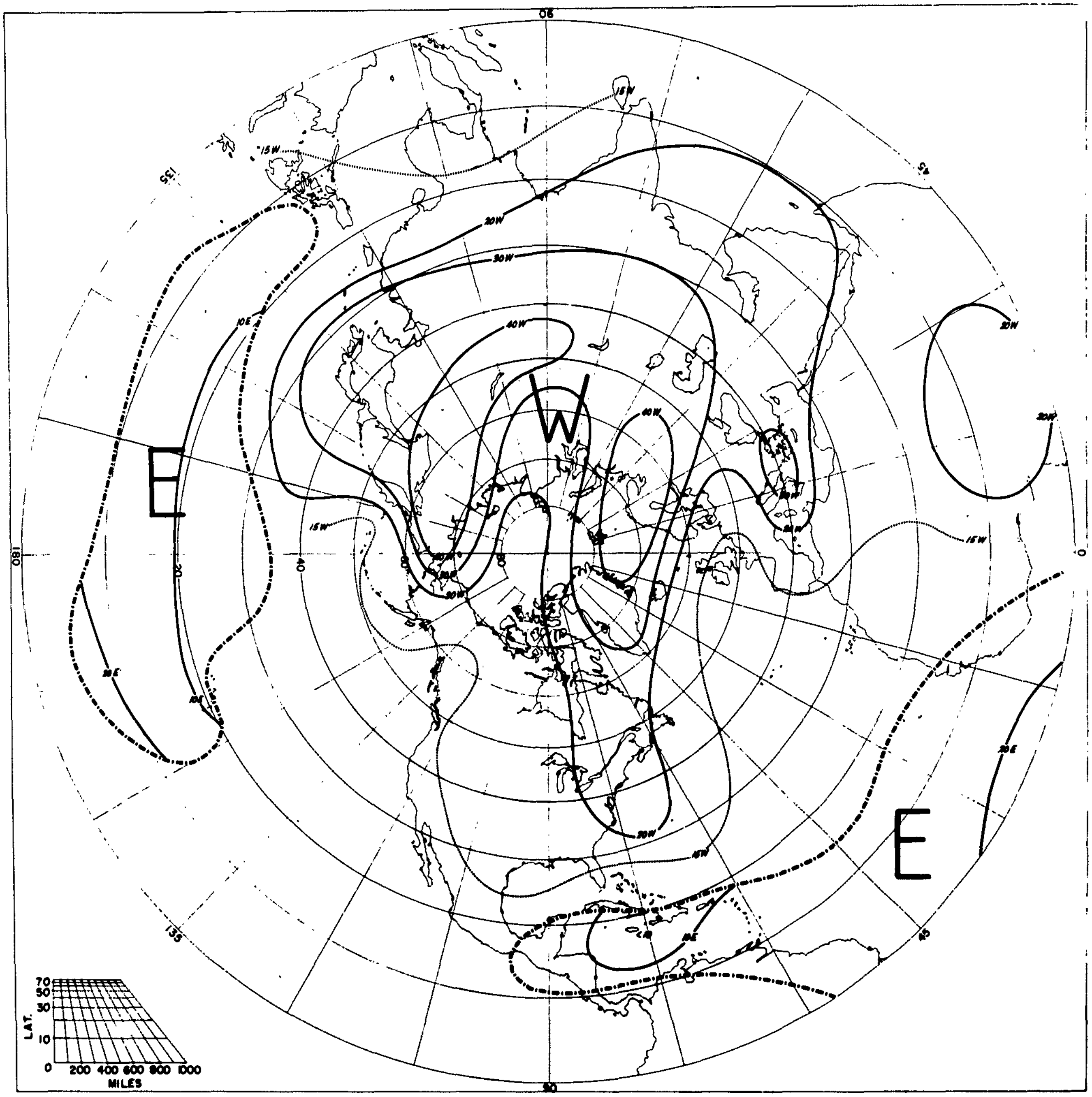

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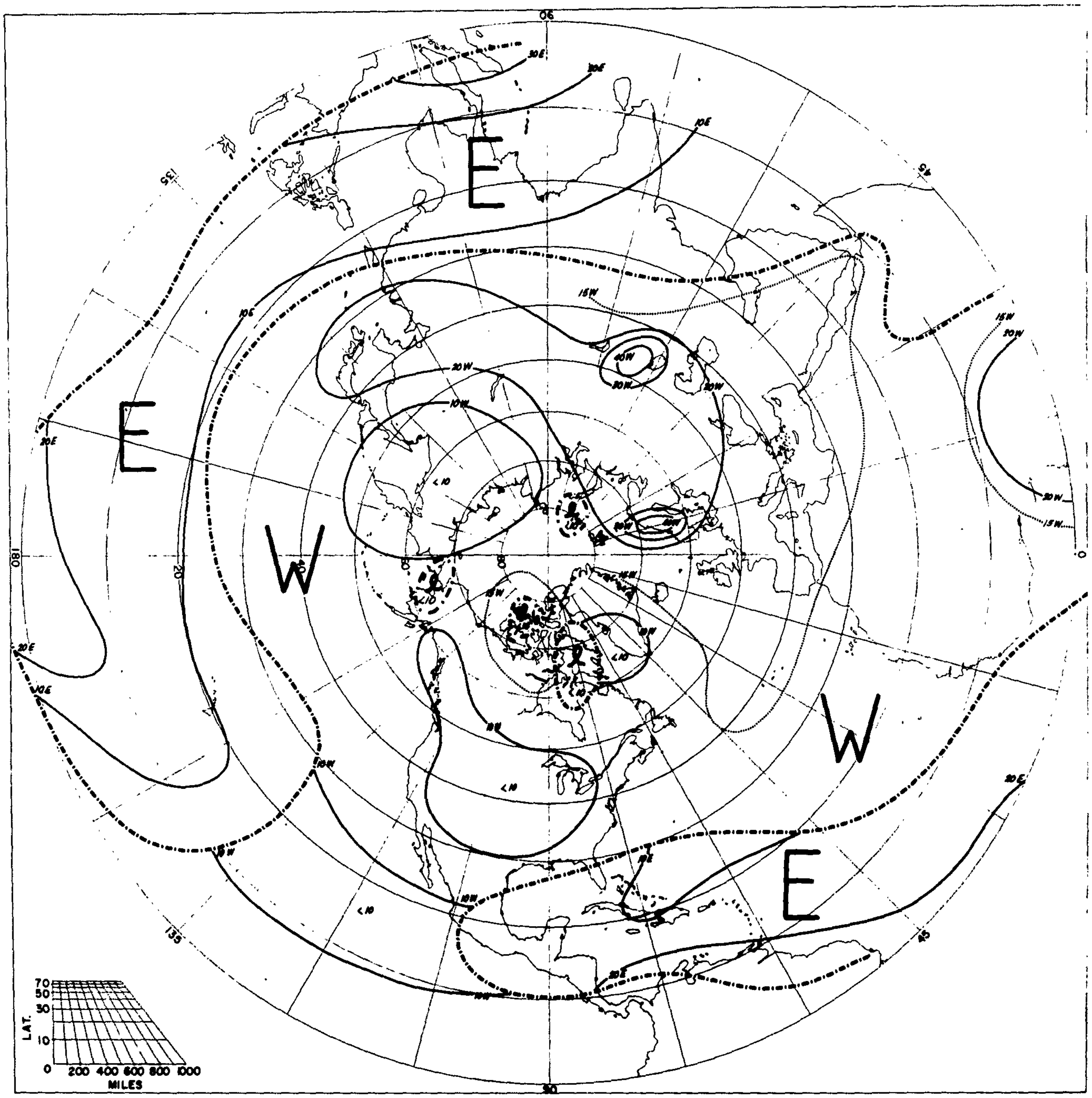

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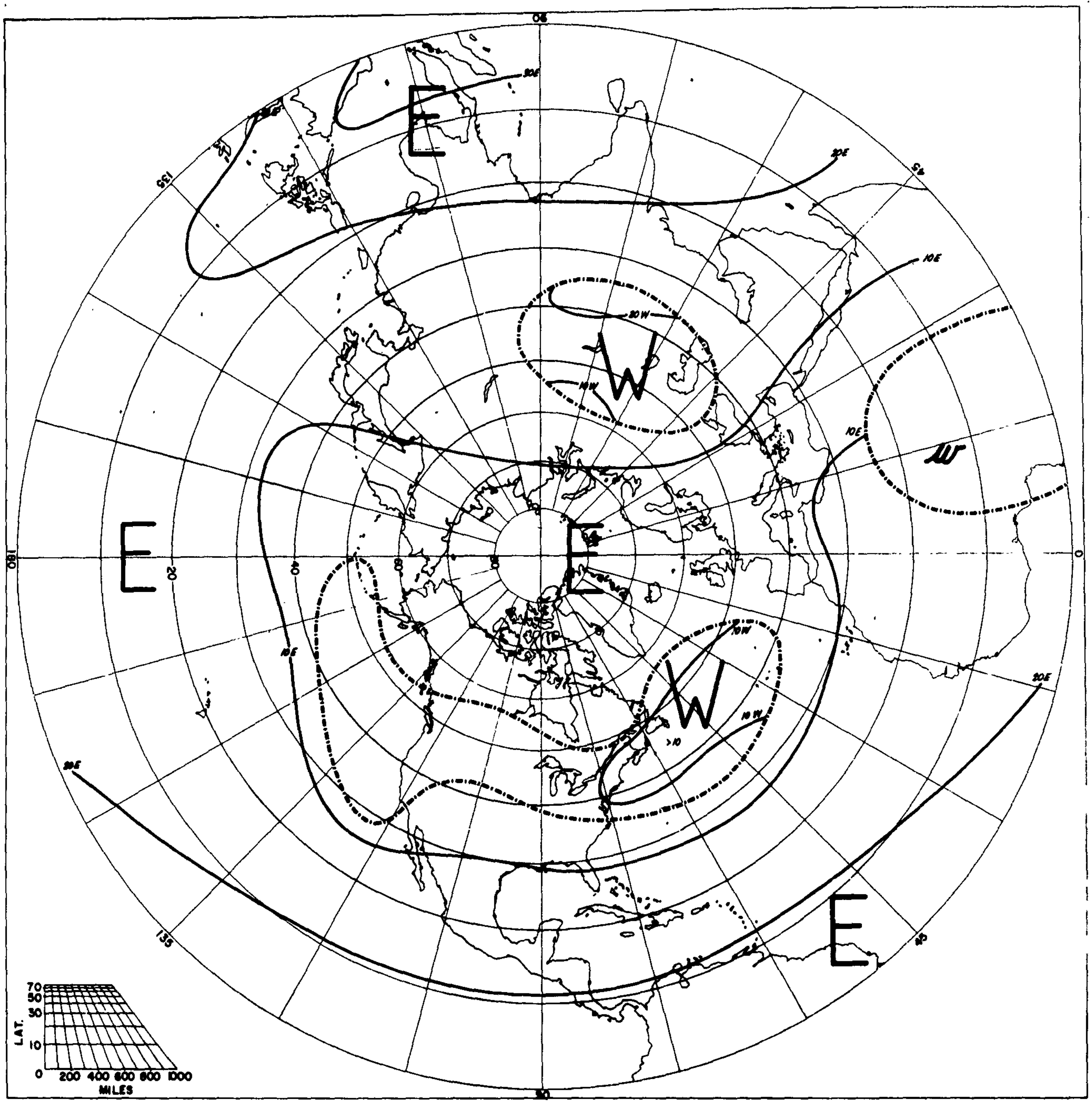

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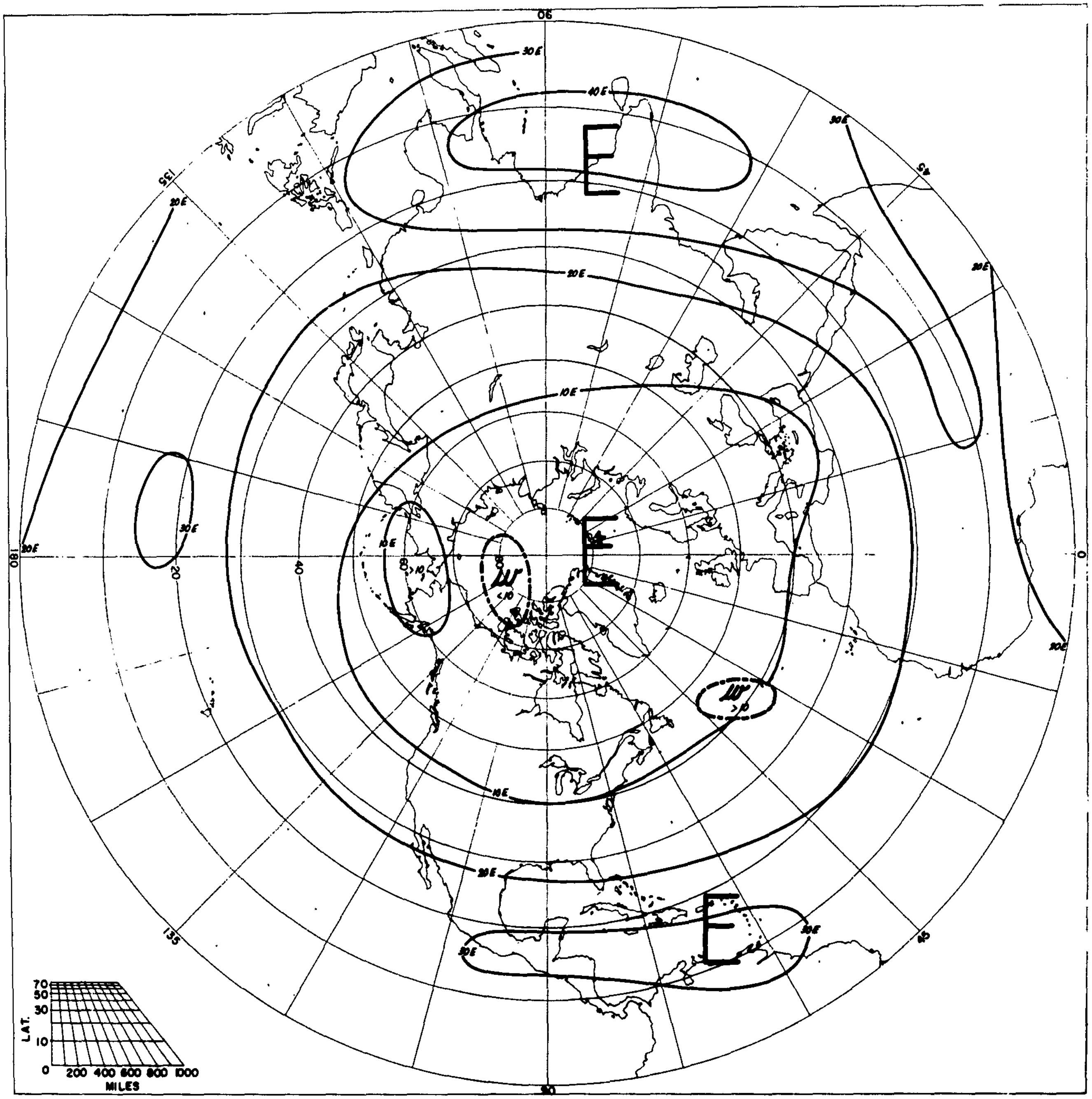

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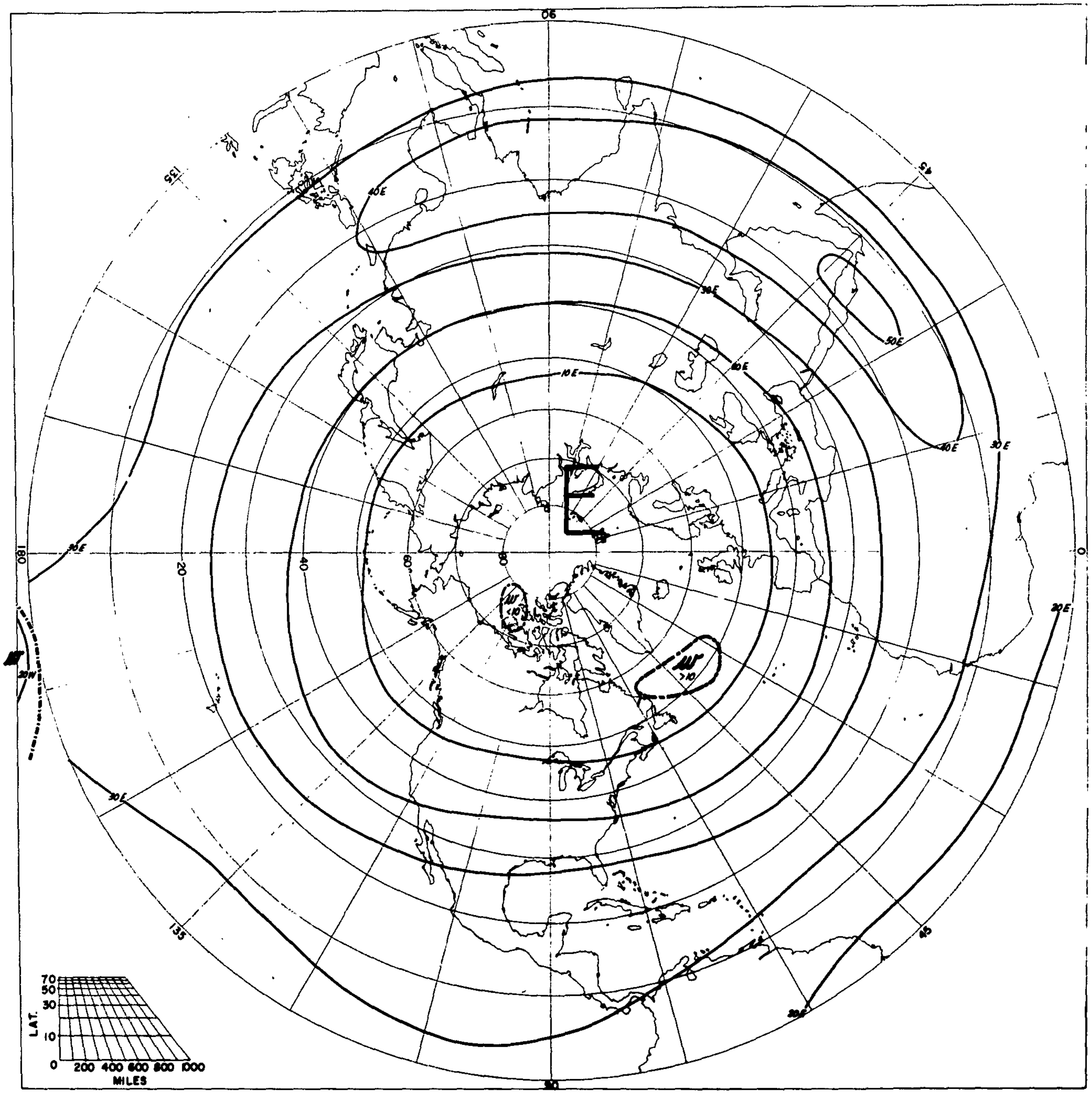

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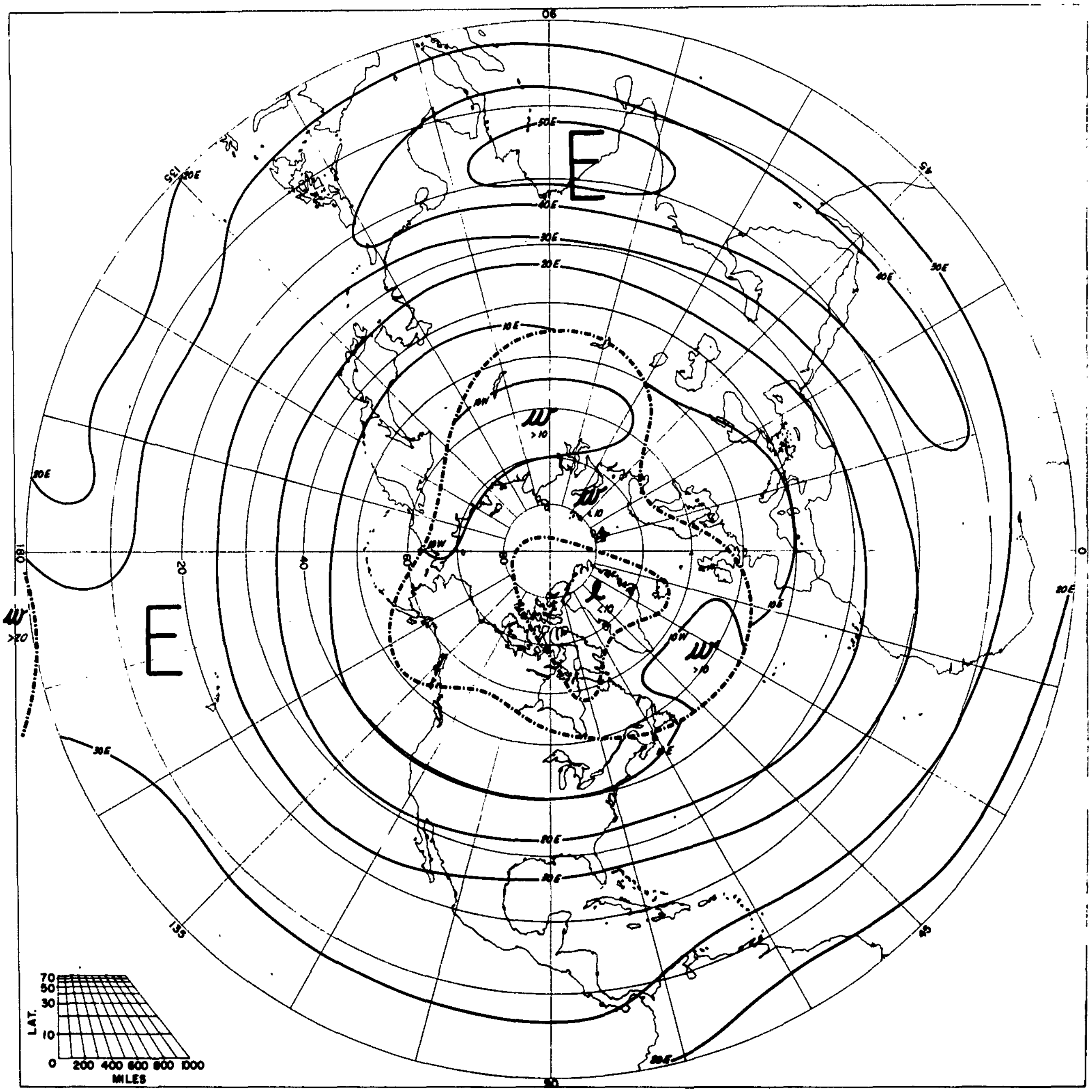

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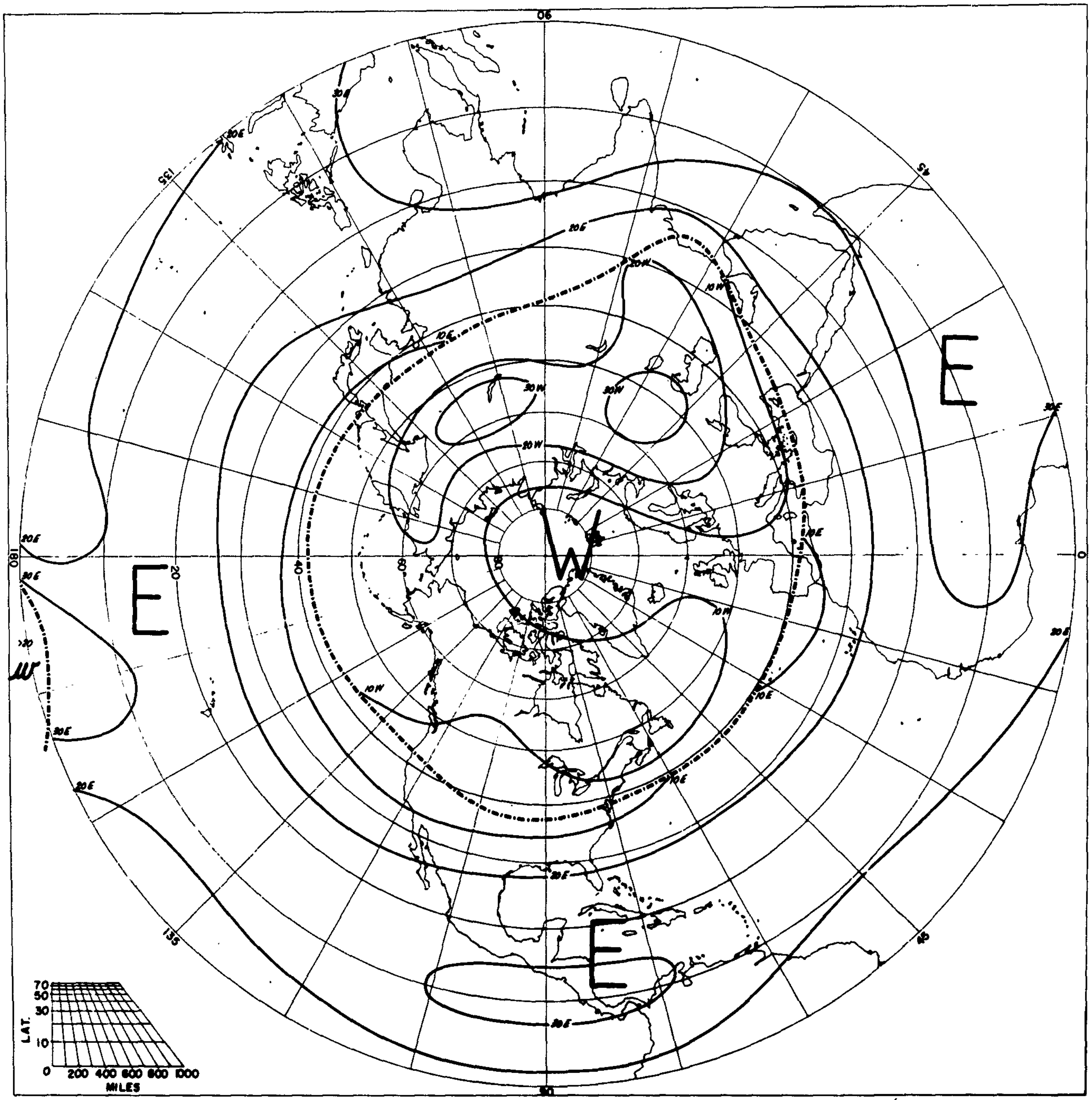

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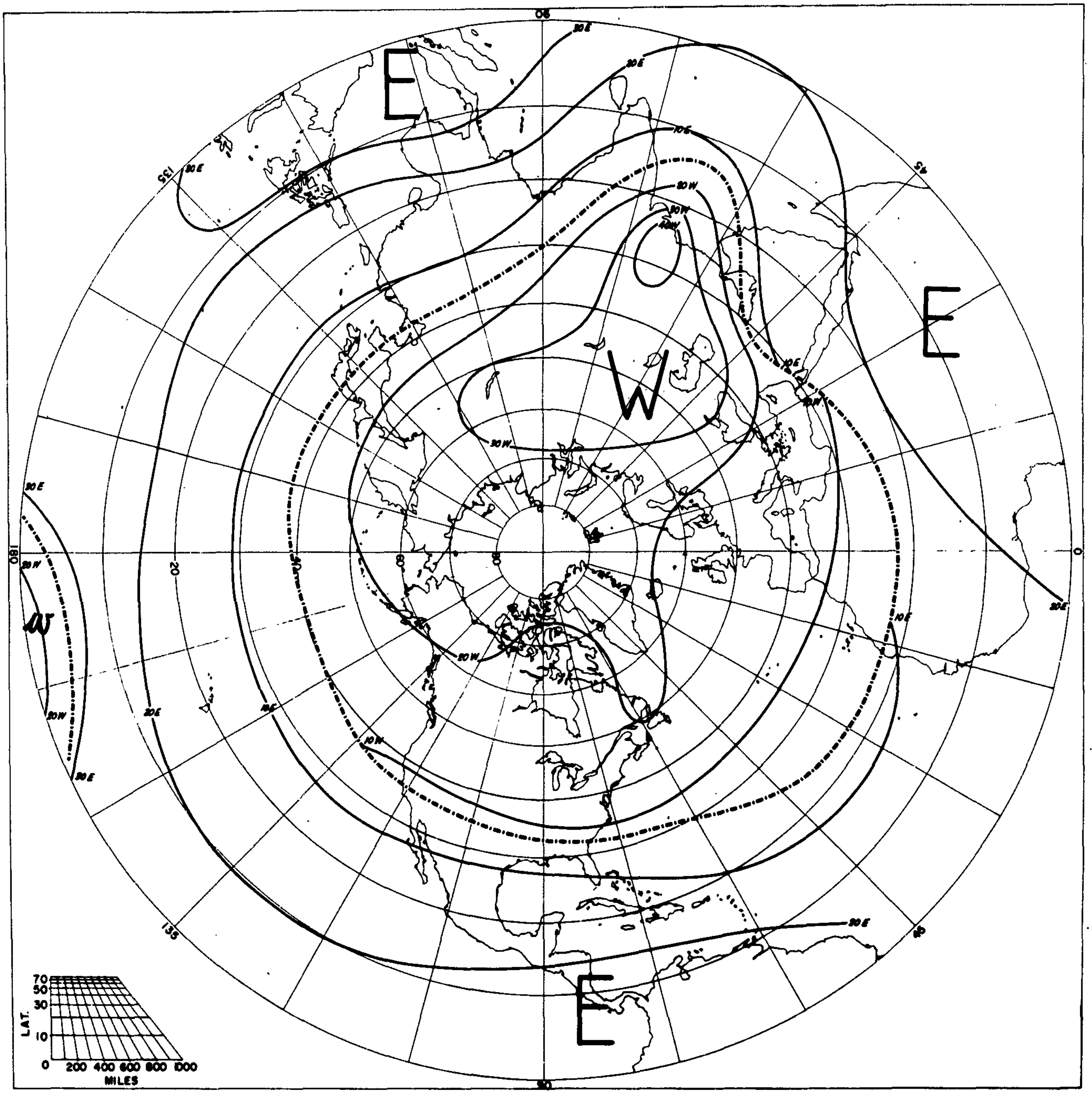

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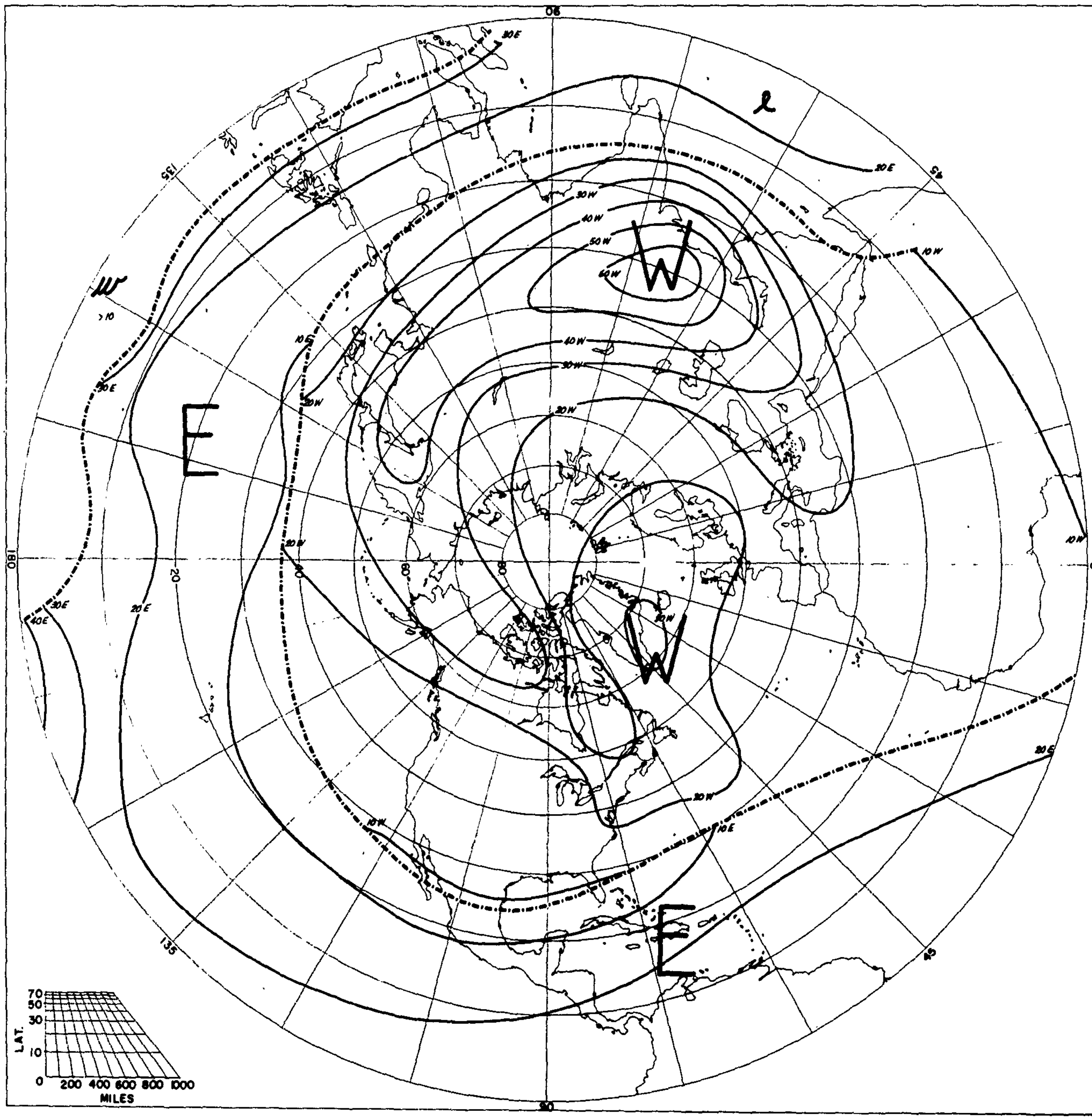

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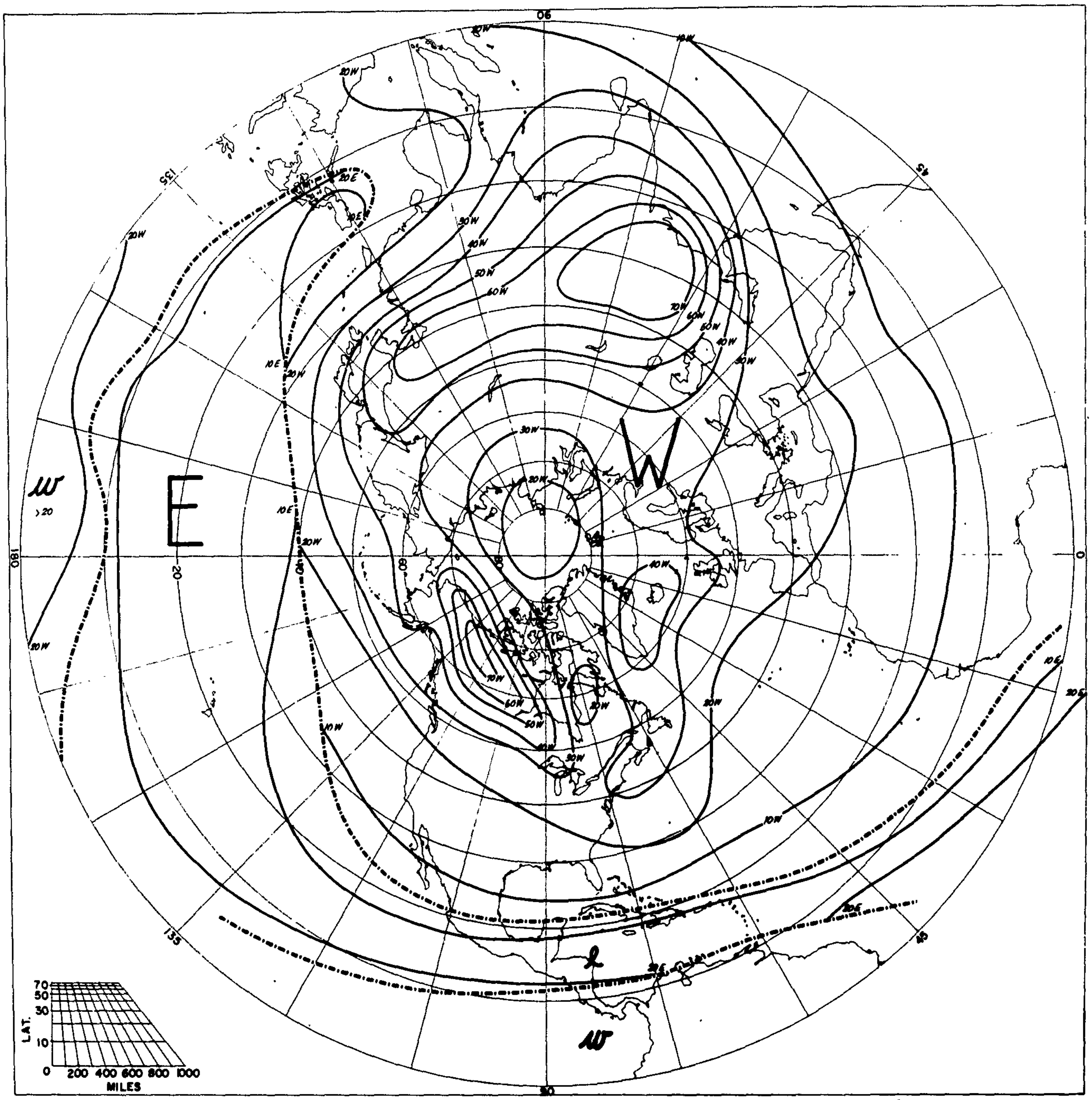

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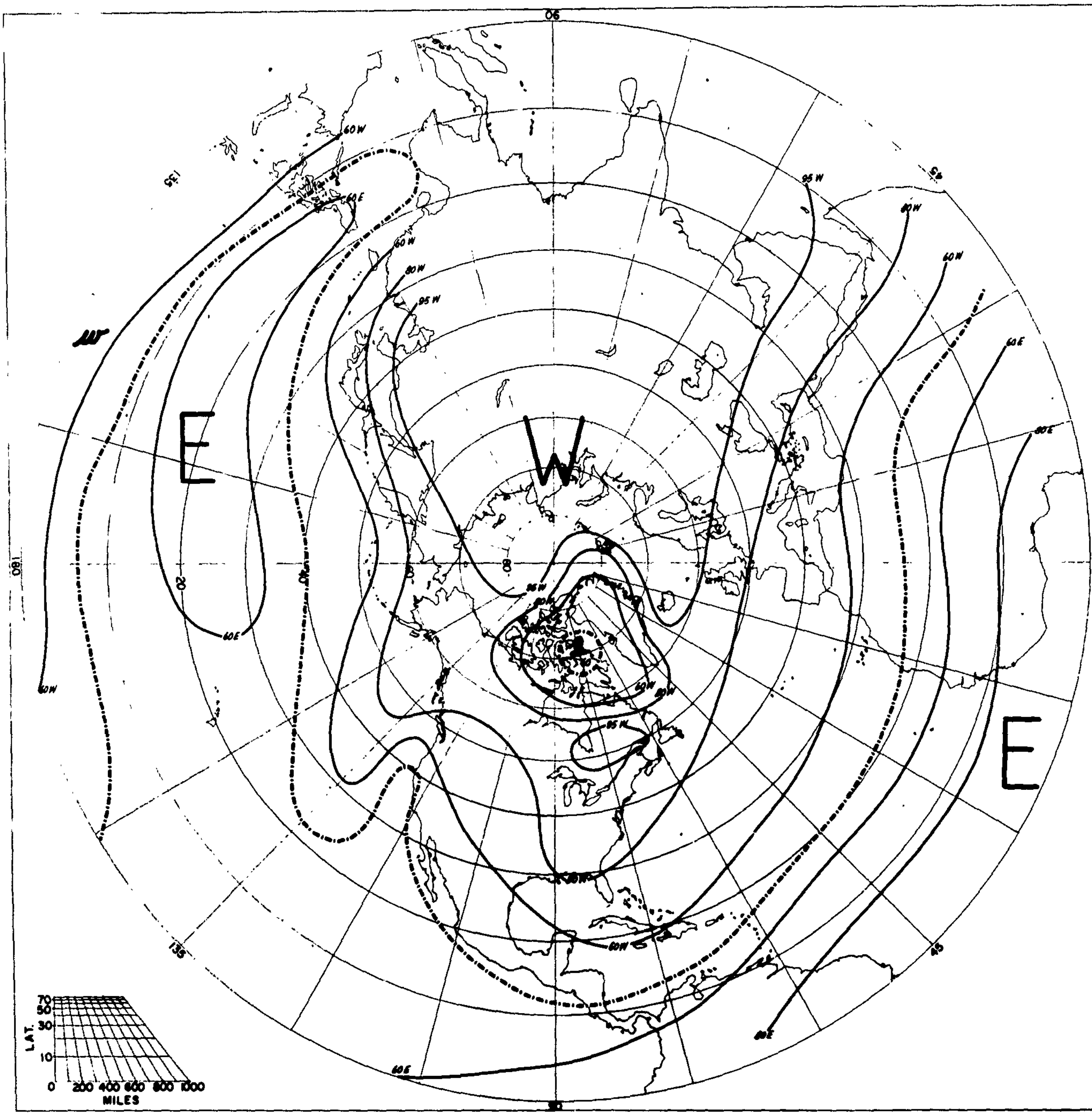

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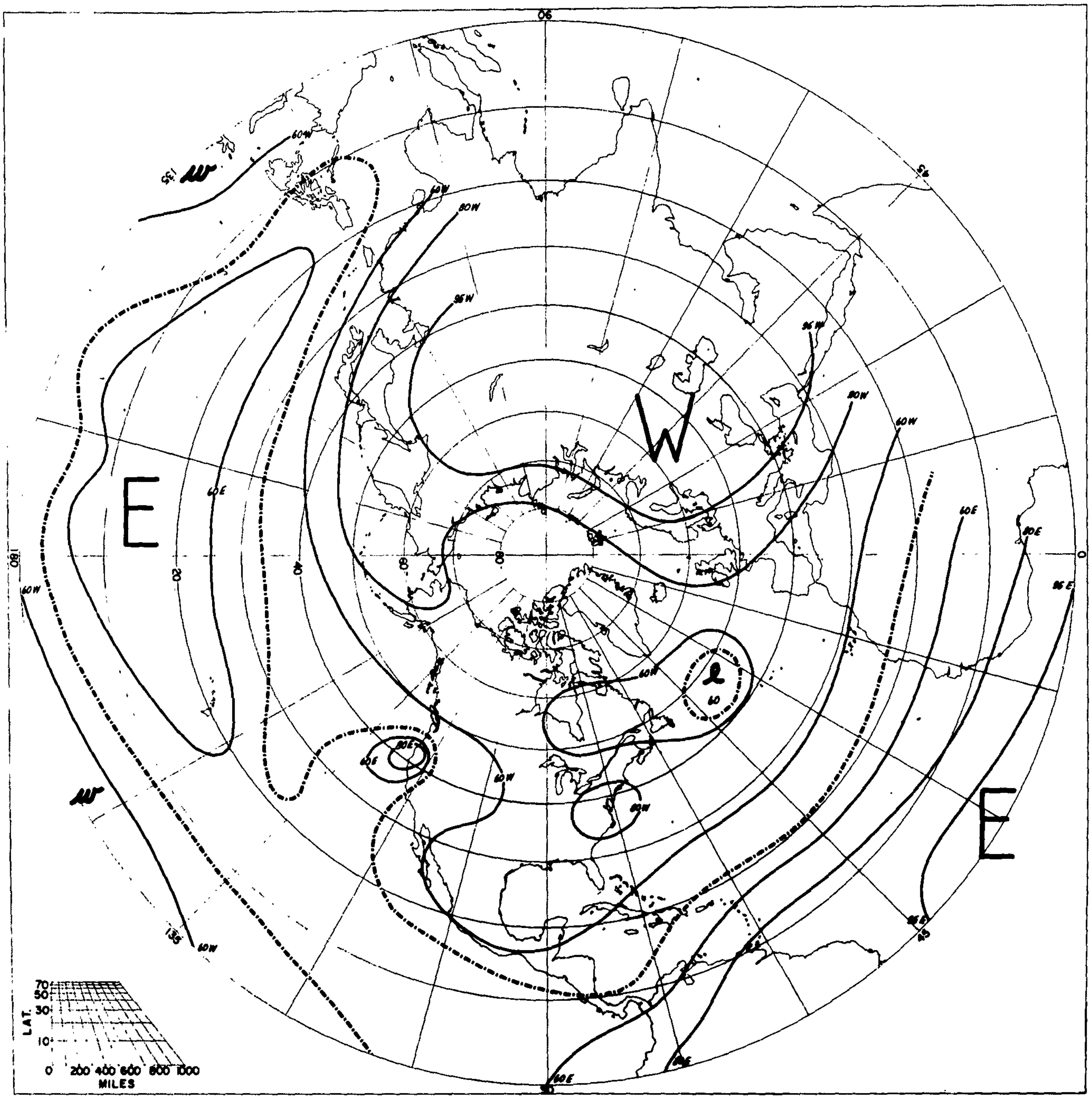

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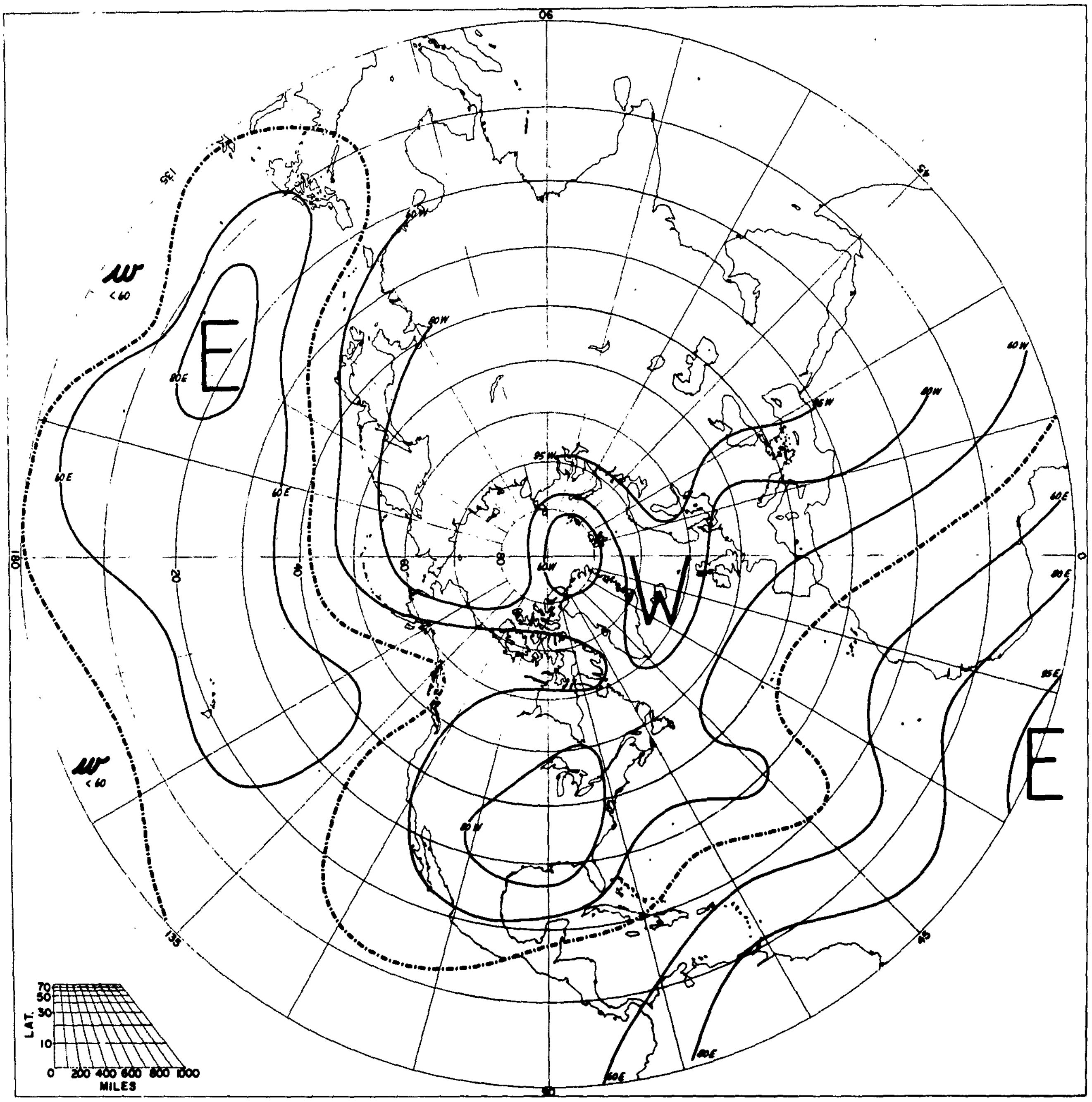

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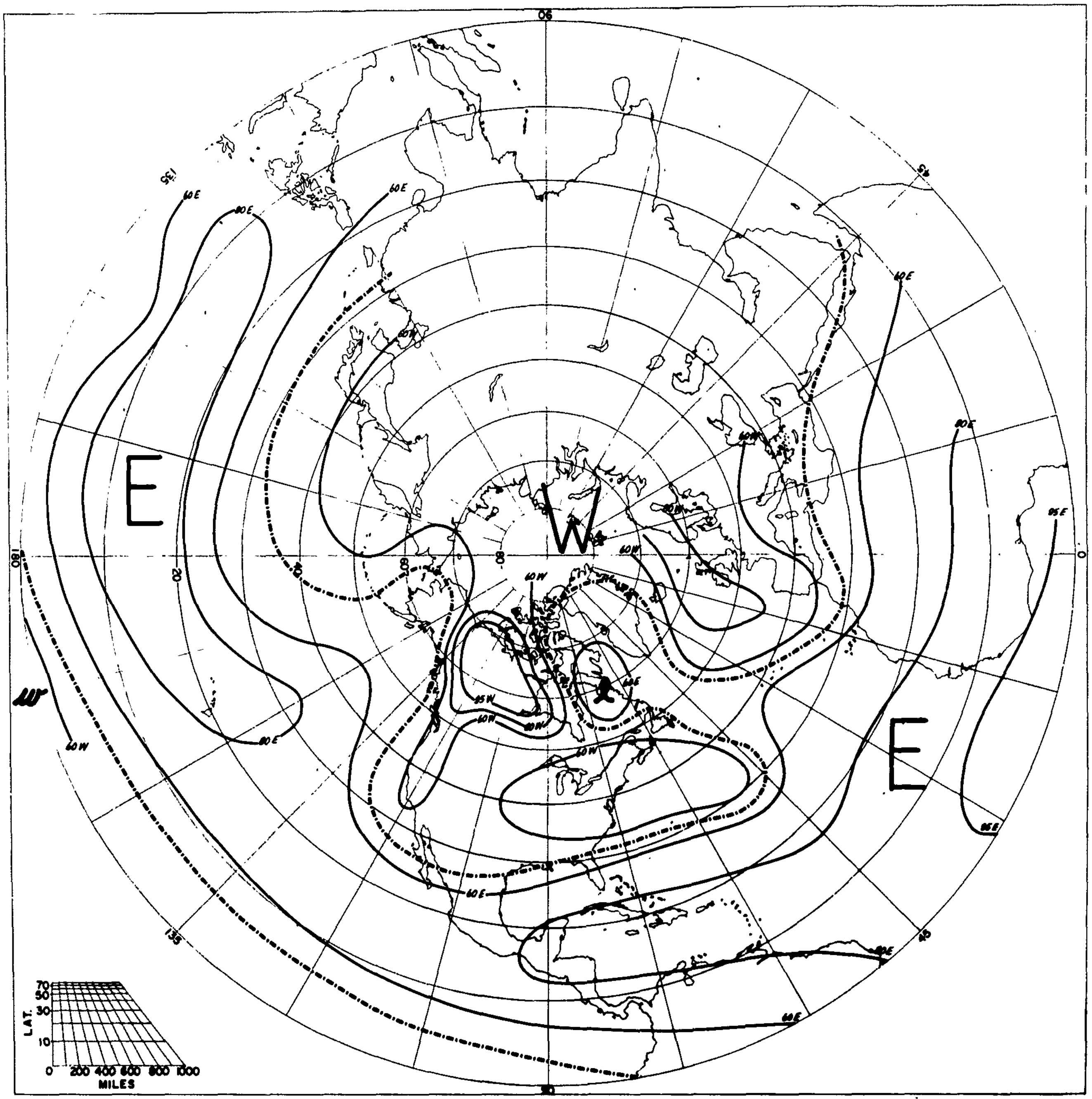

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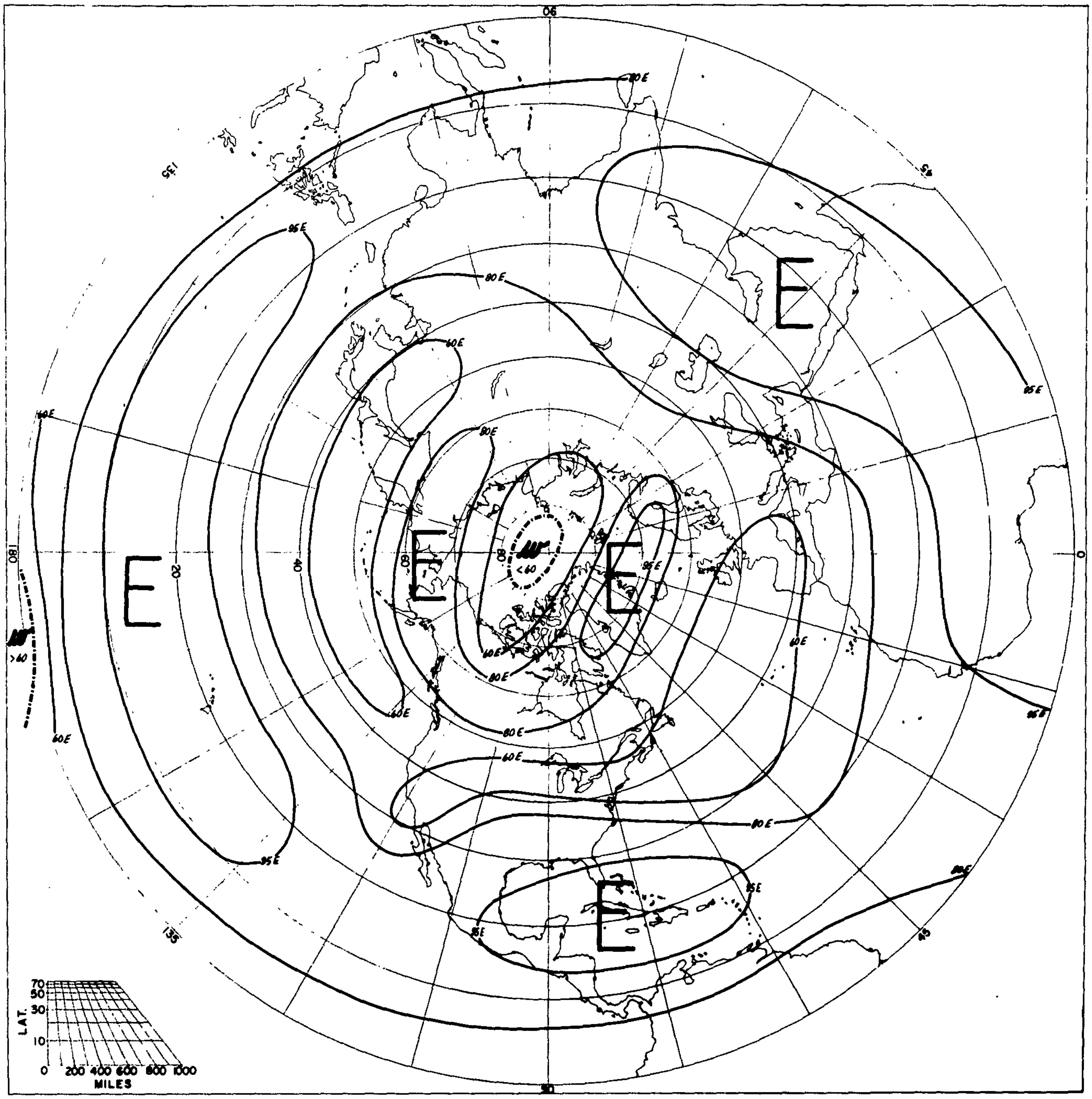

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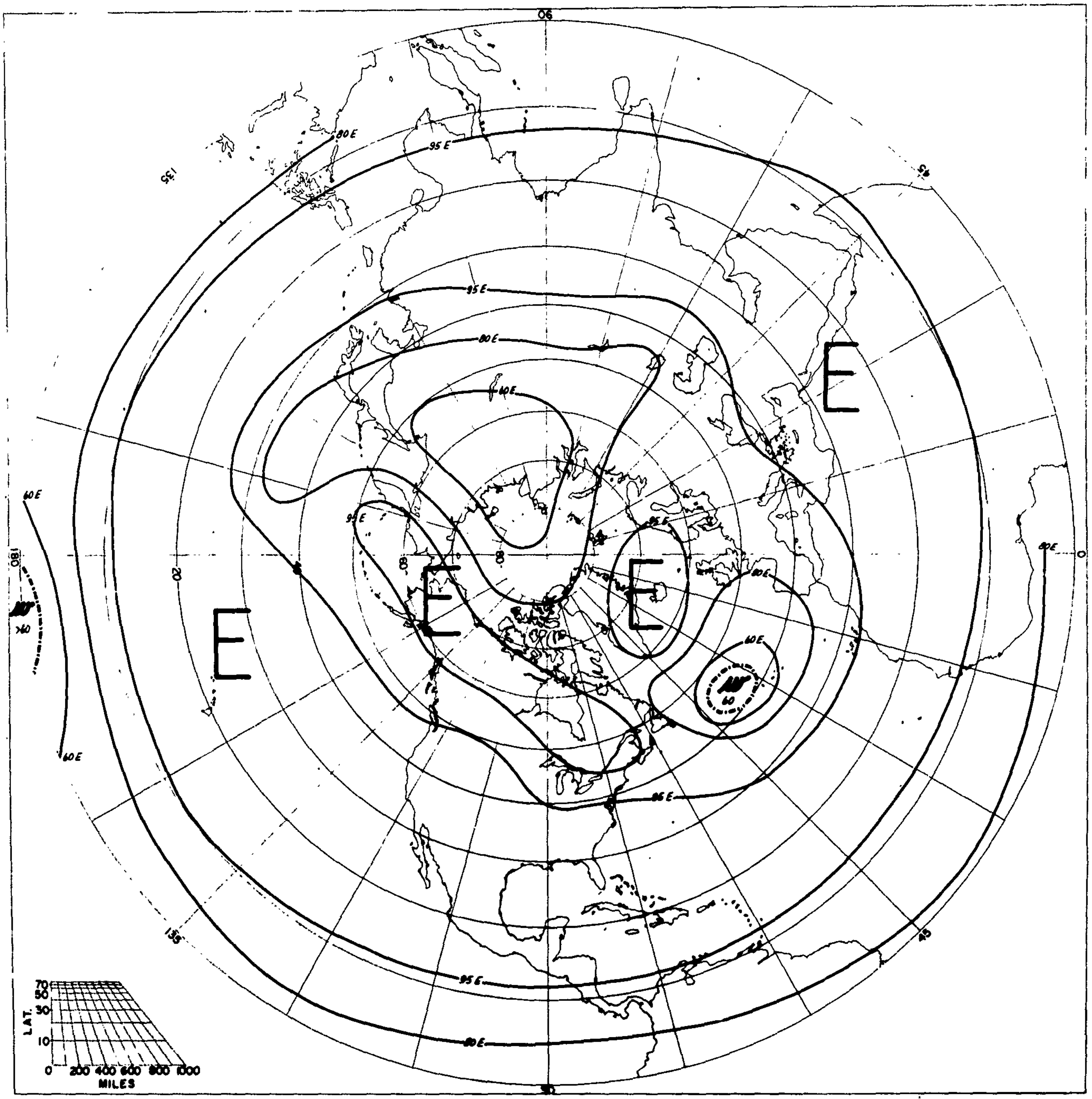

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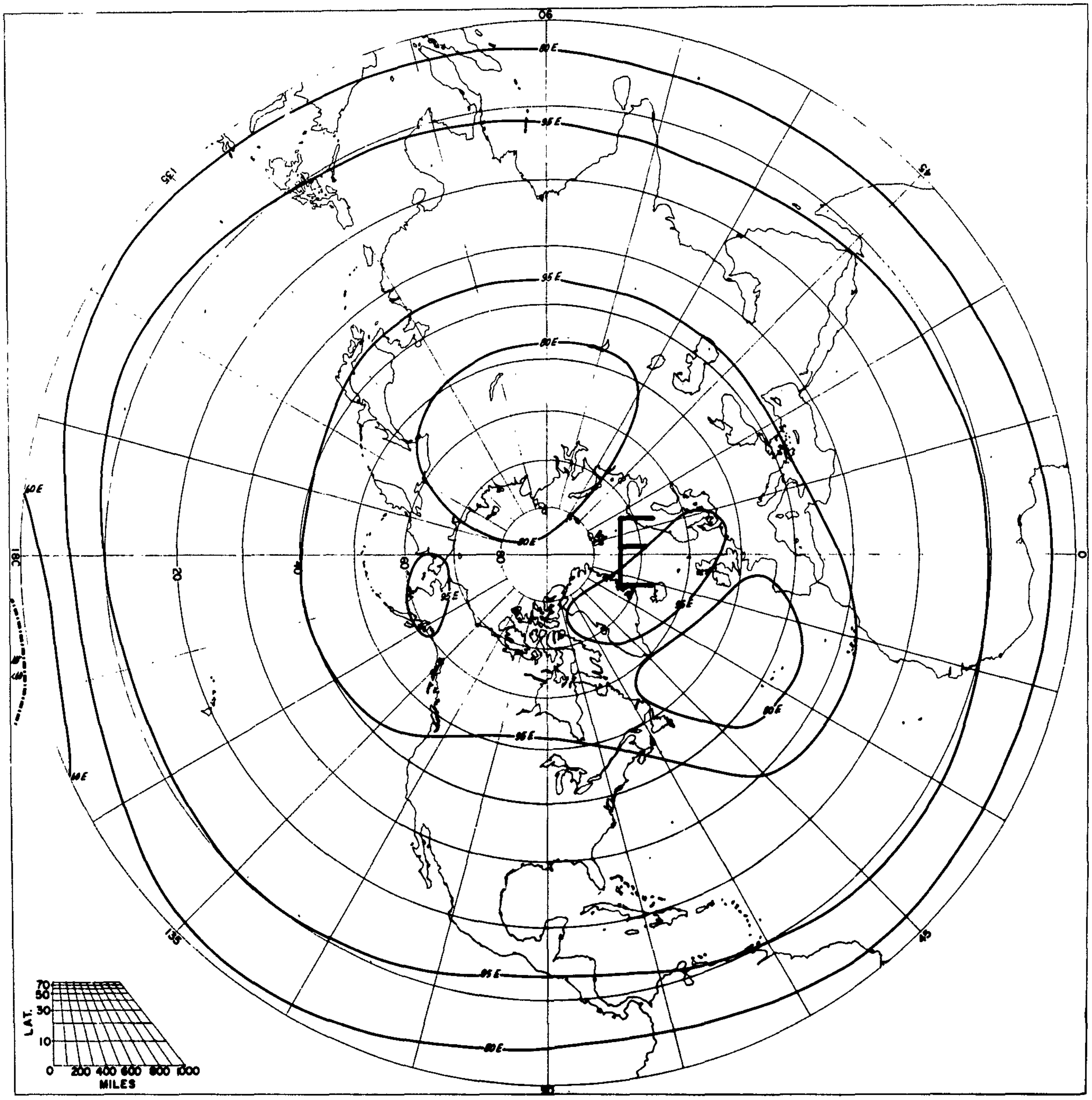

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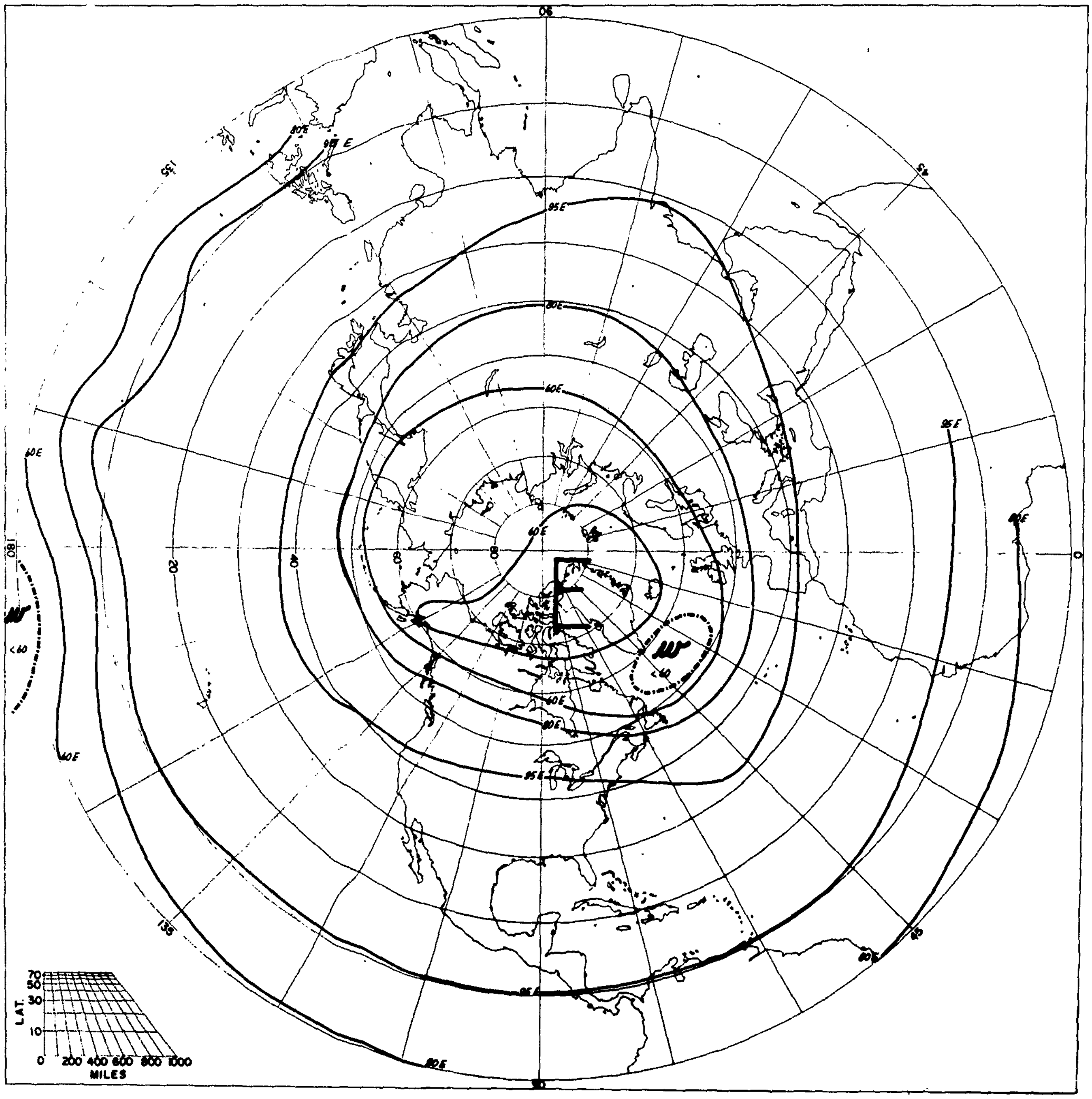

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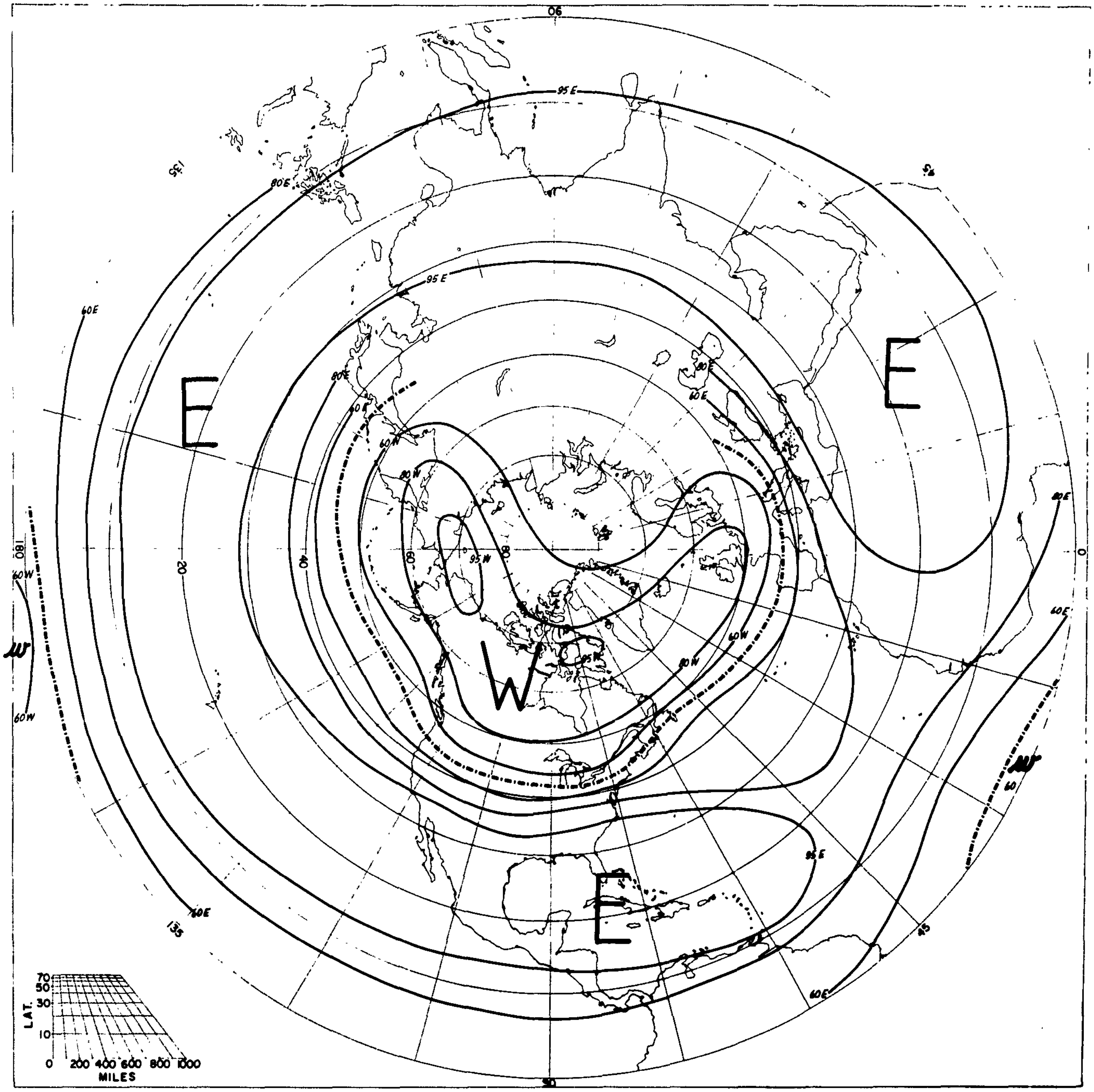

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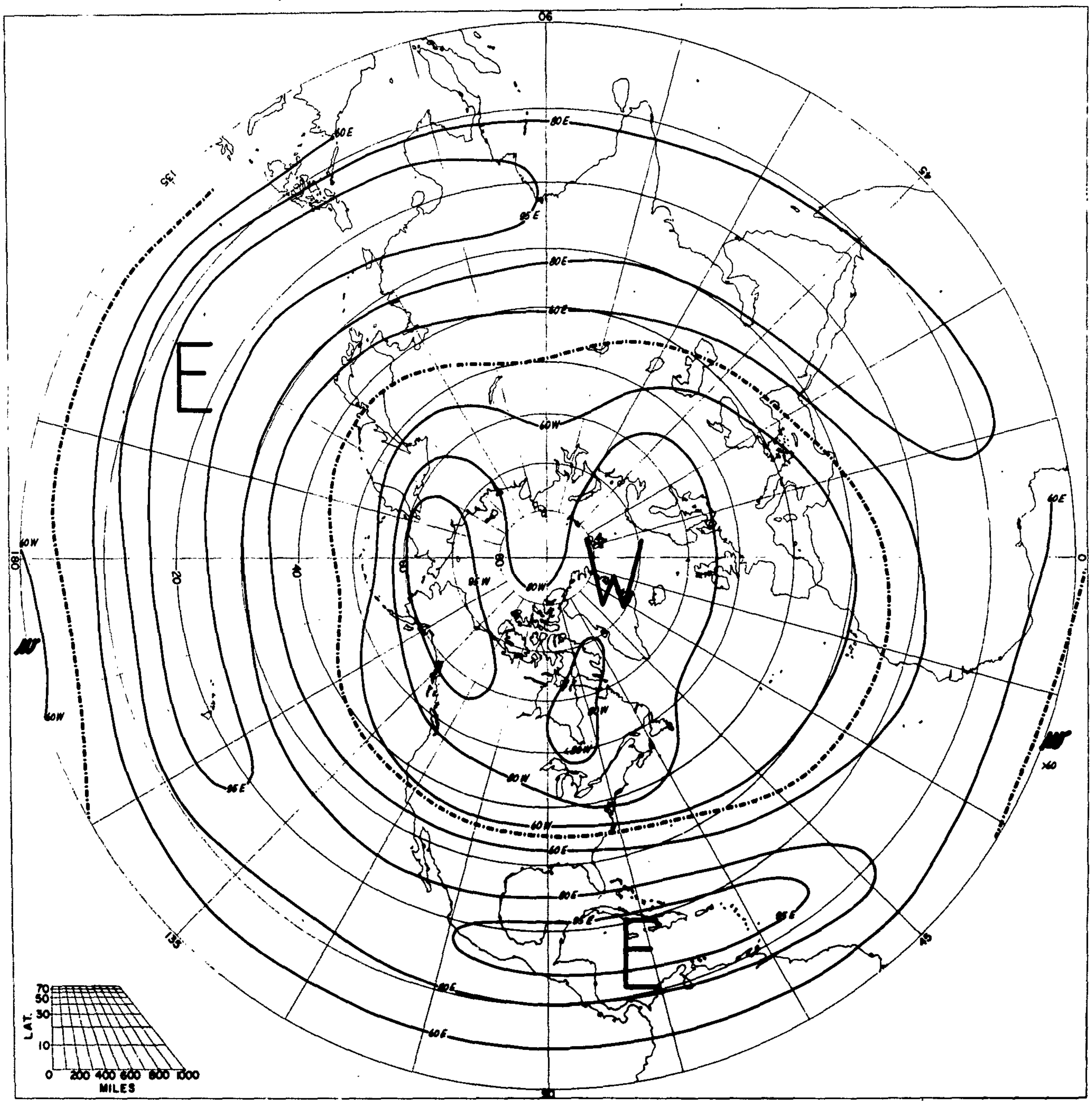

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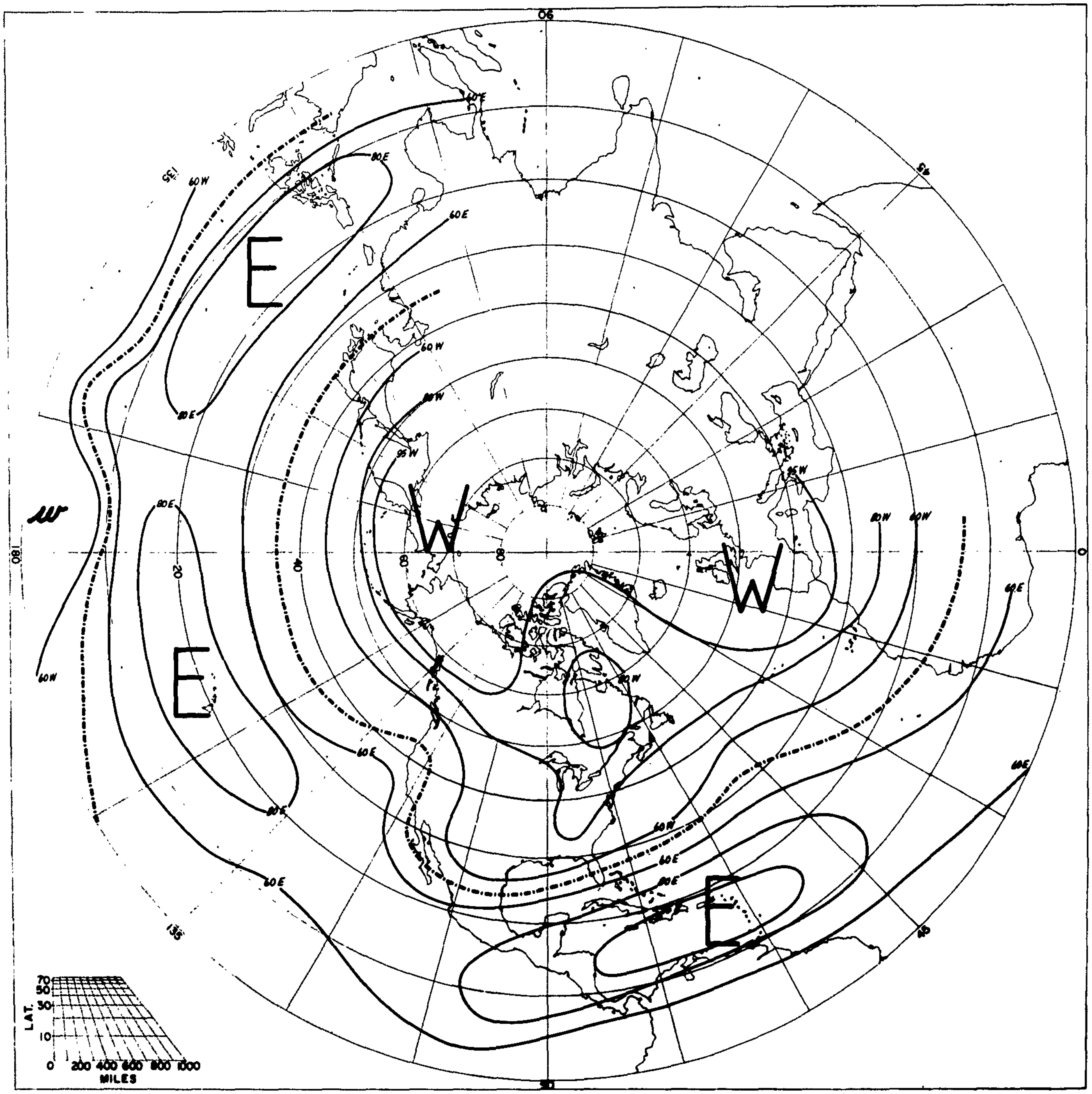

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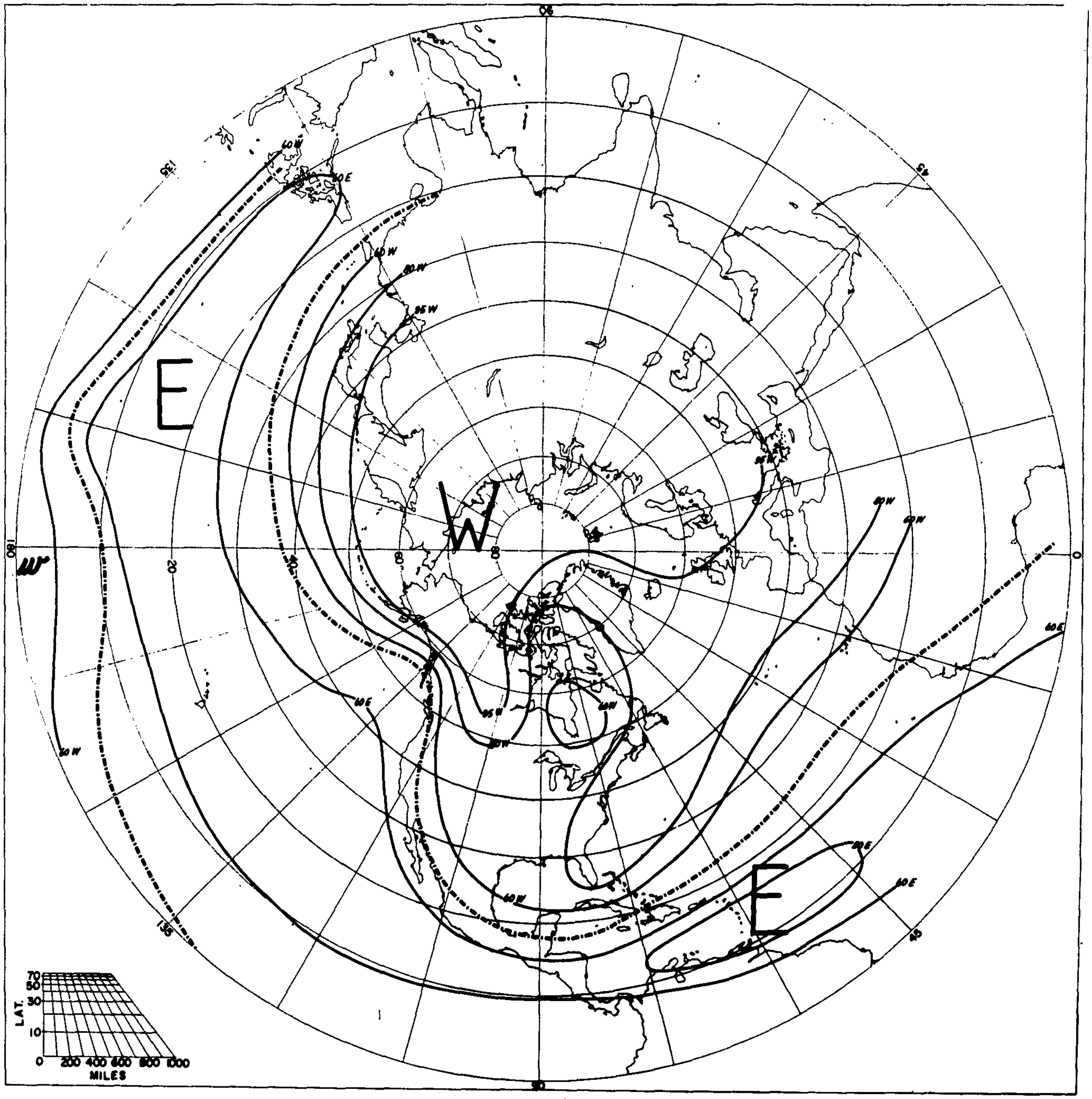

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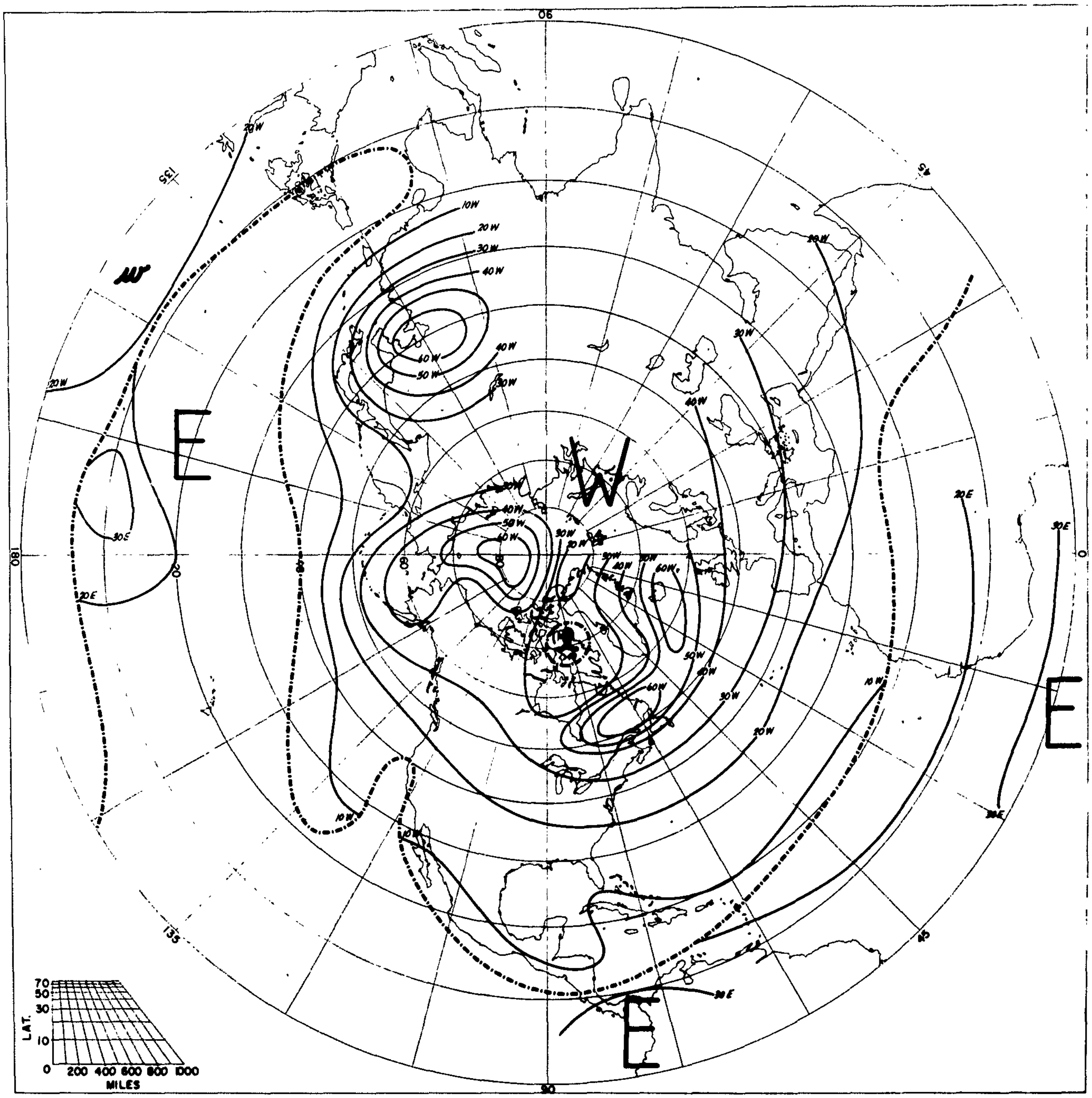

SPEED OF PREVAILING ZONAL WINDS

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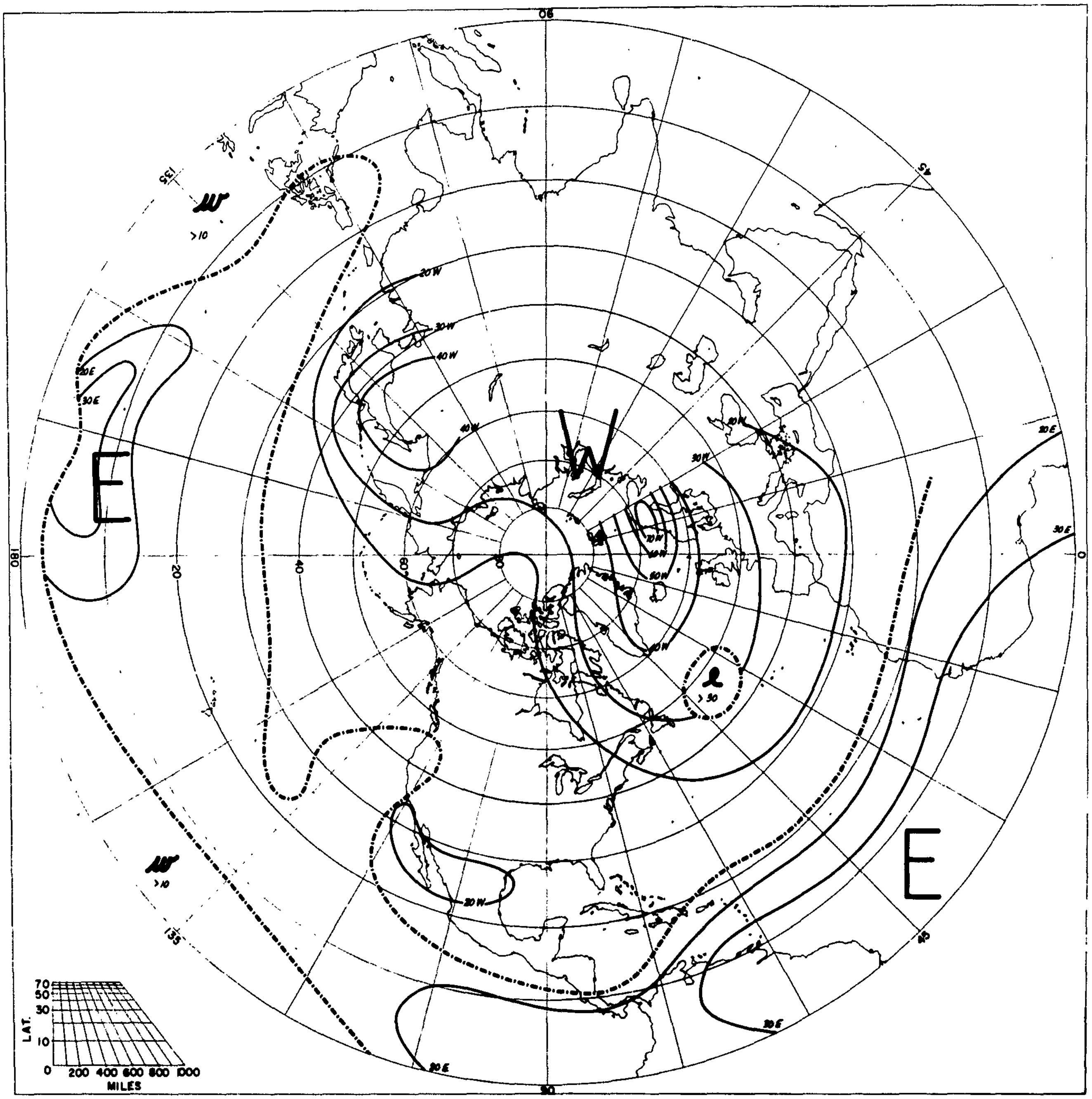

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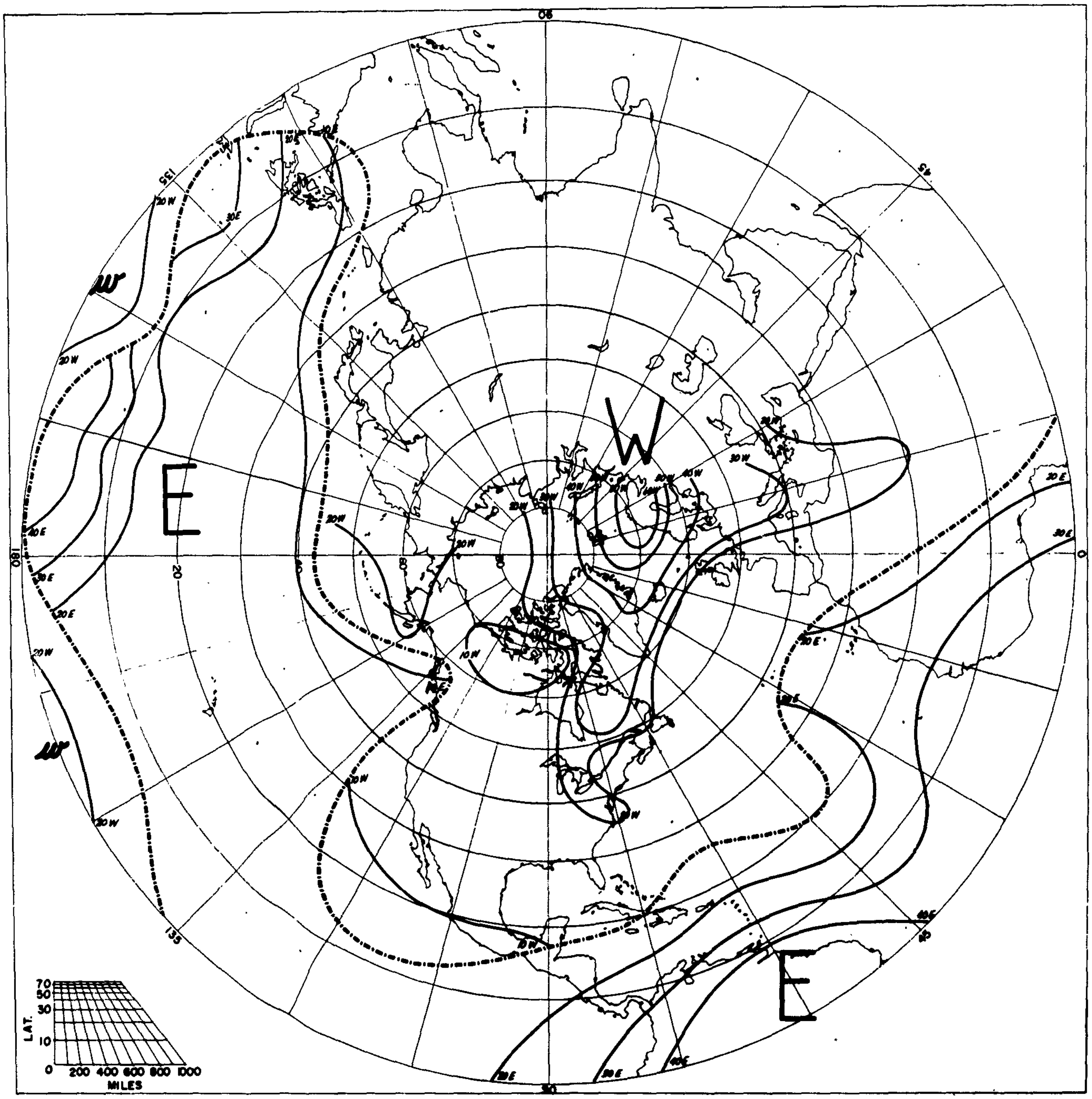

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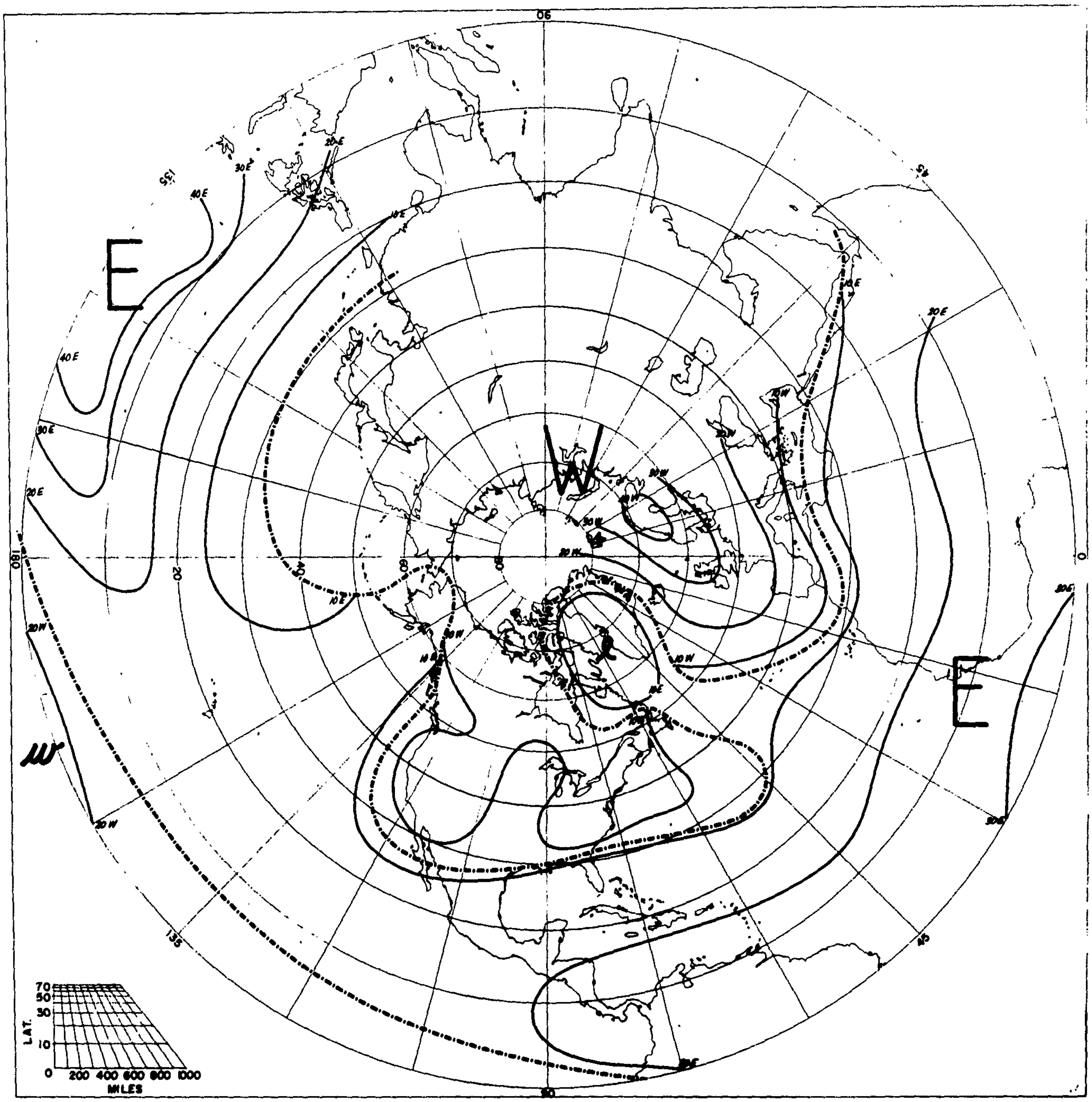

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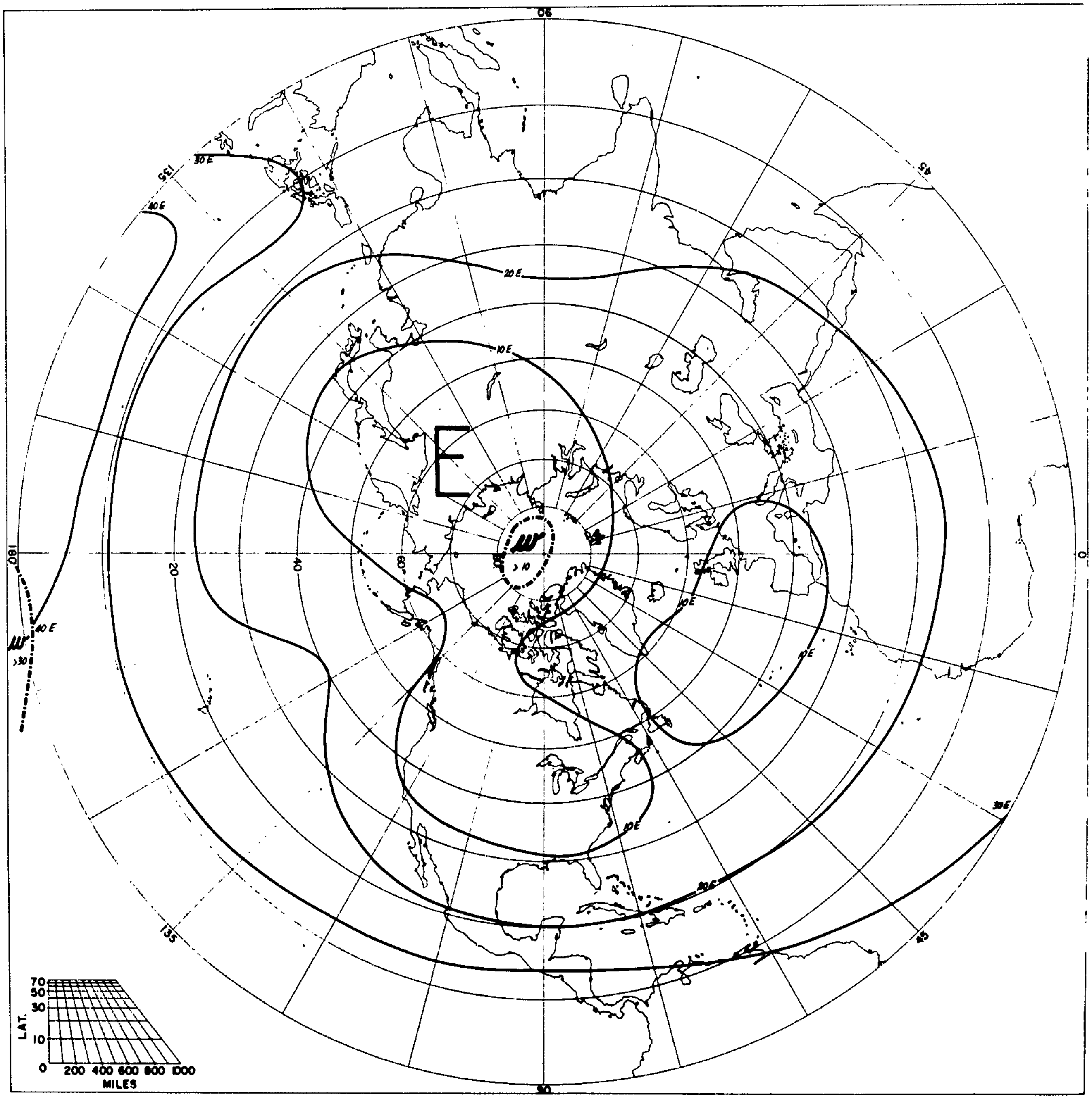

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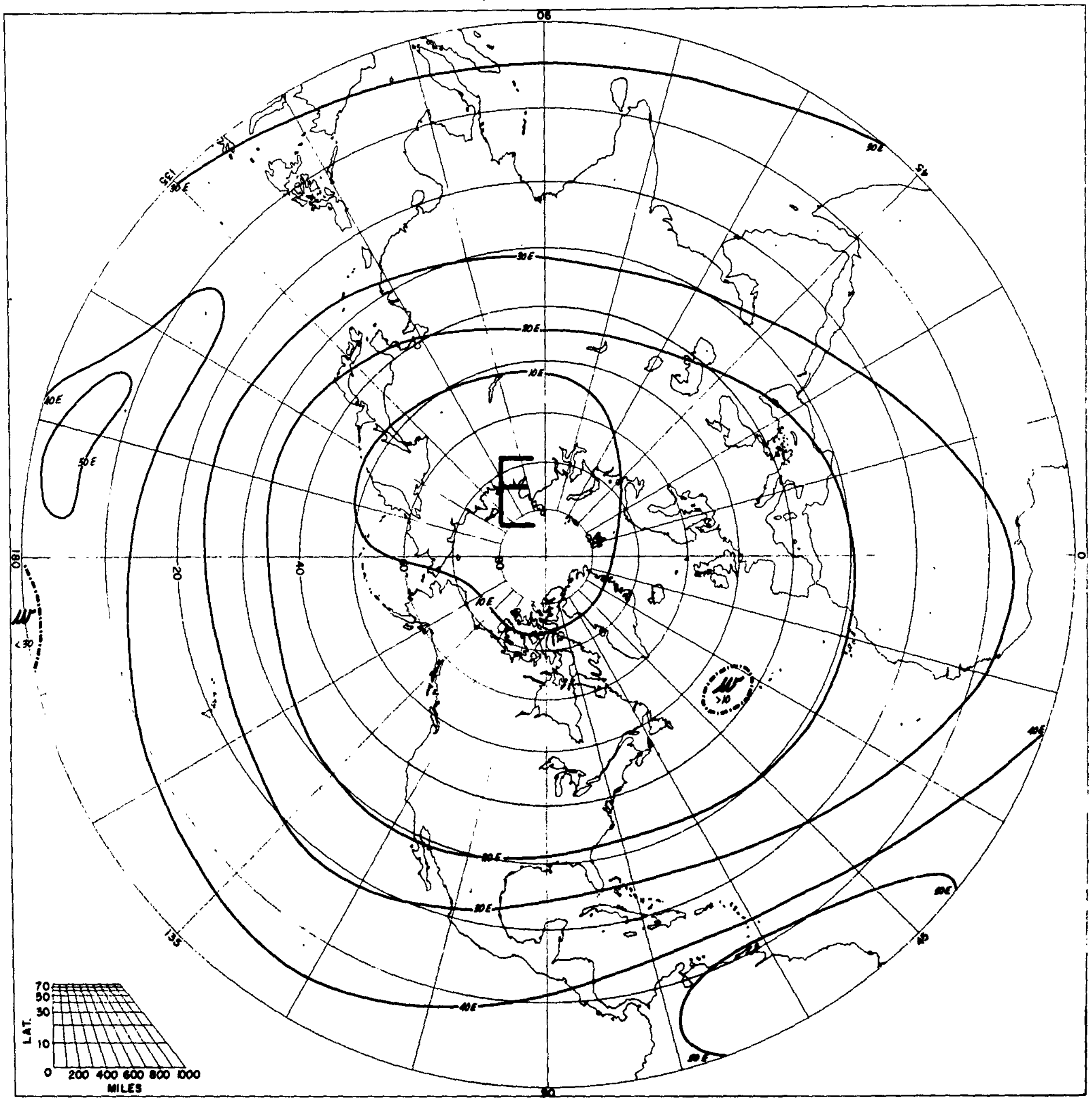

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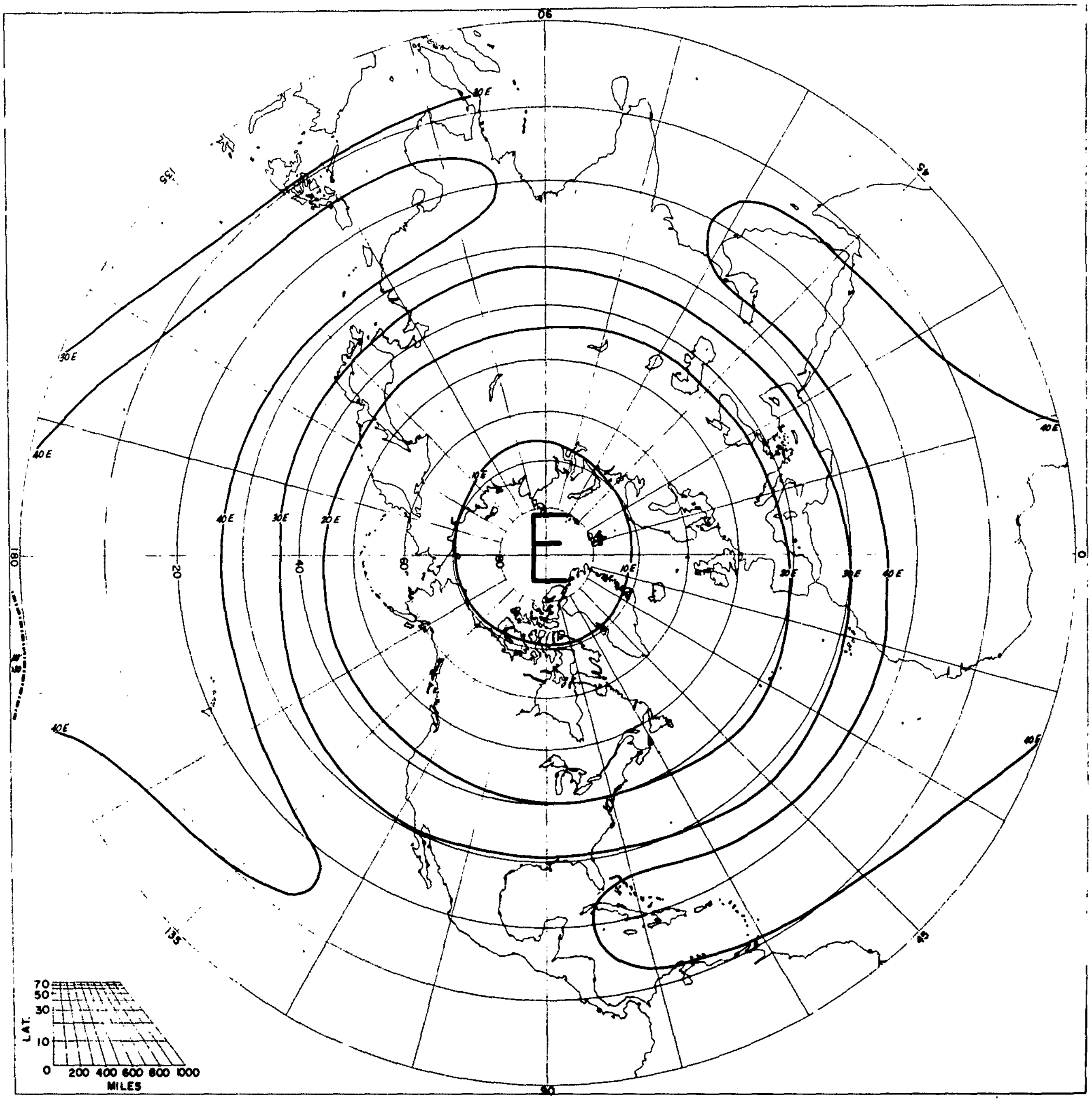

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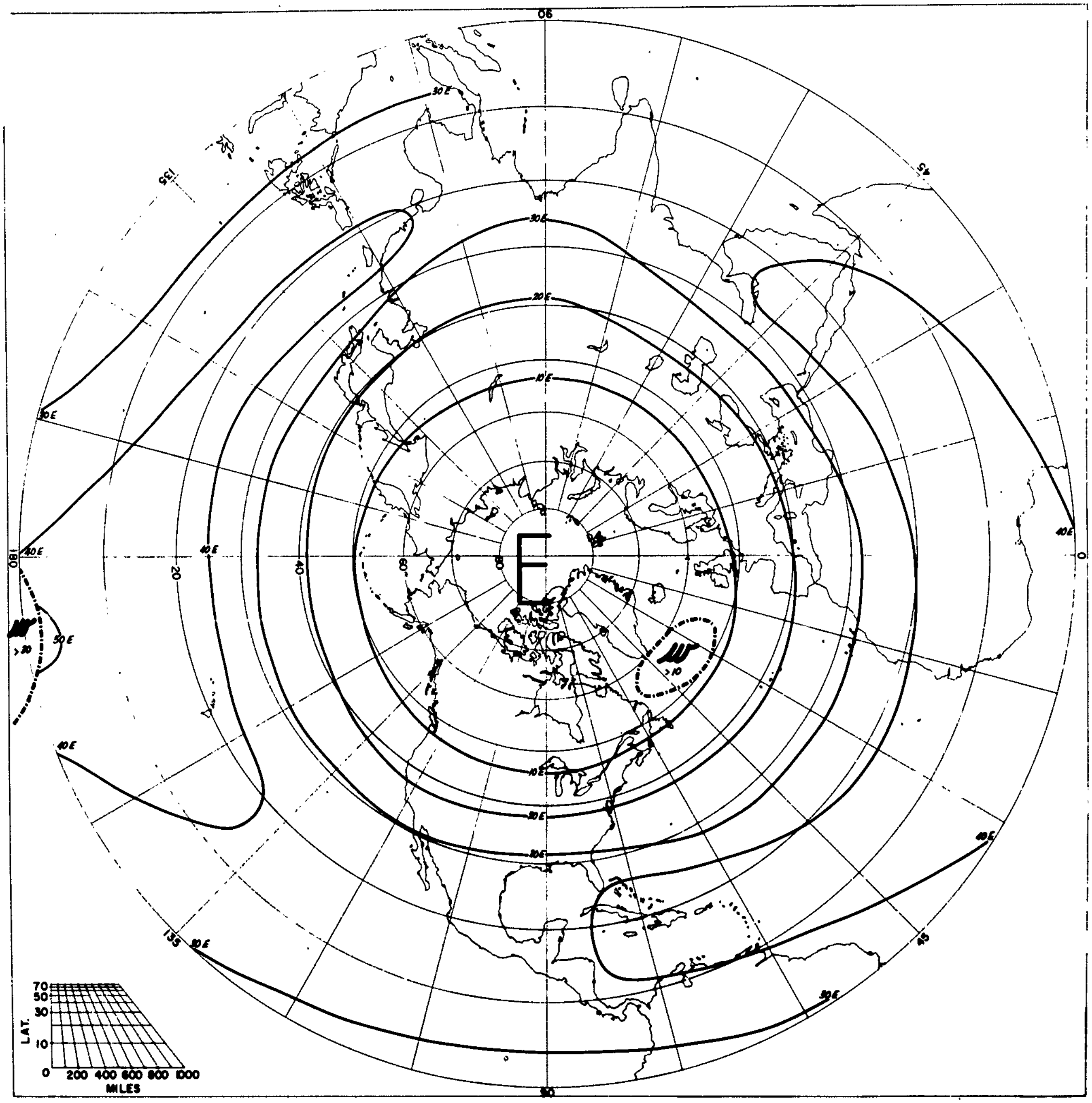

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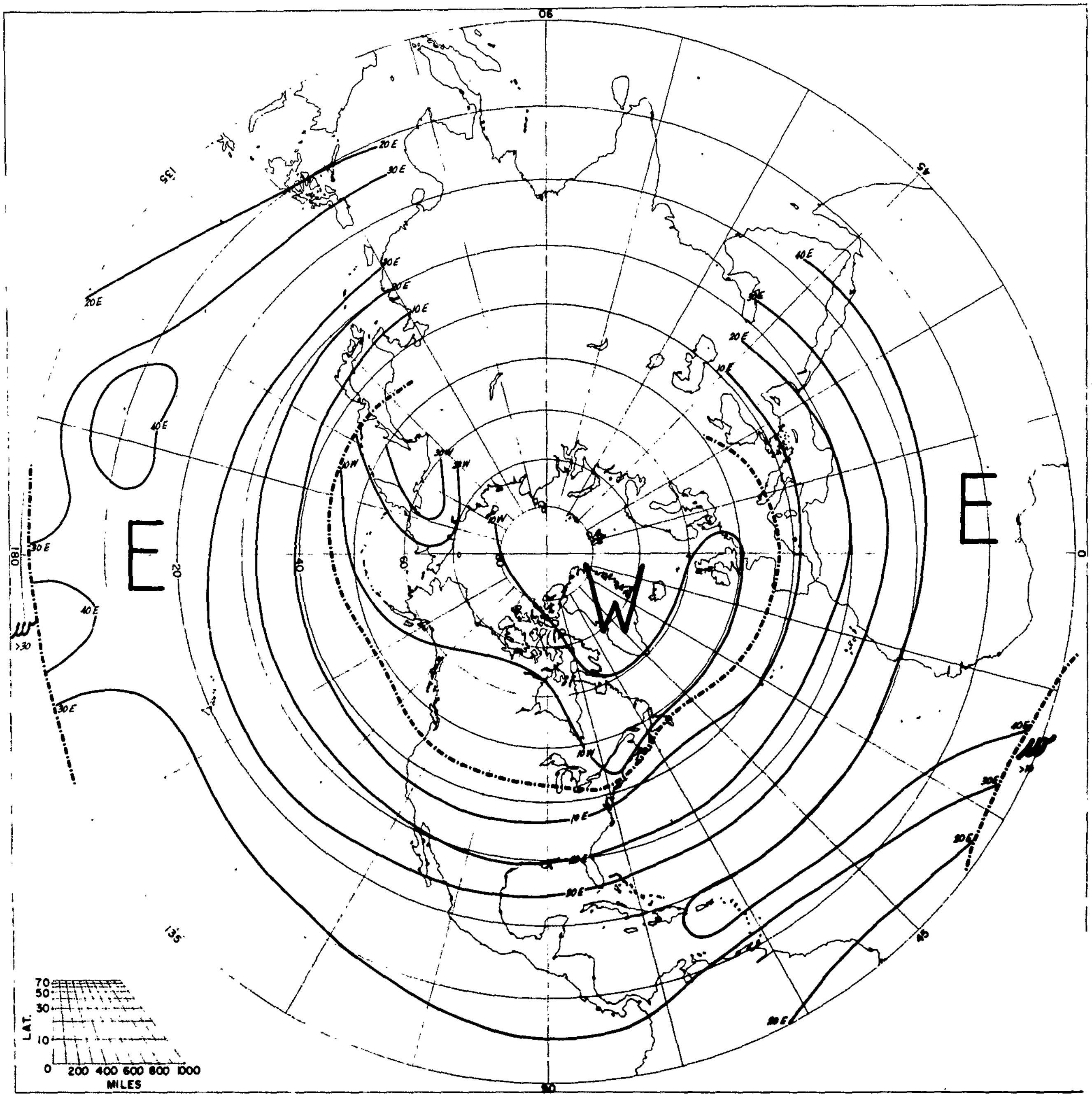

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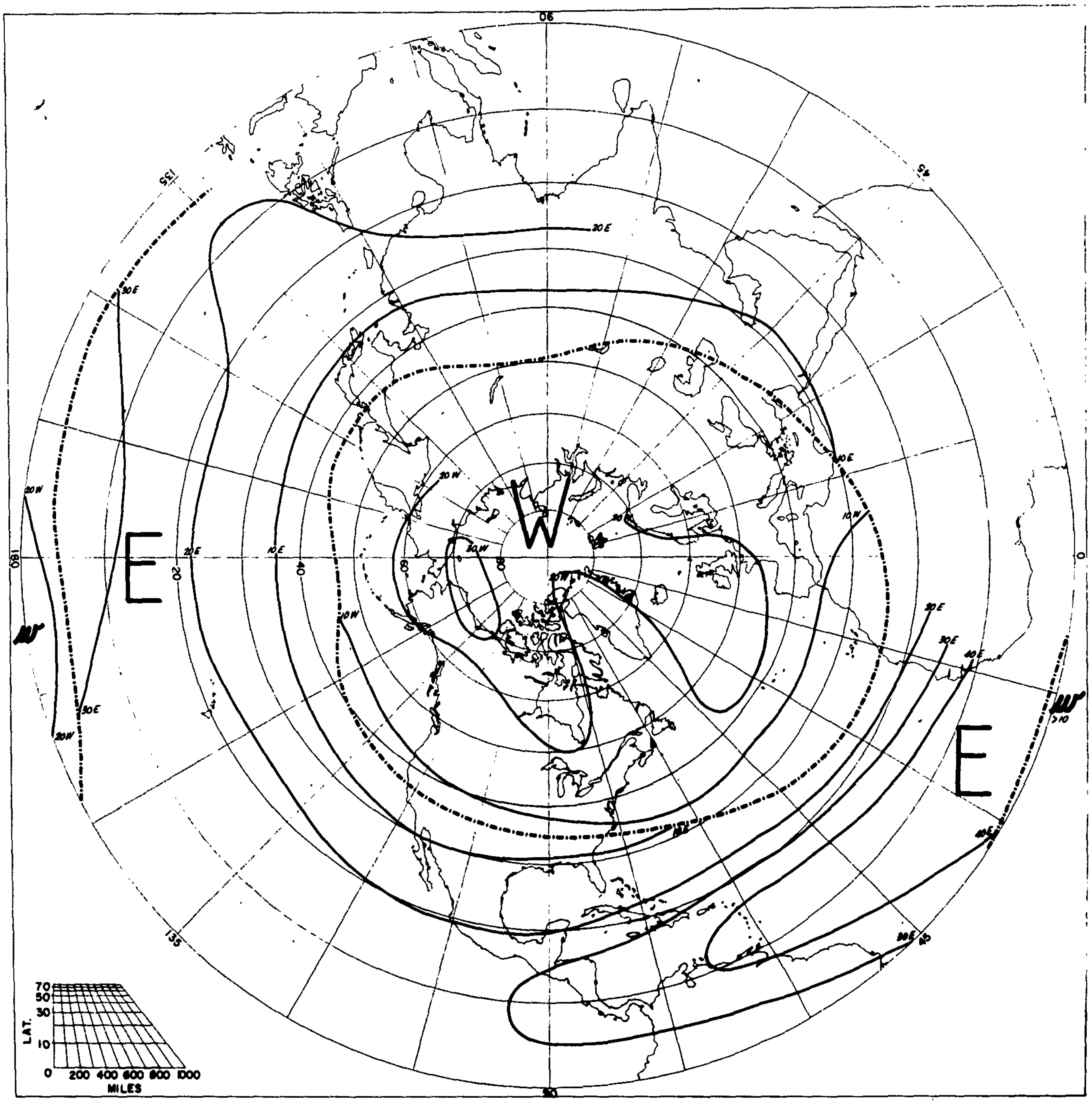

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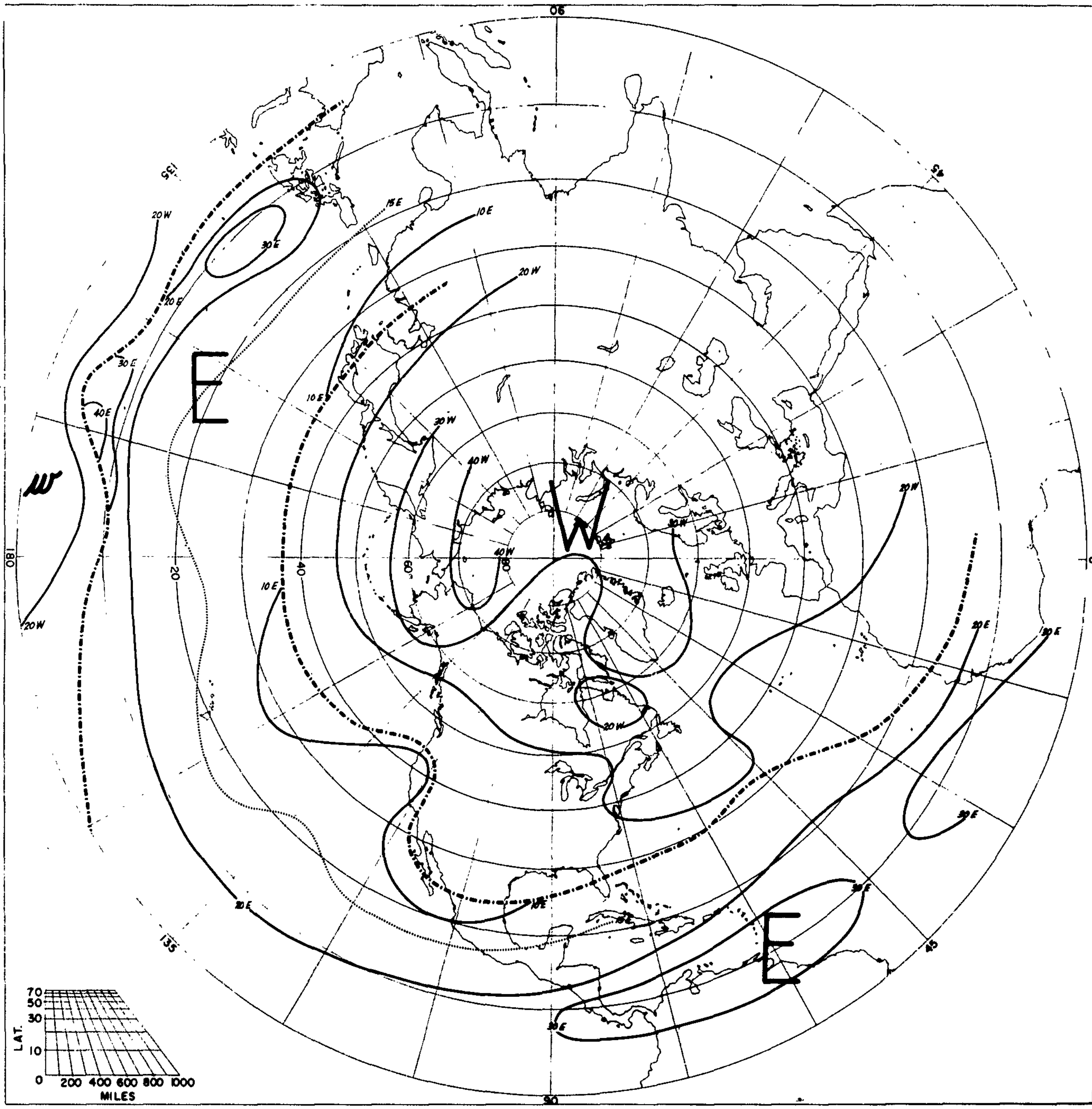

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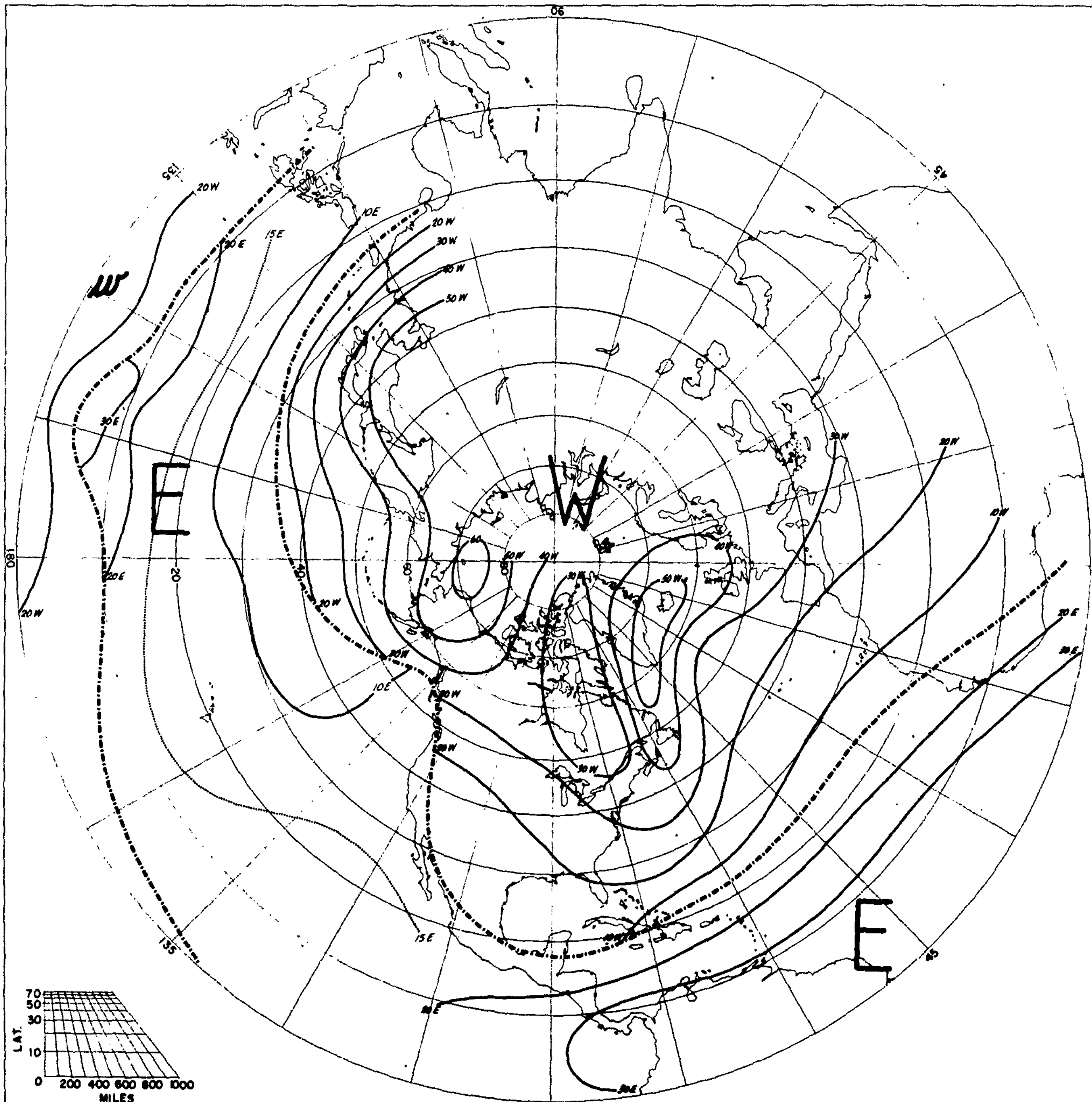

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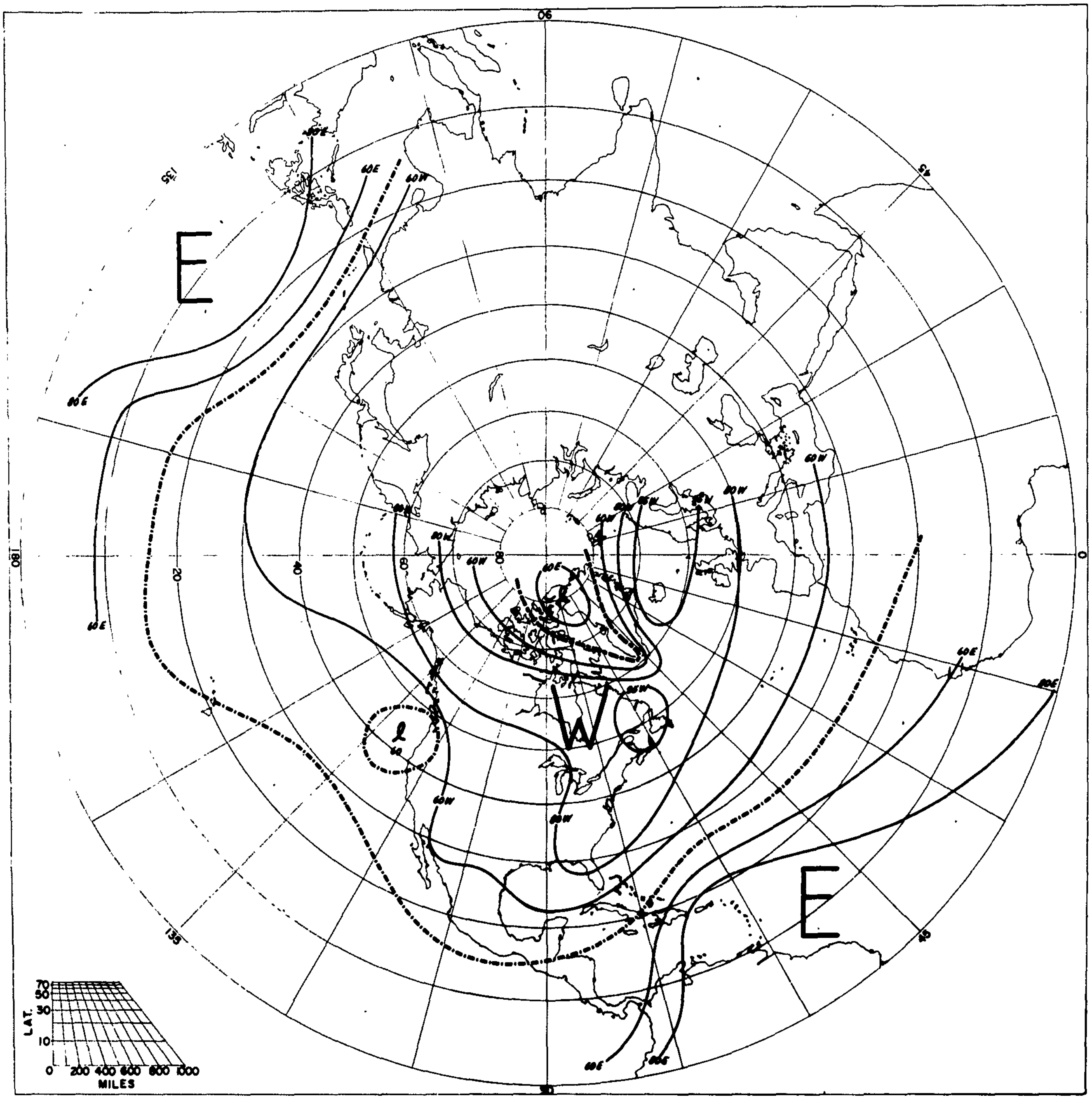

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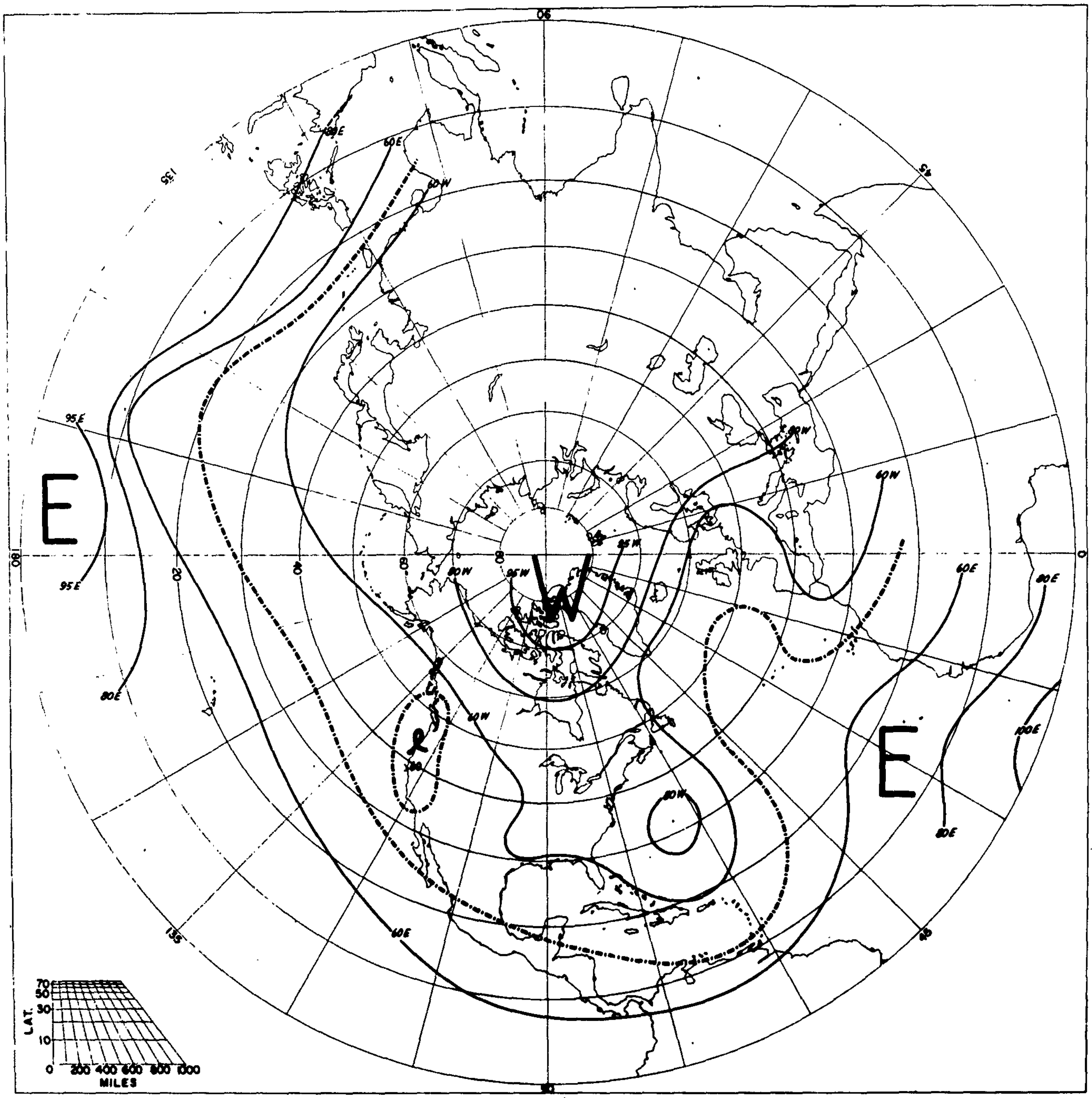

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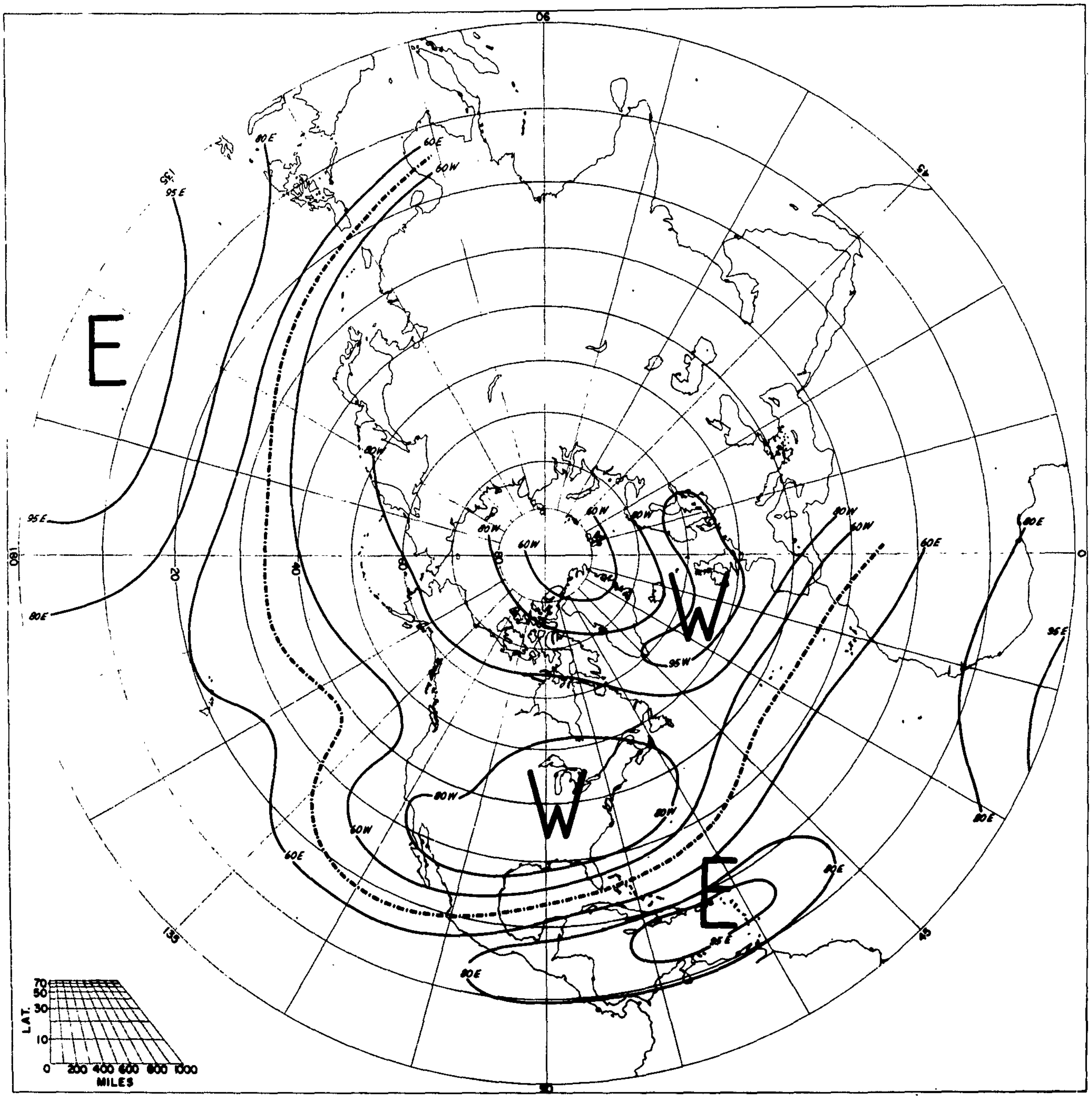

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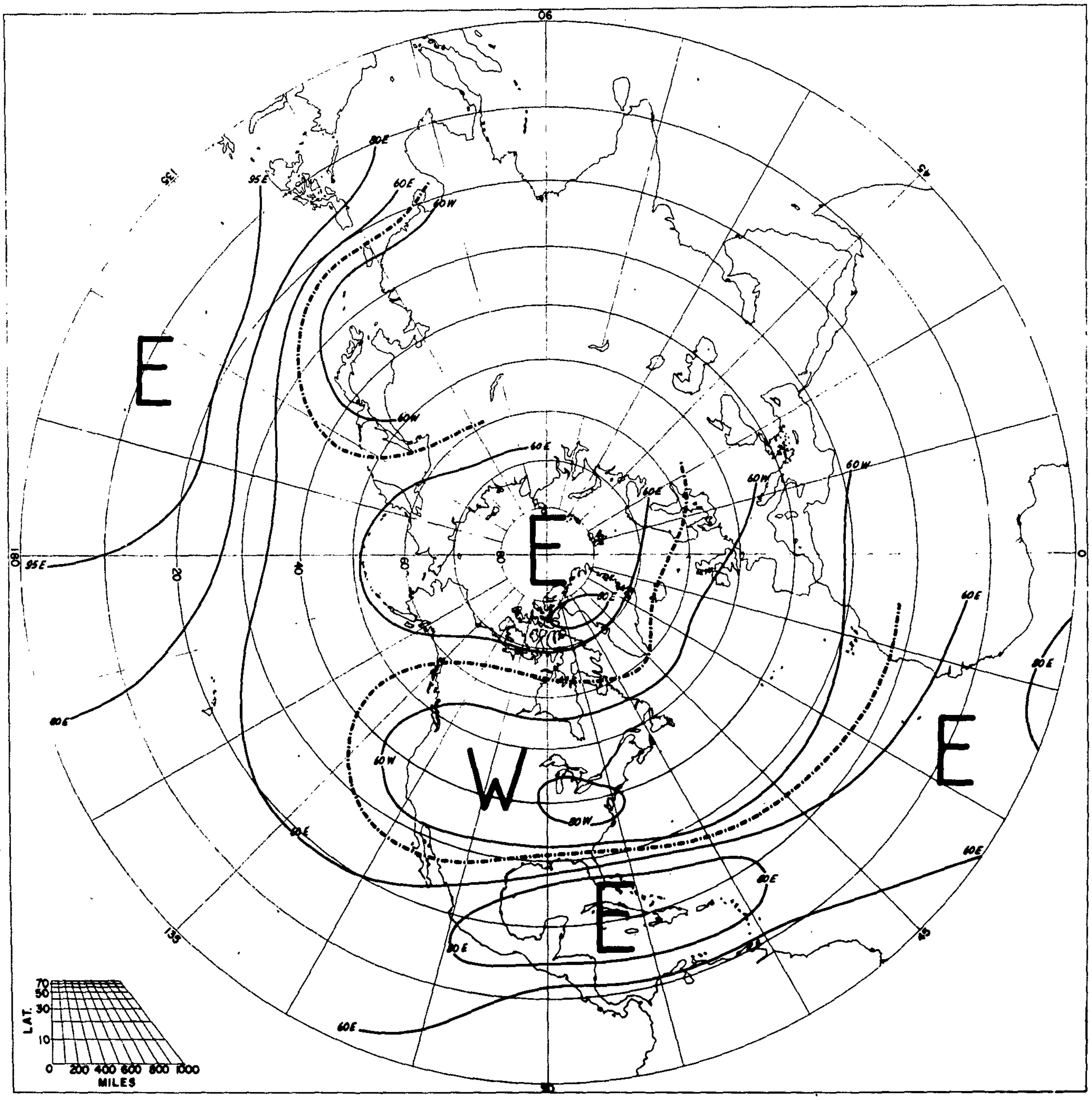

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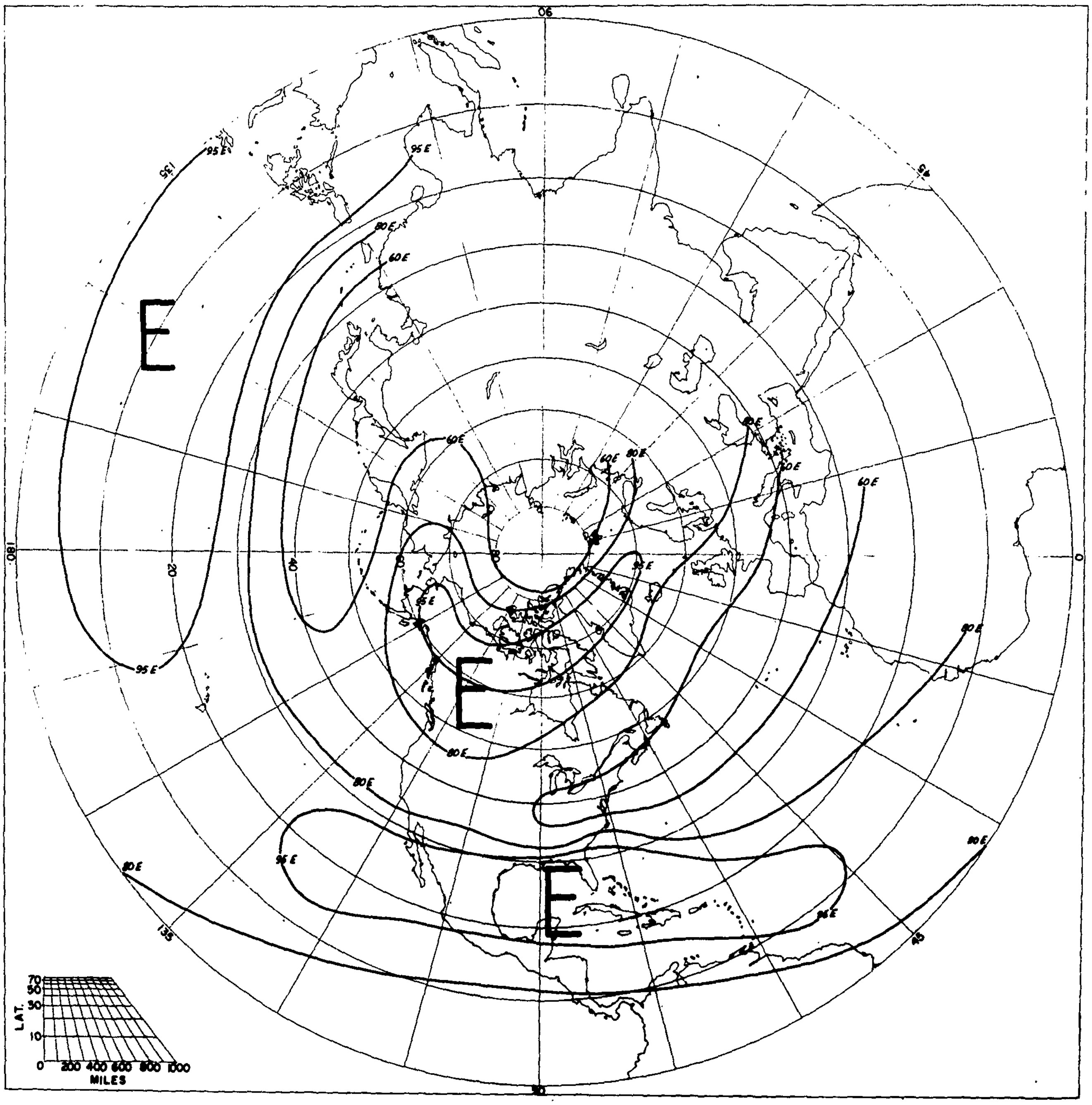

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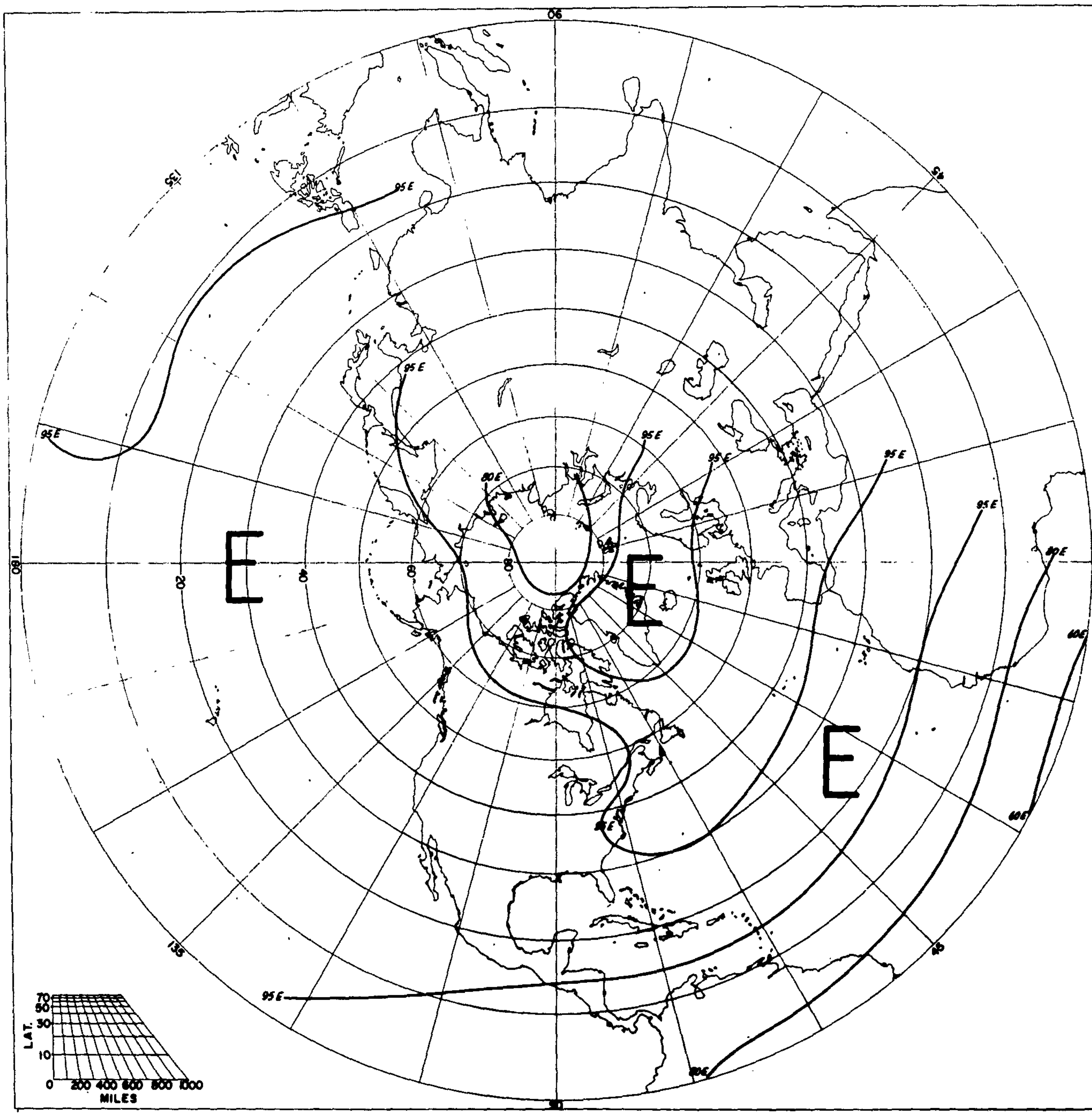

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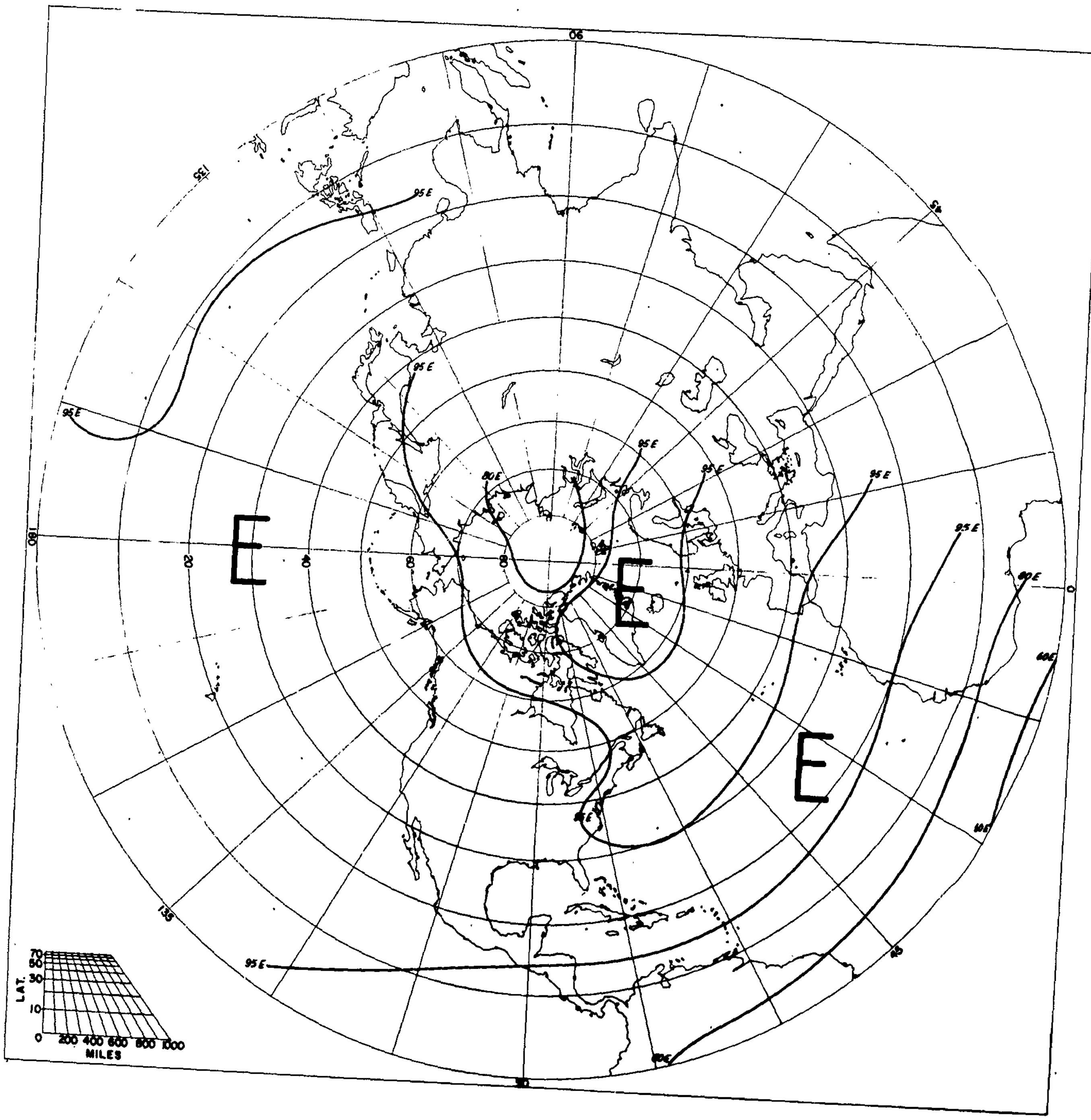

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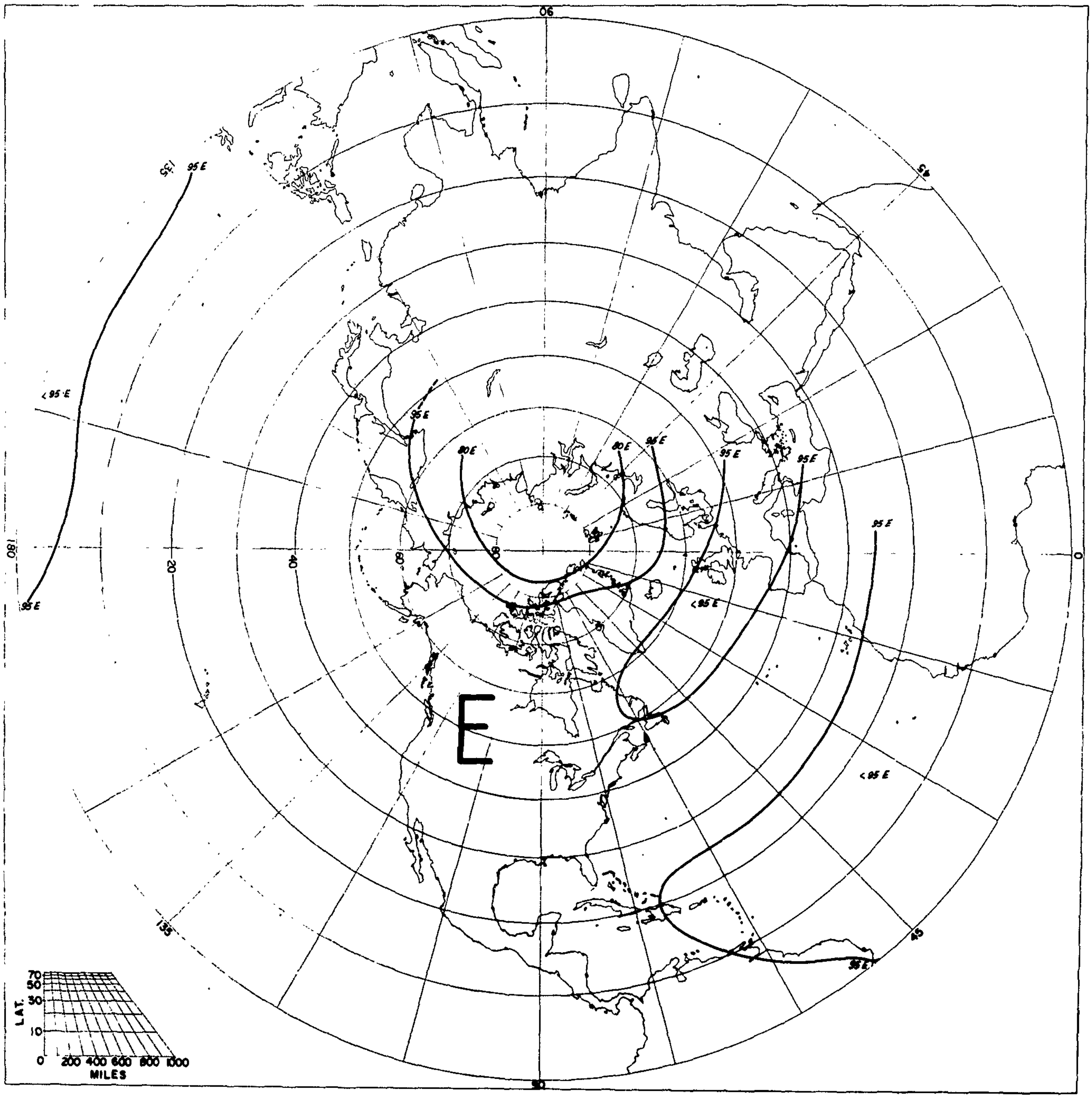

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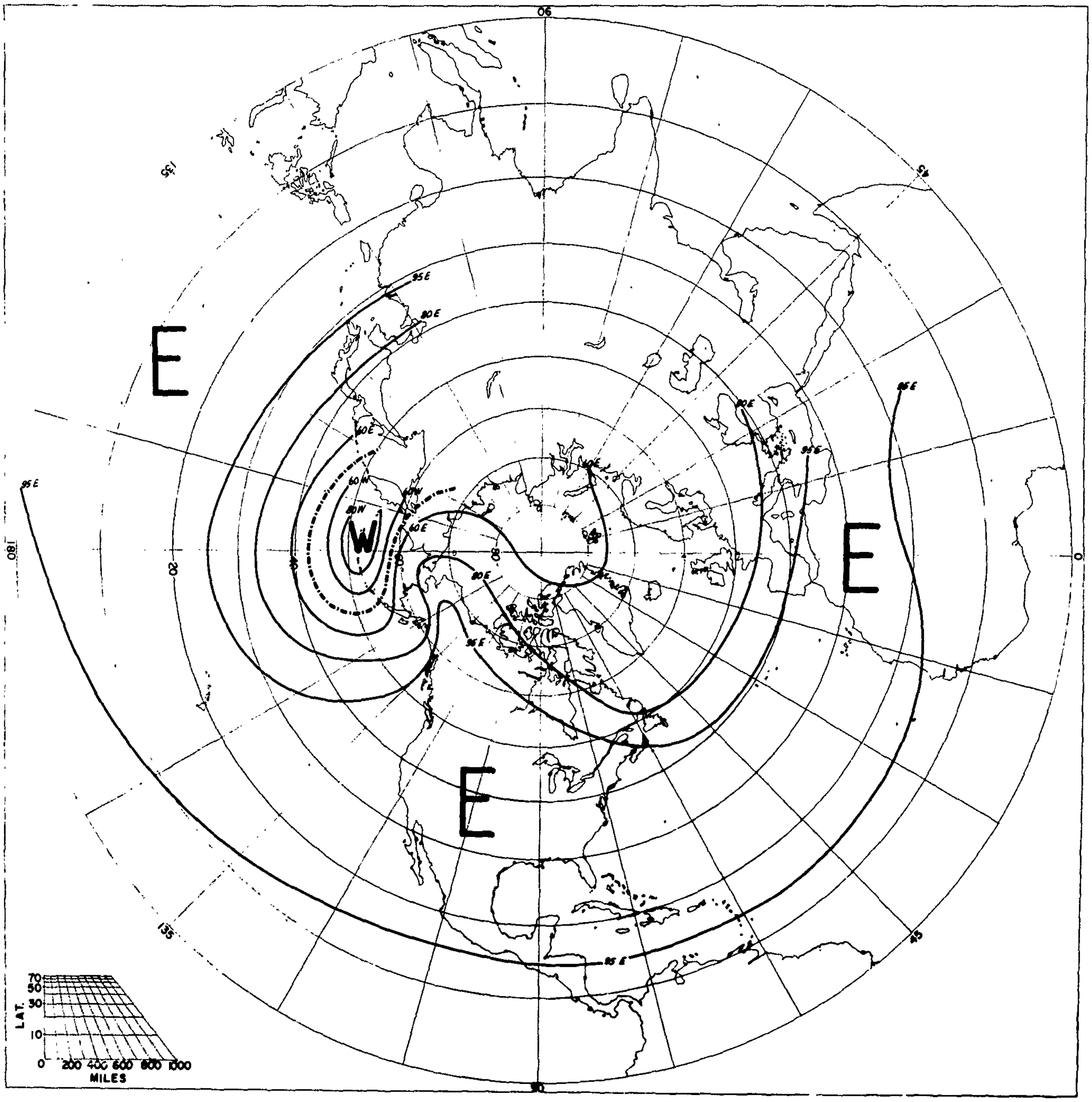

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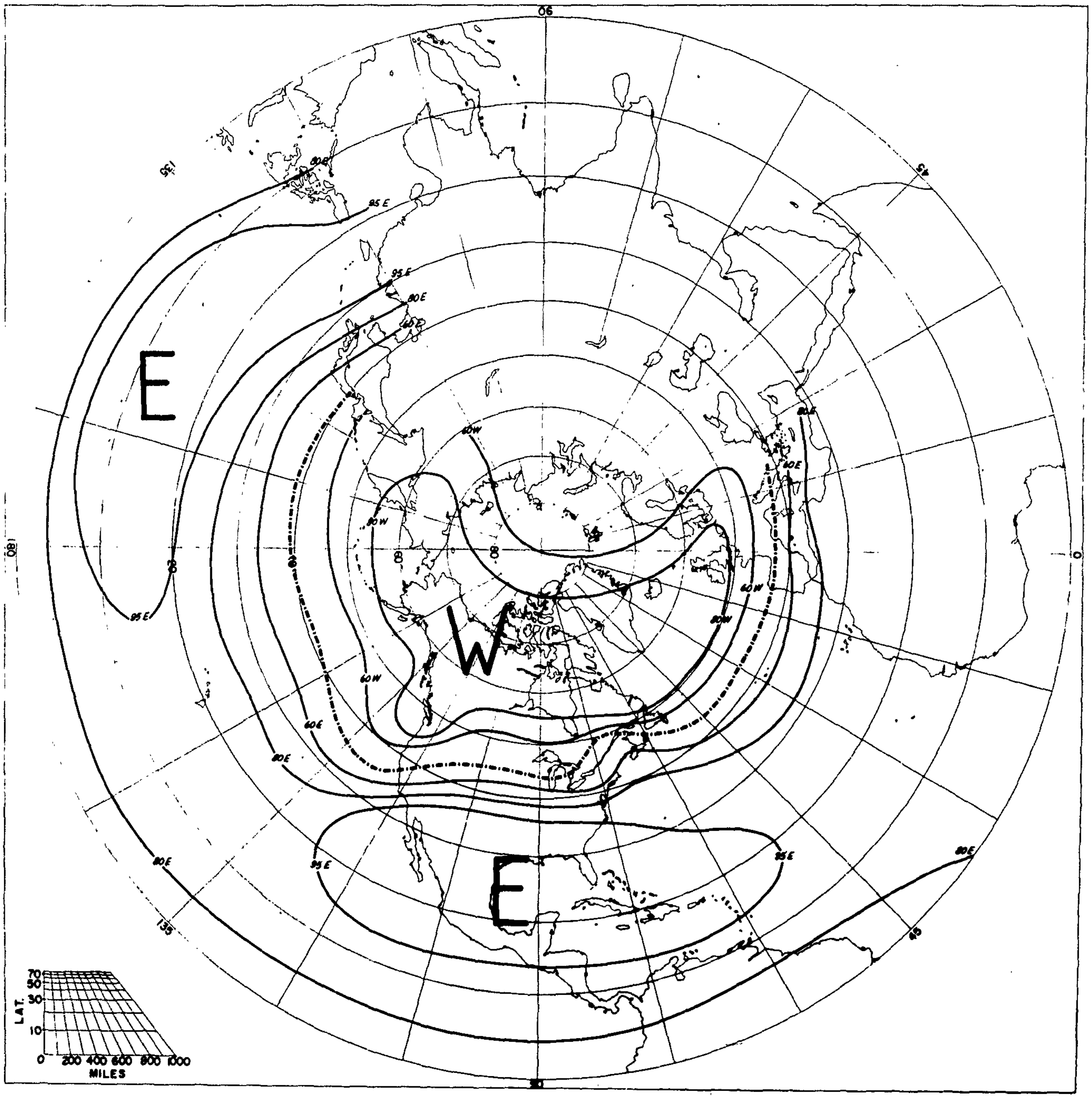

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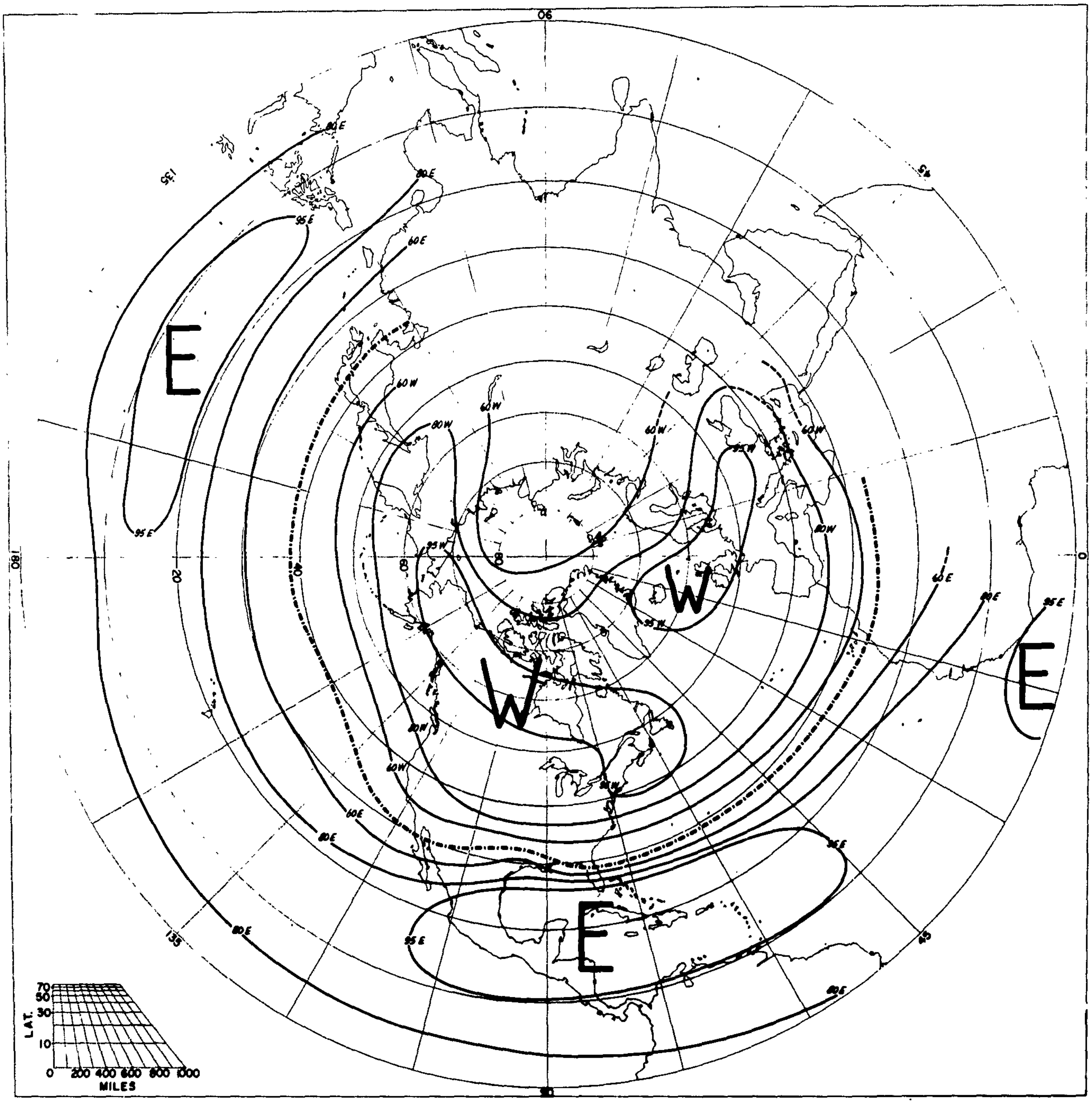

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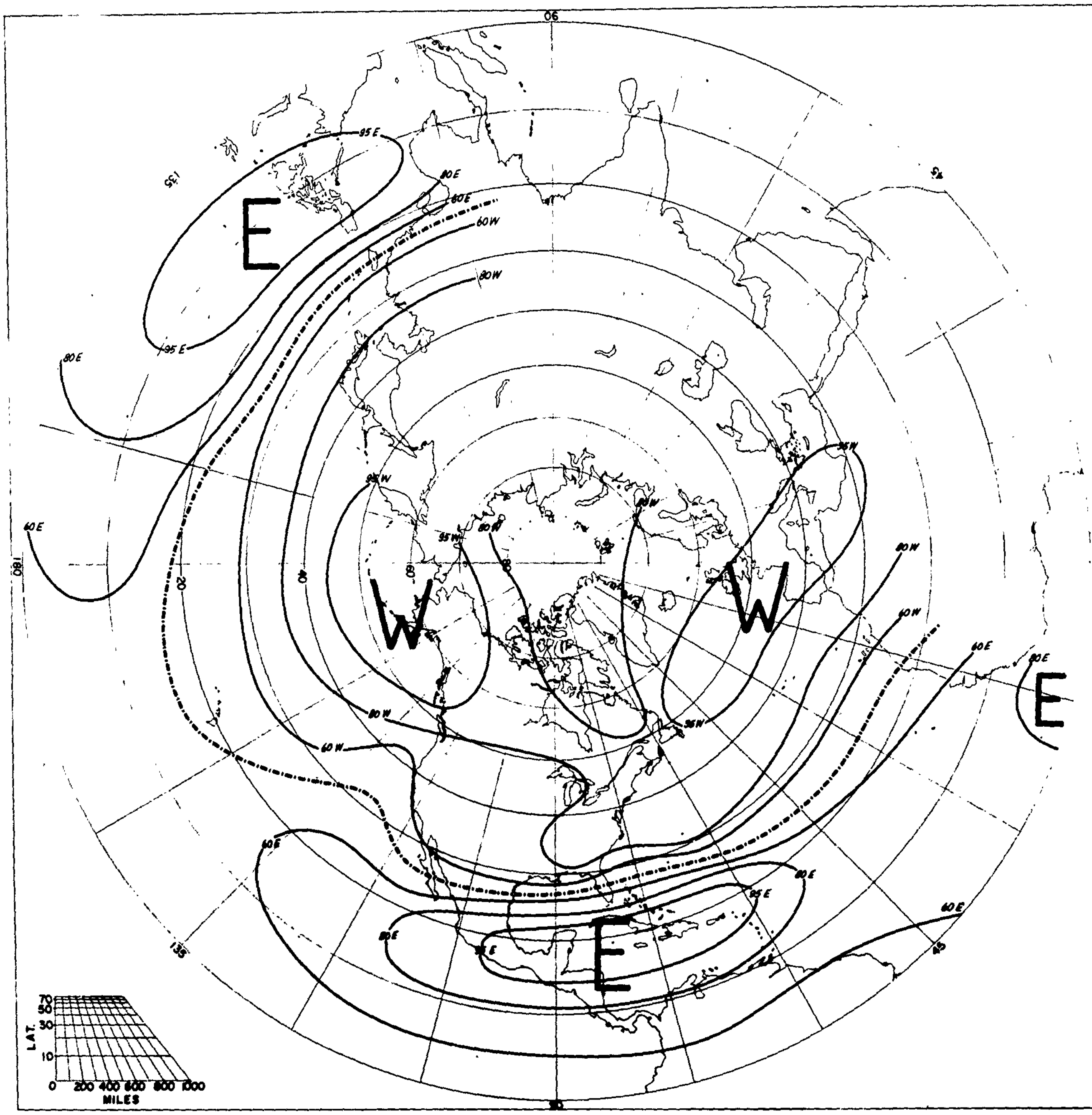

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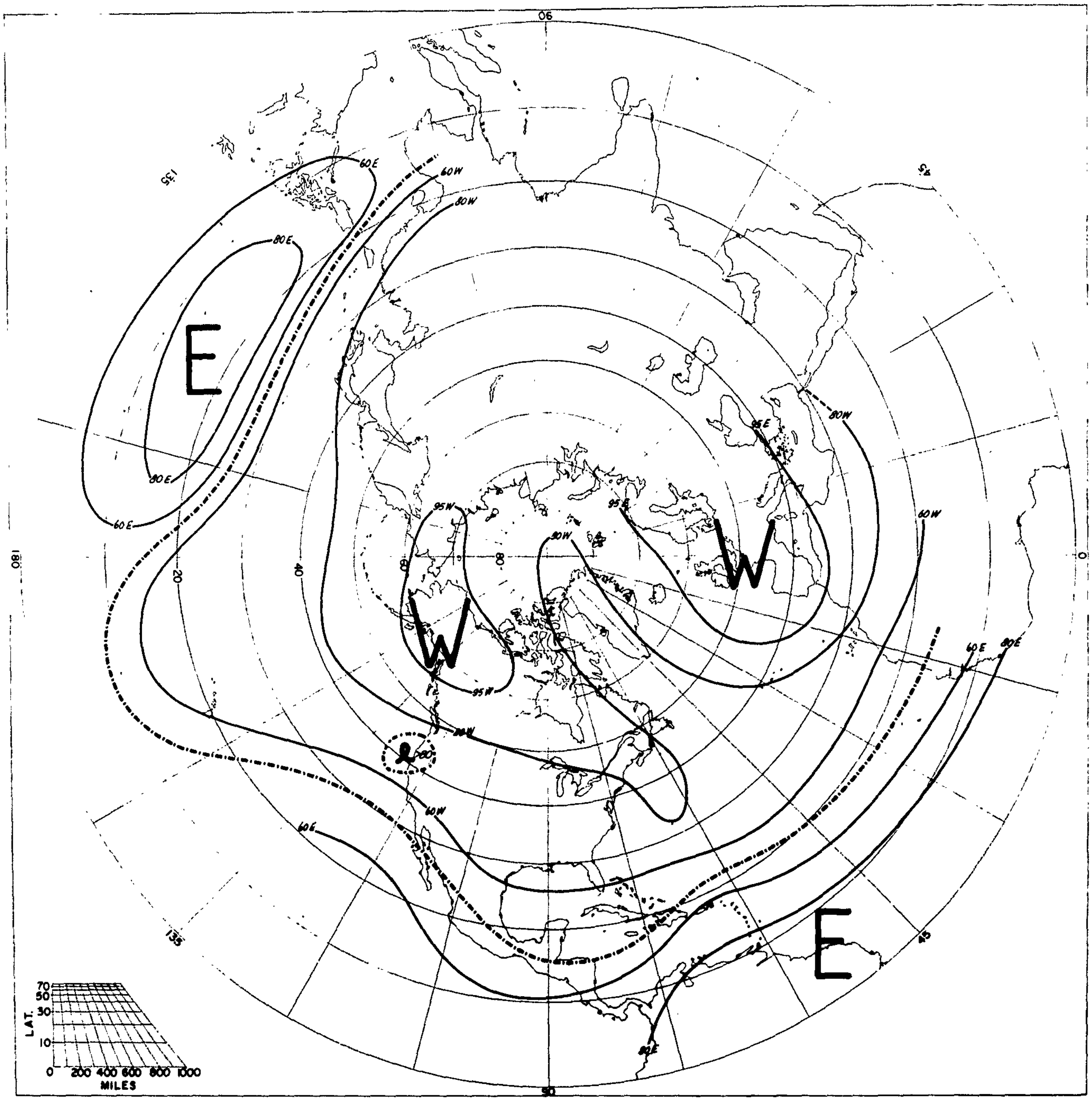

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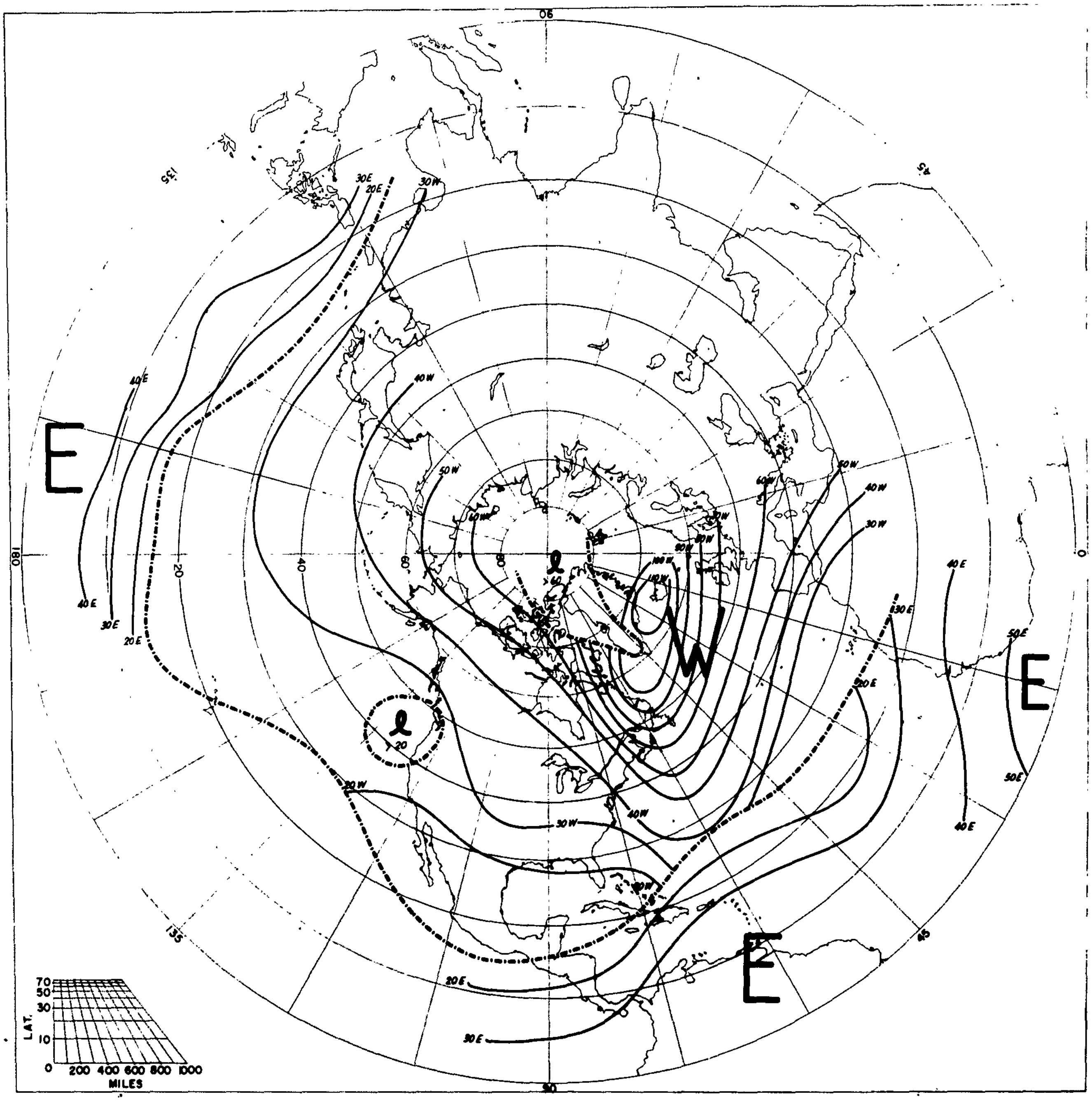

SPEED OF PREVAILING ZONAL WINDS

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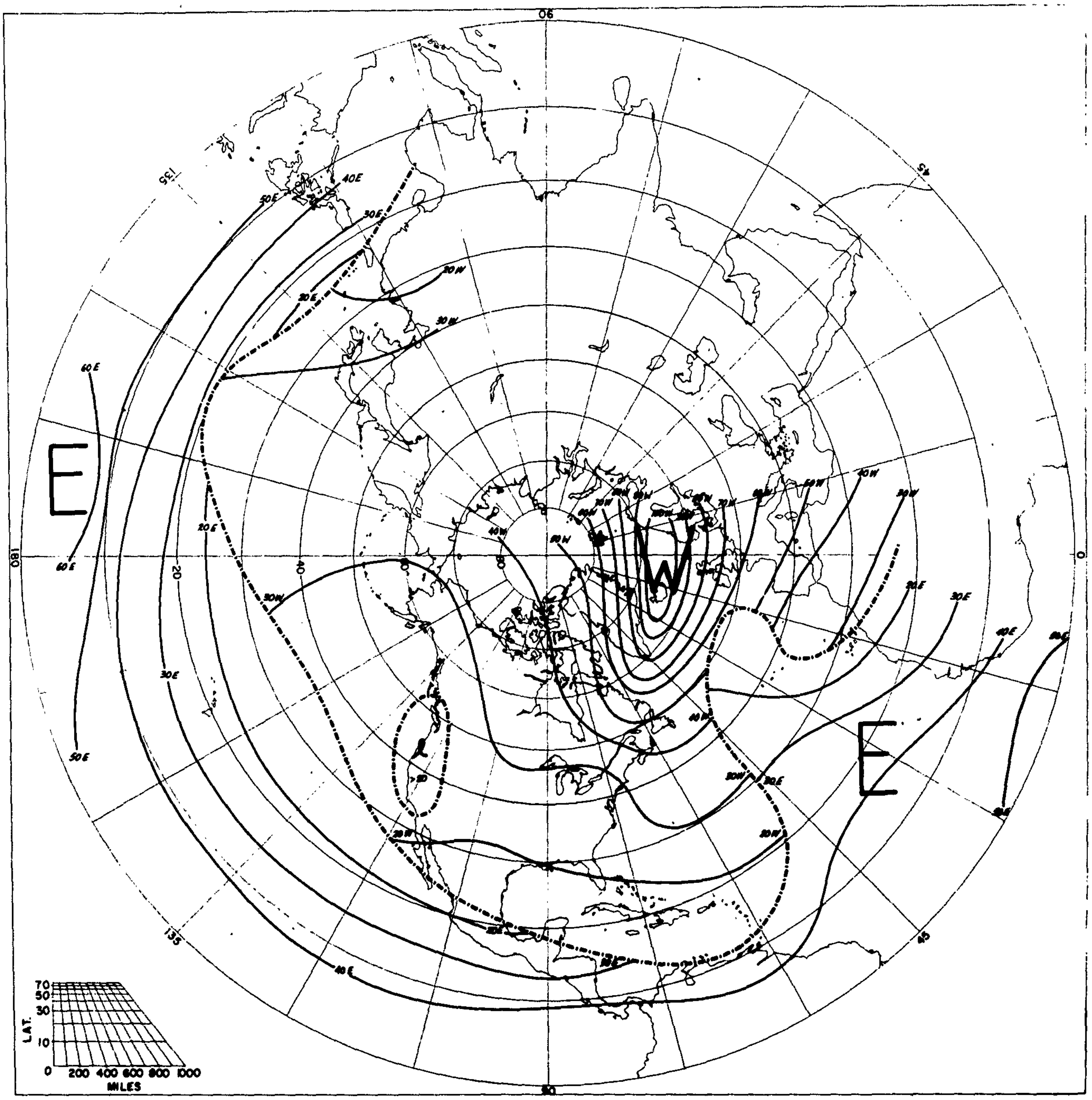

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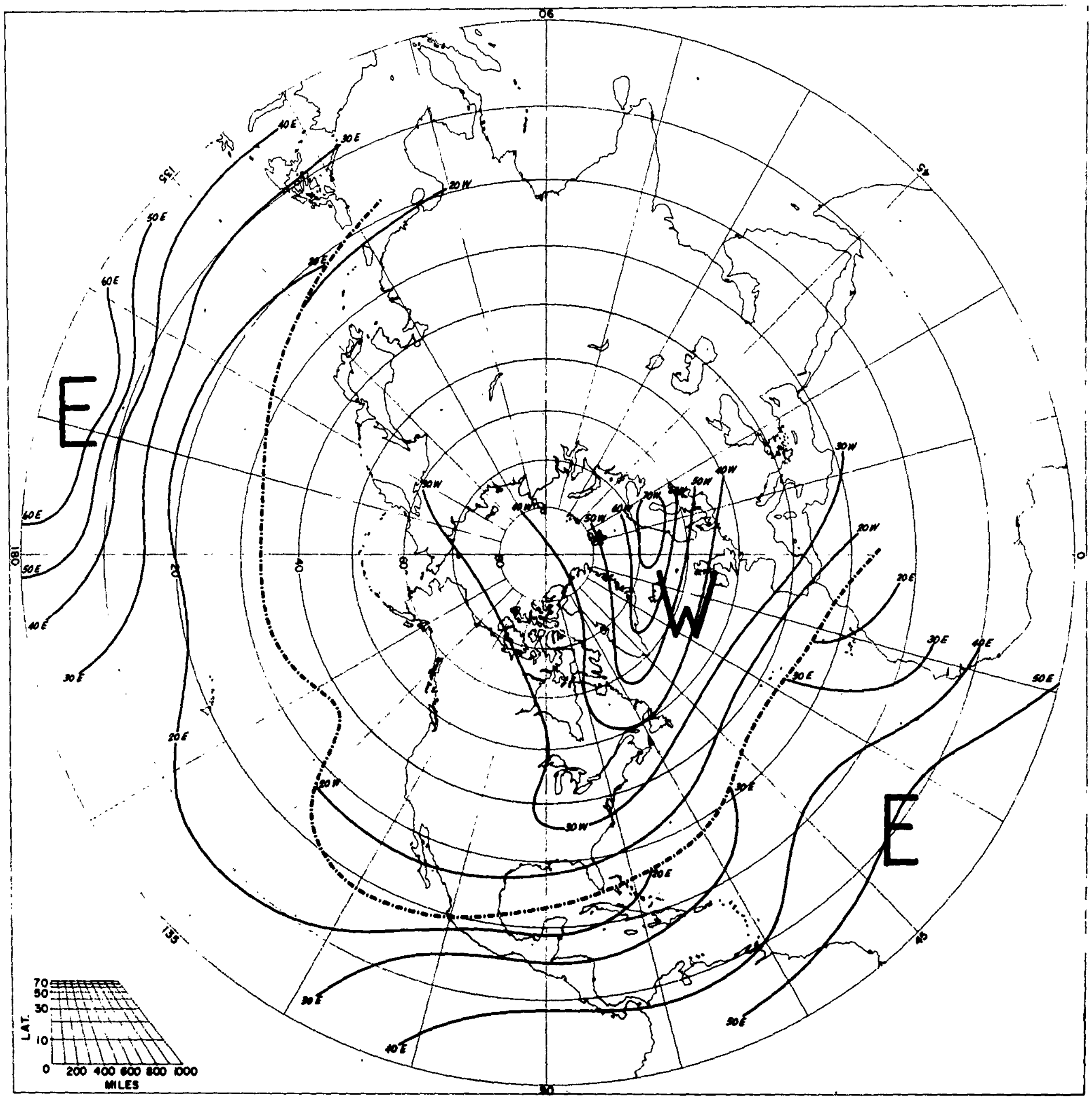

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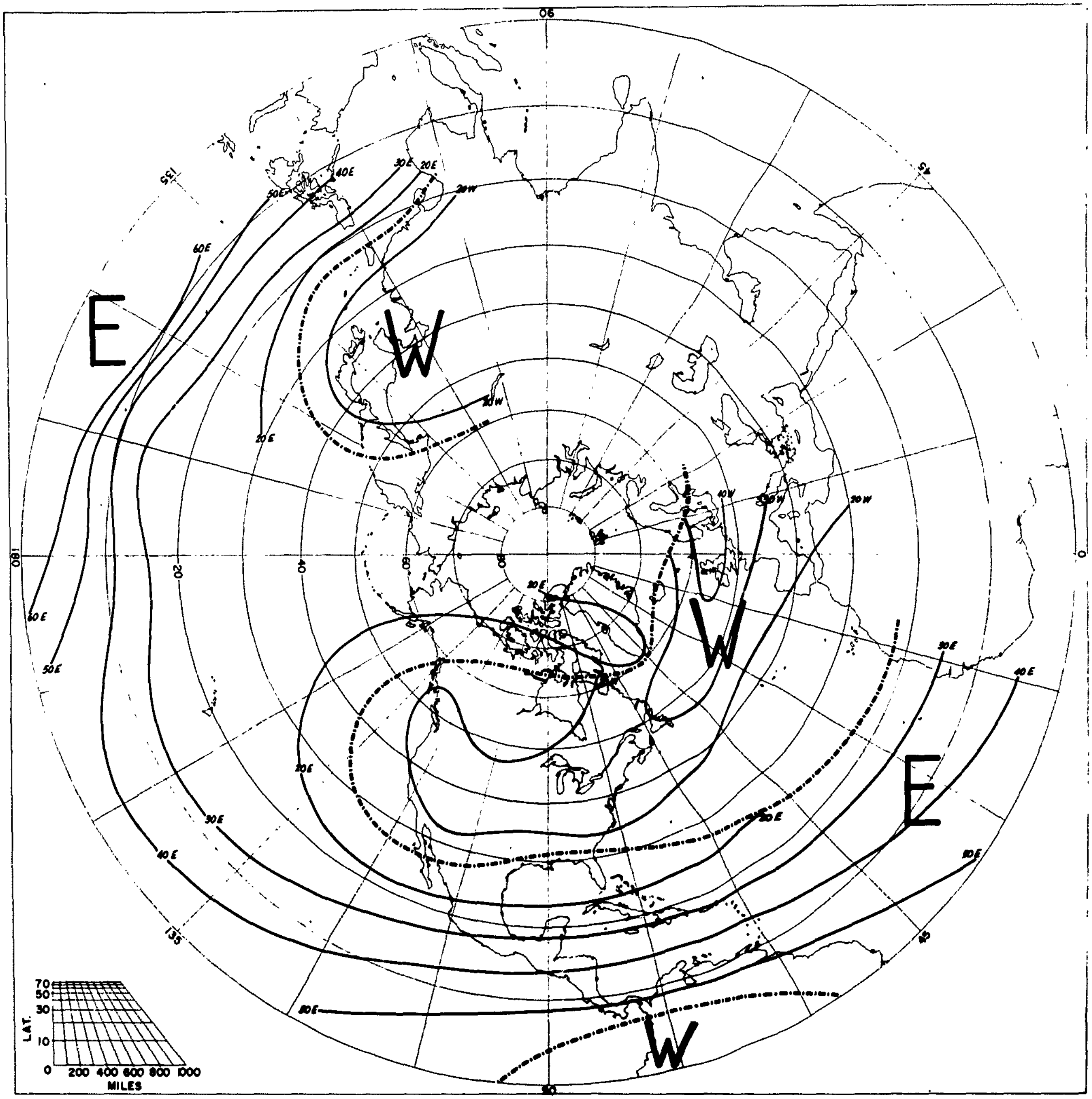

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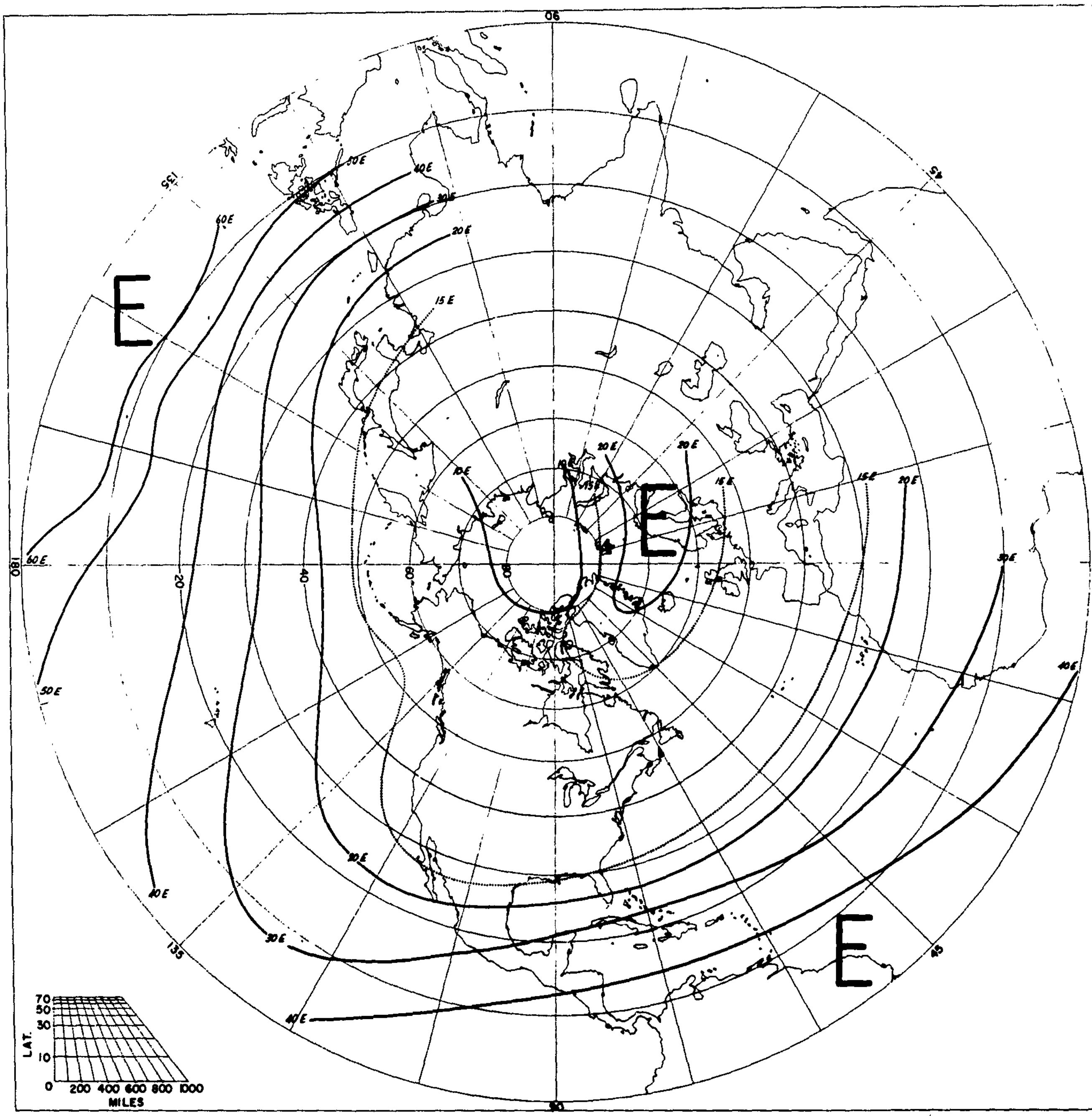

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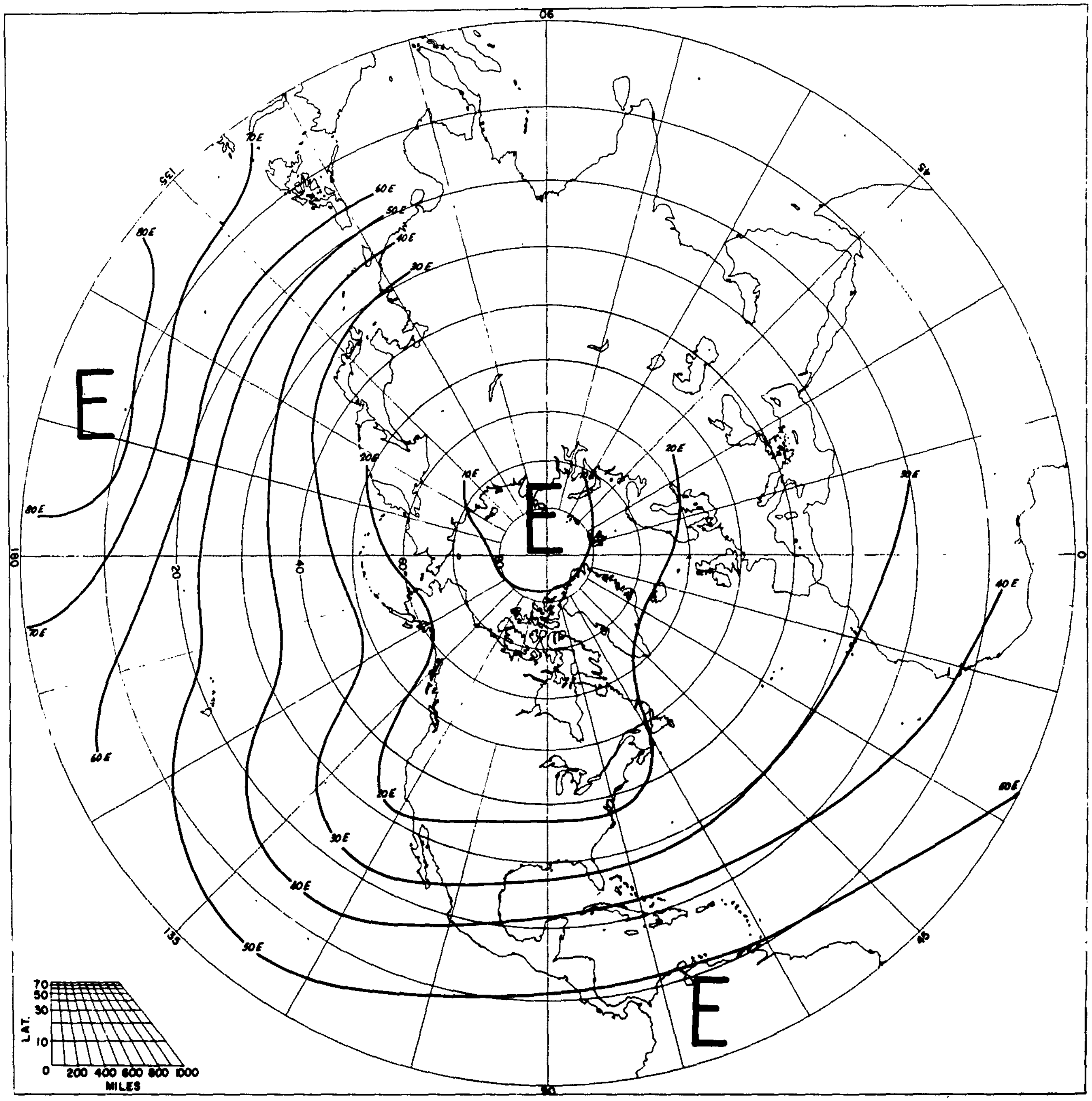

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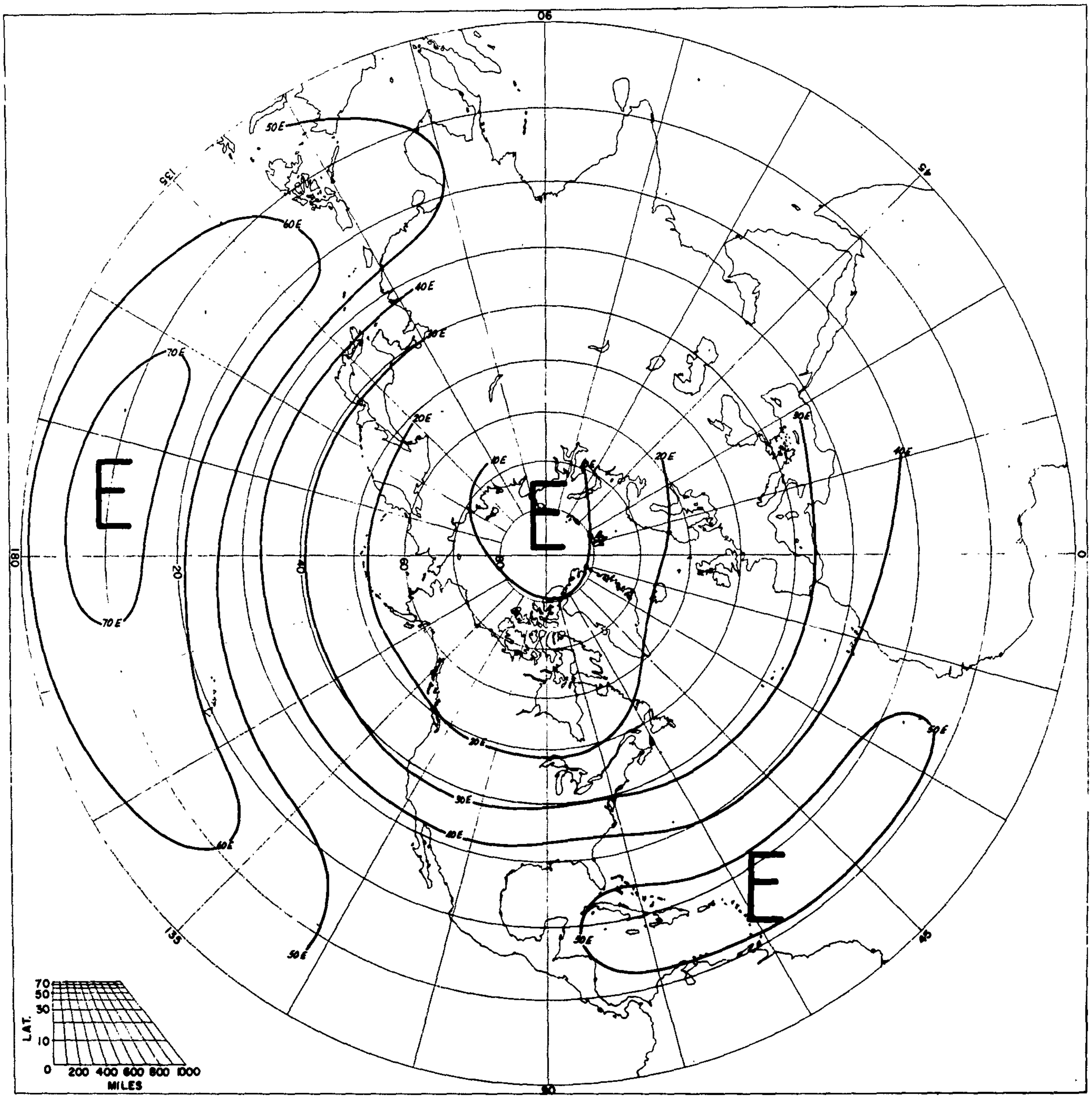

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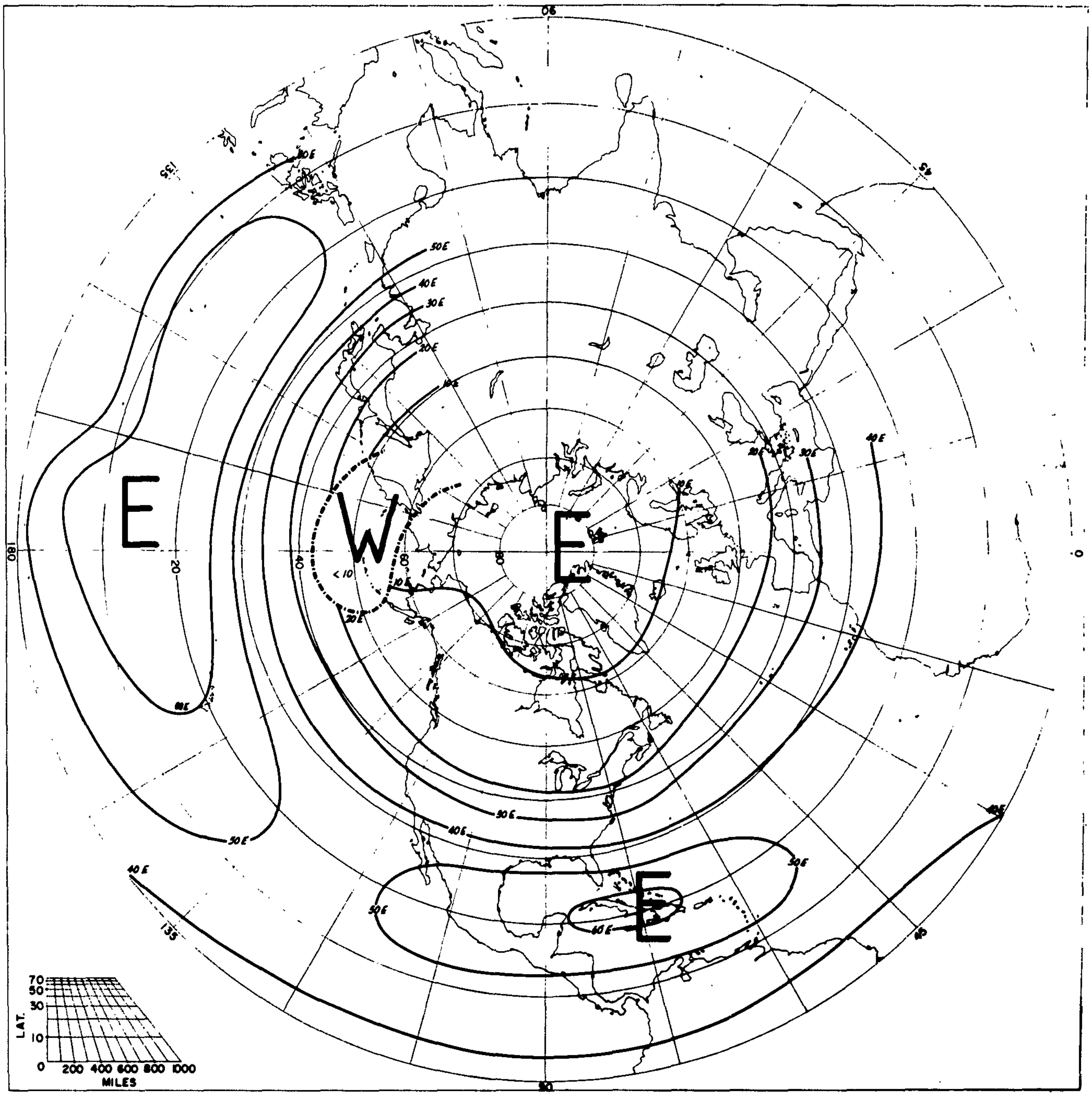

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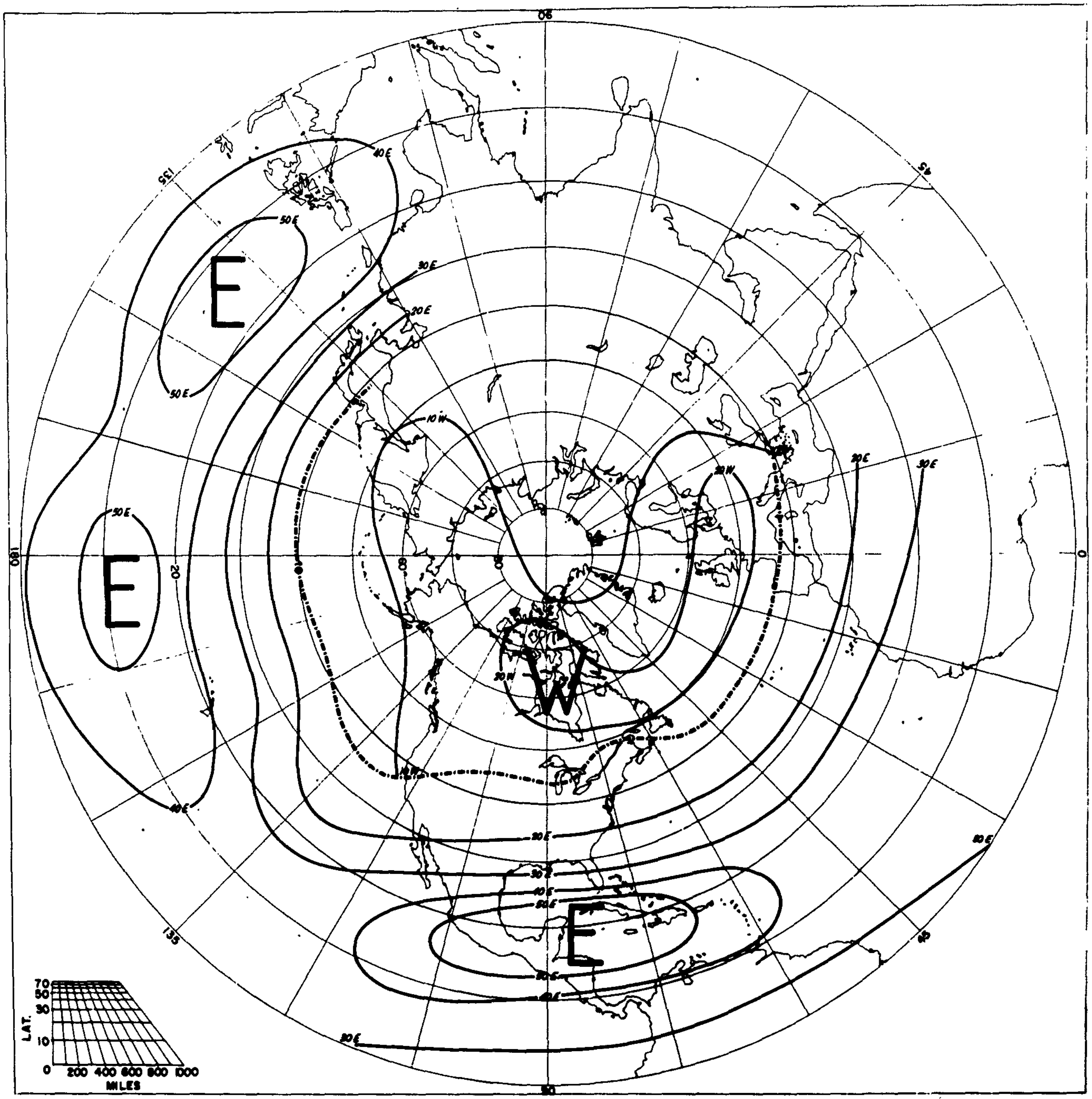
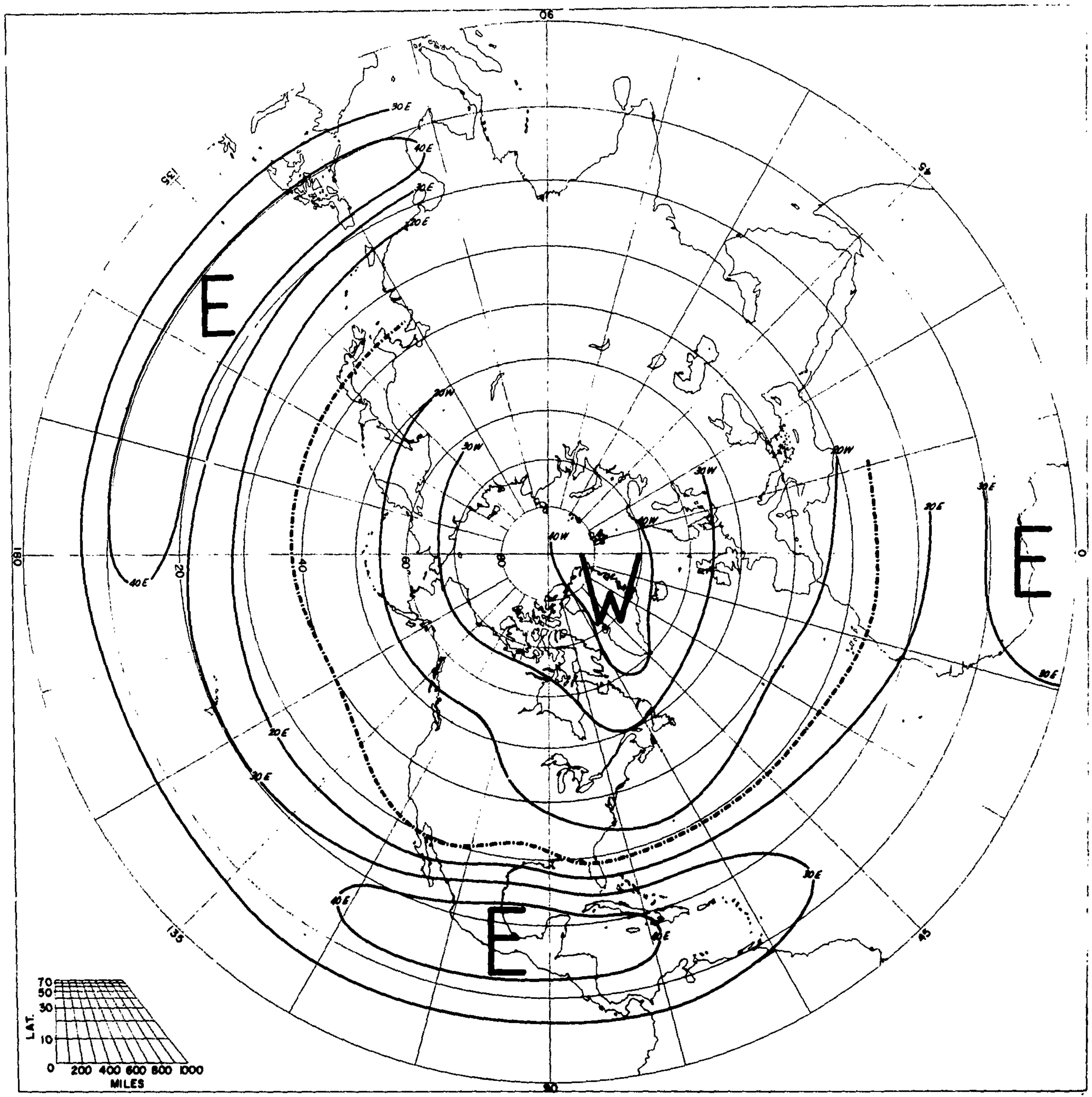


SPEED OF PREVAILING ZONAL WINDS

SEPTEMBER 10 MB



SPEED OF PREVAILING ZONAL WINDS

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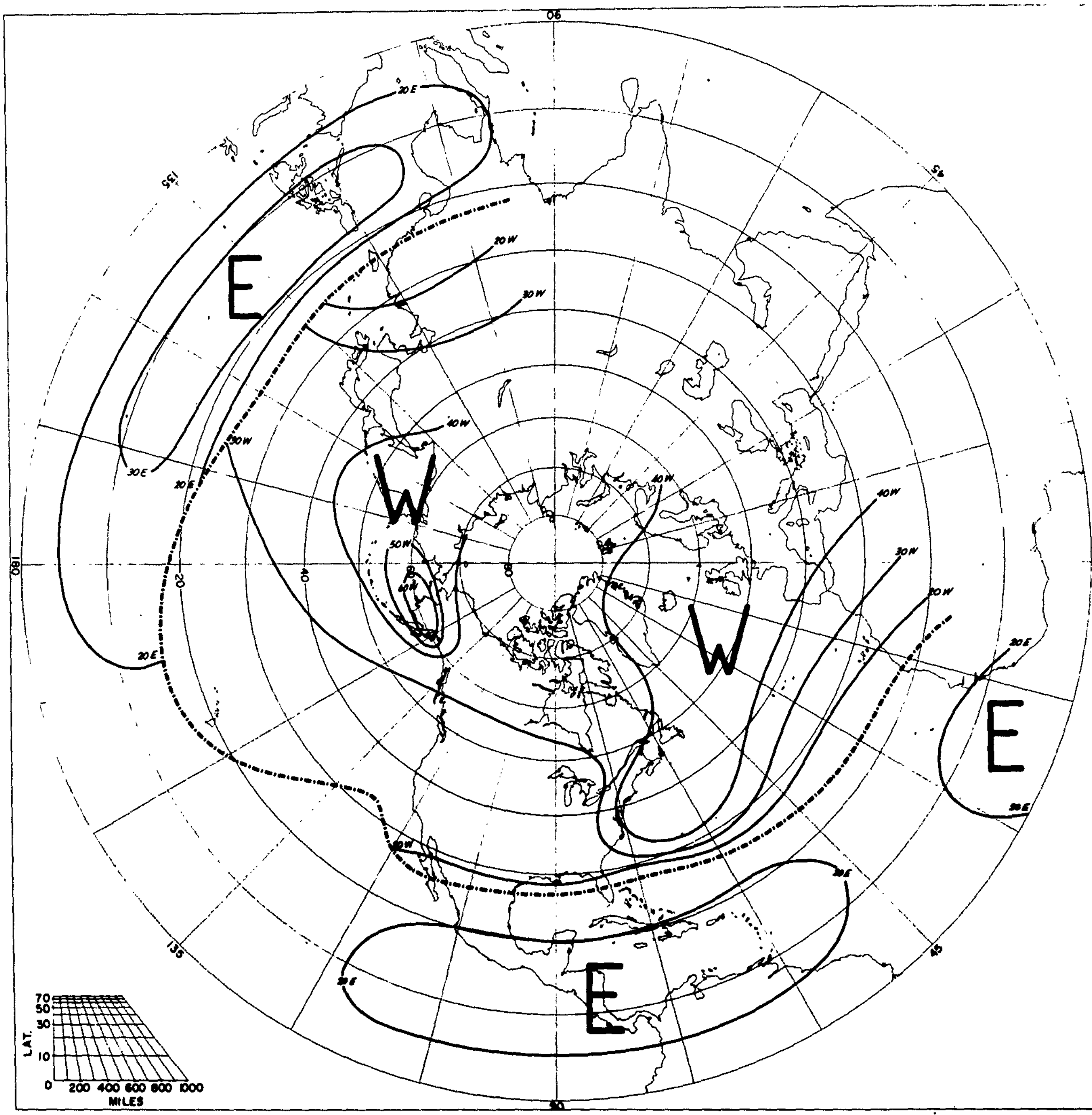

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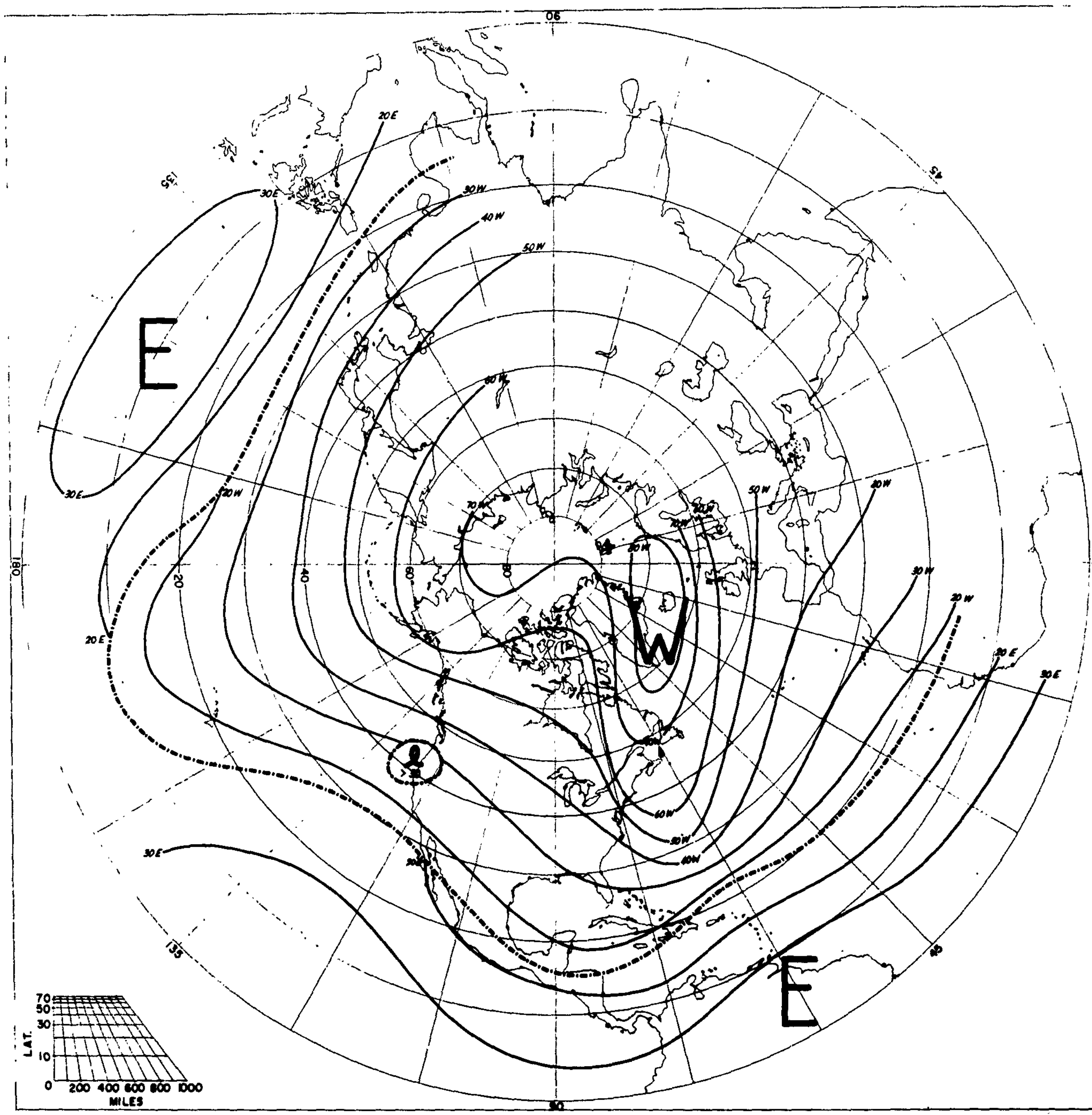

SPEED OF PREVAILING ZONAL WINDS

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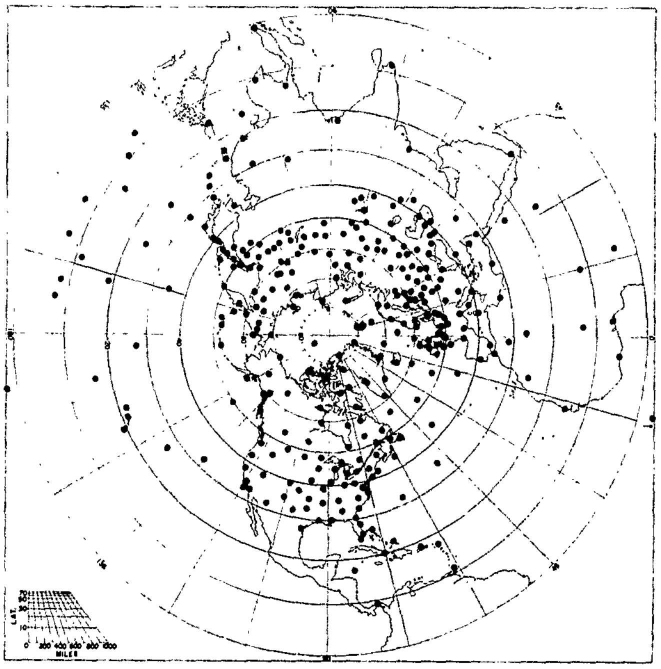

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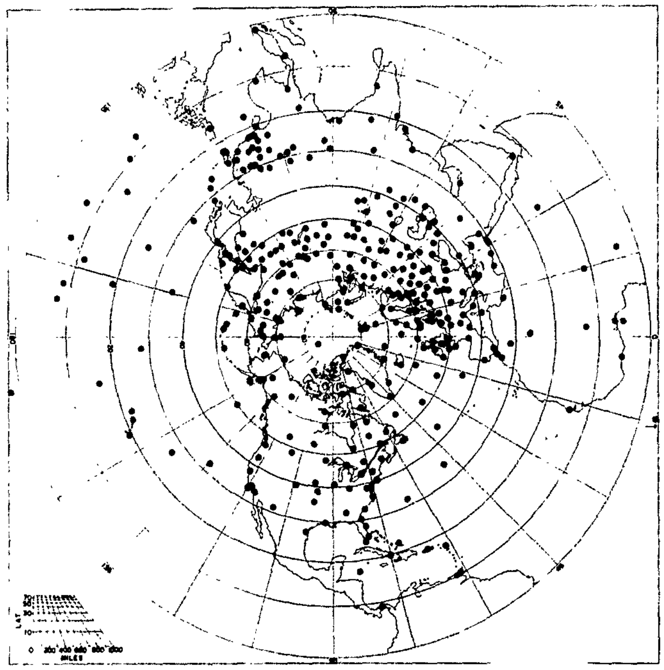

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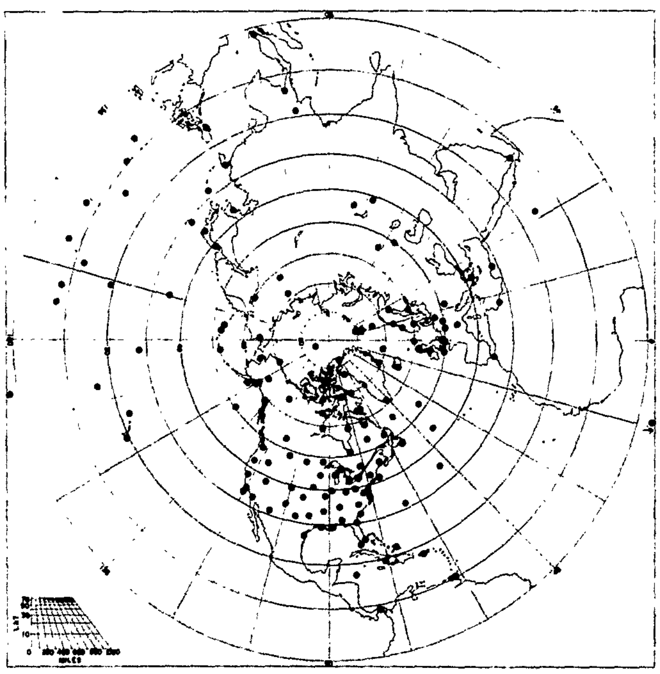

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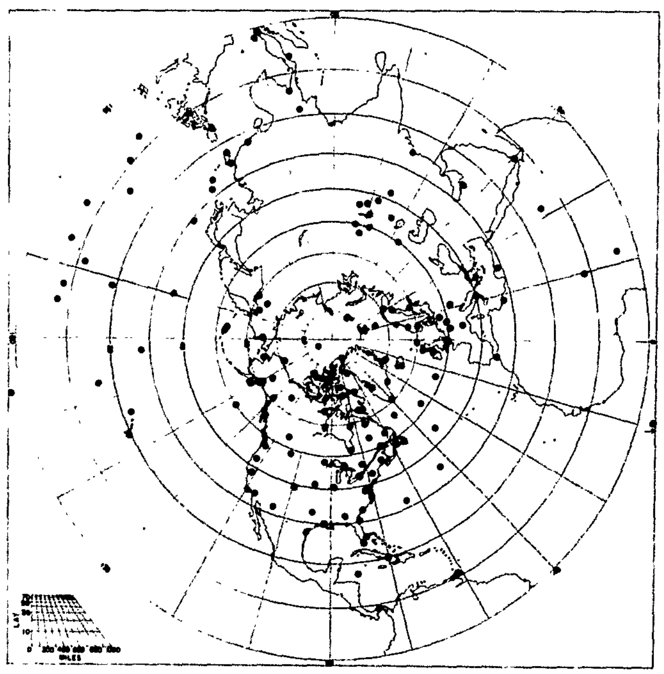
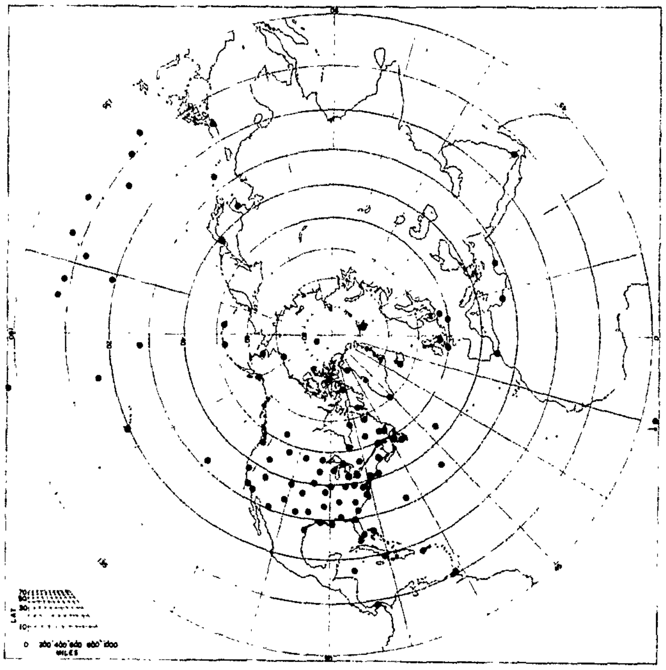


JULY 50 MB

AVAILABLE STATIONS



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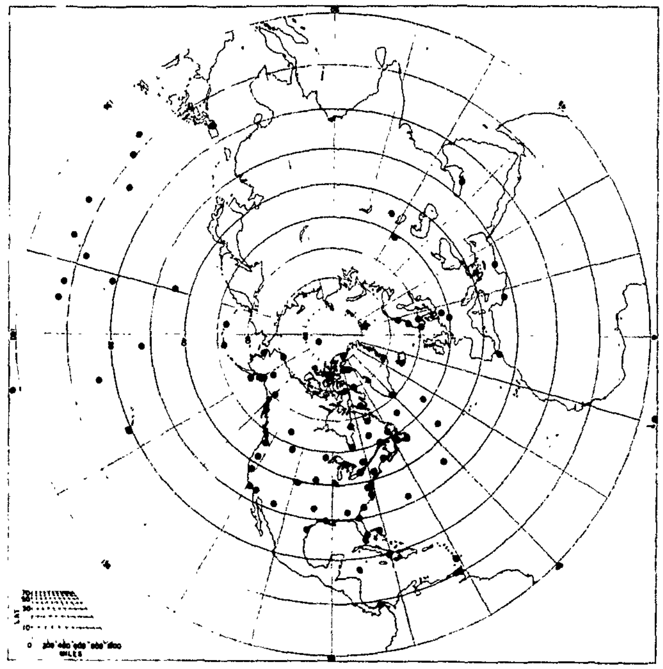

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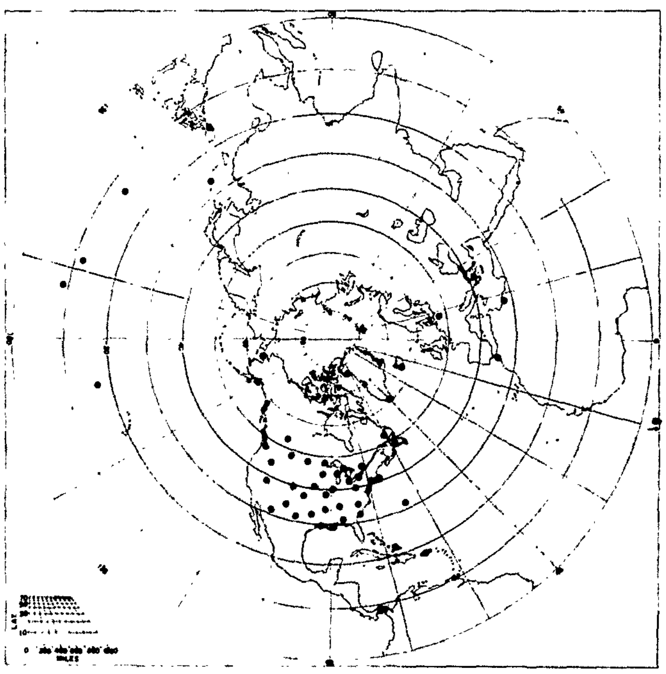

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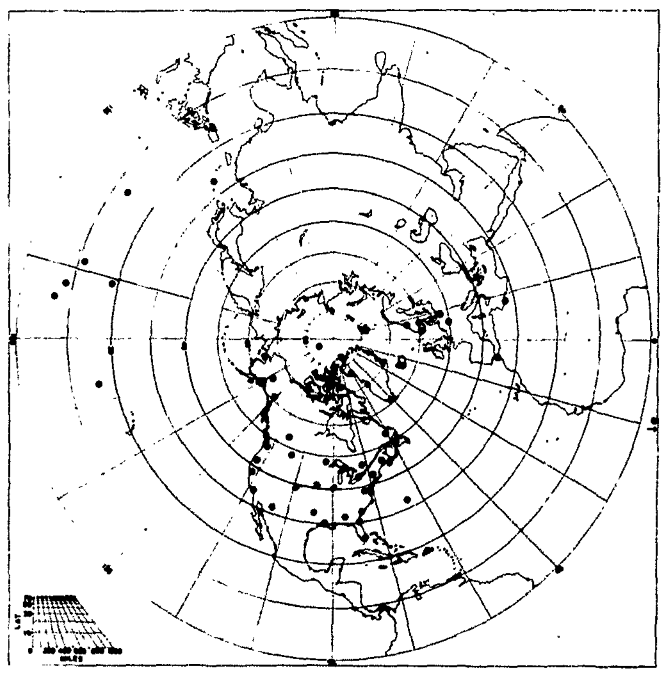

JULY 10 MB

AVAILABLE STATIONS