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Investigation of Polar Anticyclogenesis and Associated Variations of the Zonal Index

By
JEROME NAMIAS

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INVESTIGATION OF POLAR ANTICYCLOGENESIS AND ASSOCIATED VARIATIONS OF THE ZONAL INDEX

by
Jerome Namias
February 1945[1]

The formation and development of polar anticyclones constitutes one of the most important meteorological problems of extended range weather forecasting. While there have been some highly significant attempts to formulate the problem from a theoretical standpoint, notably by H. Wexler, the synoptic aspects have, up to now, received little attention. The nature of this problem has been considerably illuminated in recent years by the routine preparation of daily and five-day mean Northern Hemisphere weather charts, 3 km. pressure charts, and zonal indices (expressing the strength of the various circumpolar wind belts, such as the prevailing westerlies).

The winter of 1940-41 (December-February) was characterized by an absence of marked cold air outbreaks in the United States, and therefore did not present an abundant supply of data about strong polar anticyclones. However, an unusually strong polar high developed in the latter half of February, and it had a marked influence on the weather over North America for at least two weeks. This polar anticyclone reached its maximum intensity during the period February 19-23, when the pressure at the center averaged about 1050 mb.[2] on the mean map for the period. The tremendous extent of this development is shown in Fig. 15[3], where solid lines are isobars and five-day mean pressure changes since the preceding week are shown by broken lines. The effect of this polar anticyclone upon the weather of the United States is strikingly illustrated by departures from normal of the five-day mean temperatures (Fig. 1). In the northeastern United States the temperature did not average subnormal in spite of the strong prevailing northerly flow, because maritime air, rather than continental, was brought around the deep cyclonic vortex over Newfoundland. The five-day mean pressure maps, on which are also shown five-day mean pressure changes during the preceding week, for periods leading up to this cold air outbreak, are shown in Figs. 10-15.

The noteworthy features of these maps essential to the following discussion are:

1. The splitting of the Aleutian low from a single intense center during the period February 1-5 to a double center in the period February 5-9 and thereafter, the gradual separation of these low pressure centers and the development of a ridge between them with more or less continuously rising pressures. The eastern low center was responsible for the abnormally heavy rains in Southern California during February.

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[1]This paper was originally prepared in 1942.

[2]The lack of data over the region immediately adjacent to the North Pole makes it impossible to fix this value more definitely.

[3] Figs. 10-15 are given at the end of the report.

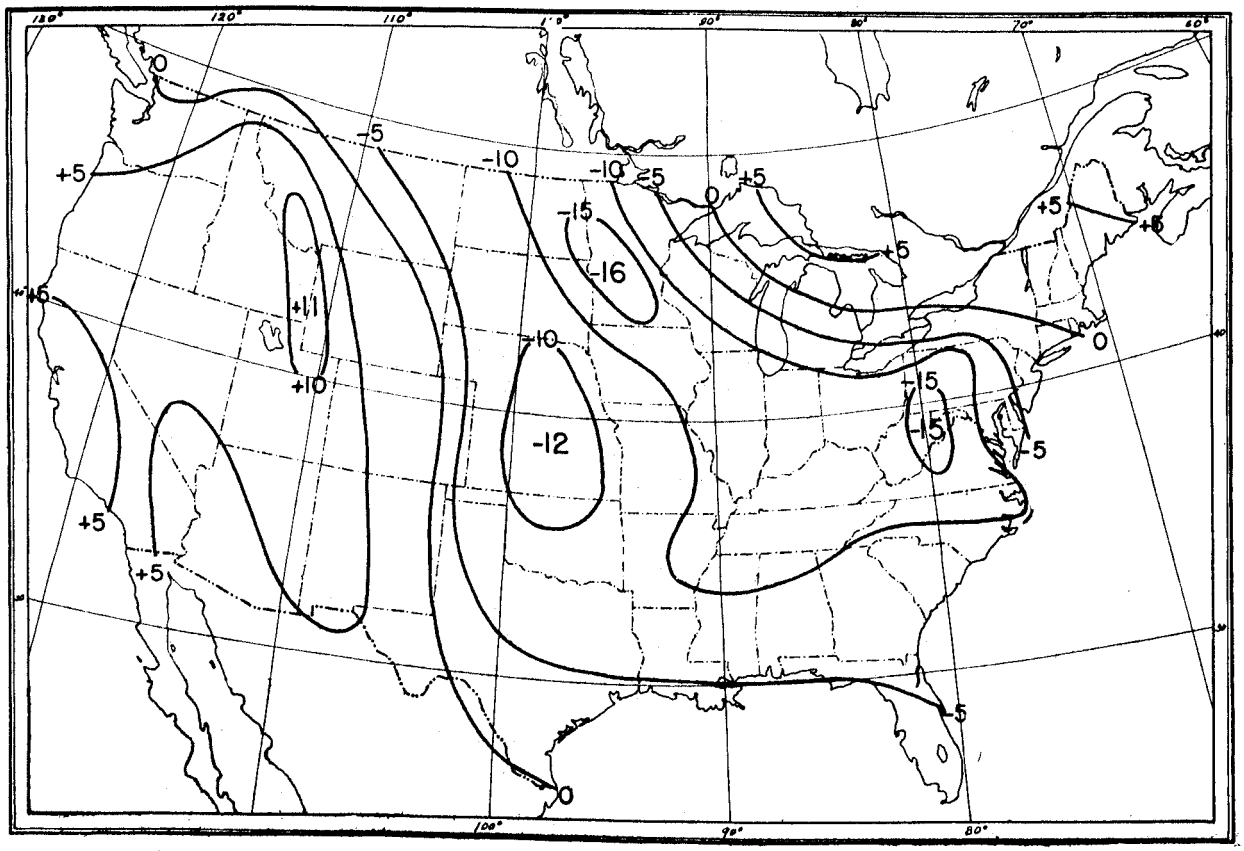

Fig. 1 – Mean temperature departure from normal for the period February 19 – 23, 1941

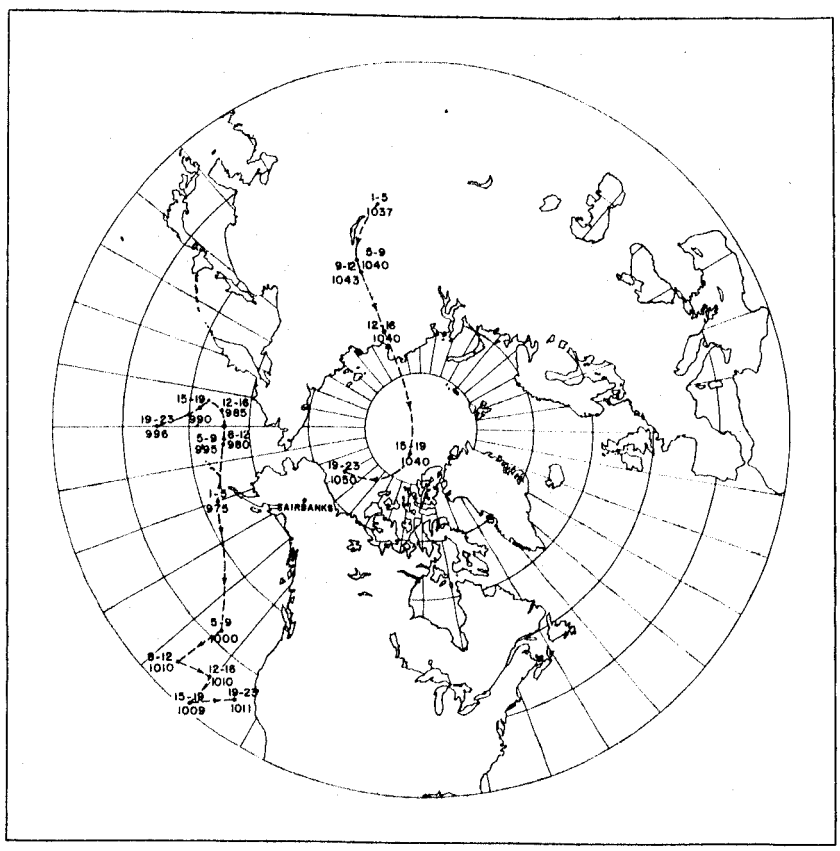

Fig. 2 – Successive positions of certain five-day mean pressure centers during February 1945

2. The gradual northward displacement of the Siberian anticyclone, with the anticyclone finally crossing the polar regions.

For the sake of convenience the successive positions and intensities of the various cells with which we are concerned are shown in Fig. 2. The regularity of movement of these cells must not be considered as the movement of a single low or high pressure area. Indeed, the individual daily Northern Hemisphere maps for this period show a complex series of occluding wave disturbances which on the average go to make up the eastern Pacific low pressure center, and another set of waves which results in the formation of the western center. In the mean, however, we get a picture which shows that these apparently complex daily perturbations are superimposed upon a fairly regular long-period trend.

It will be noted that the ridge separating the two cells of the Aleutian Low coincides with the position of centers of maximum pressure rise. Moreover, the direction of movement of this pressure change area suggests that it is related to the subsequent building up of the polar high, that is, that the Pacific pressure rise in some manner combines with the Siberian high (and its associated pressure rise), eventually producing the strong polar high developed during the period February 19-23.

It is apparent that very marked polar anticyclogenesis takes place during the period February 12-23. This may be seen by comparing the areas enclosed by the 1035 mb. isobar in Figs. 13,14, and 15. It is the purpose of this paper to suggest a hypothesis for combining the Pacific pressure rises, which takes place aloft, with the subsequent polar anticyclogenesis, and also to suggest a physical mechanism by means of which the variations in zonal index may eventually lead to development of strong polar highs such as this one.

During the past several years daily radiosonde observations have been made at a number of stations in Alaska. These soundings offer an especially illuminating picture of the behavior of the upper air during the period preceding and during the formation of the polar anticyclone. The daily variations in the height of the tropopause and the temperature at this level for Fairbanks, Alaska, are presented in the upper portion of Fig. 3 while in the lower portion are shown the simultaneous daily fluctuations in surface pressure and the difference in pressure between the surface and 15,000 feet. The height of the tropopause was determined by assuming it to be the level of greatest significance discontinuity of lapse rate in the upper atmosphere. During this particular period multiple tropopauses were not common. Typical soundings during the period are shown in Fig. 4. The graphs of Fig 3 bring out among other things the well-known fact that the pressure variations observed at the ground are the result of complex changes of mass in the atmosphere. For example, the rise in surface pressure from the 15th to the 18th was due in large part to changes which were taking place above 15,000 ft., as the pressure at the surface from the 15th to the 18th increased by 23 mb., while the contribution due to changes in the layer of atmosphere between the surface and 15,000 ft. was only 10 mb. Thus, the rise in pressure at the surface

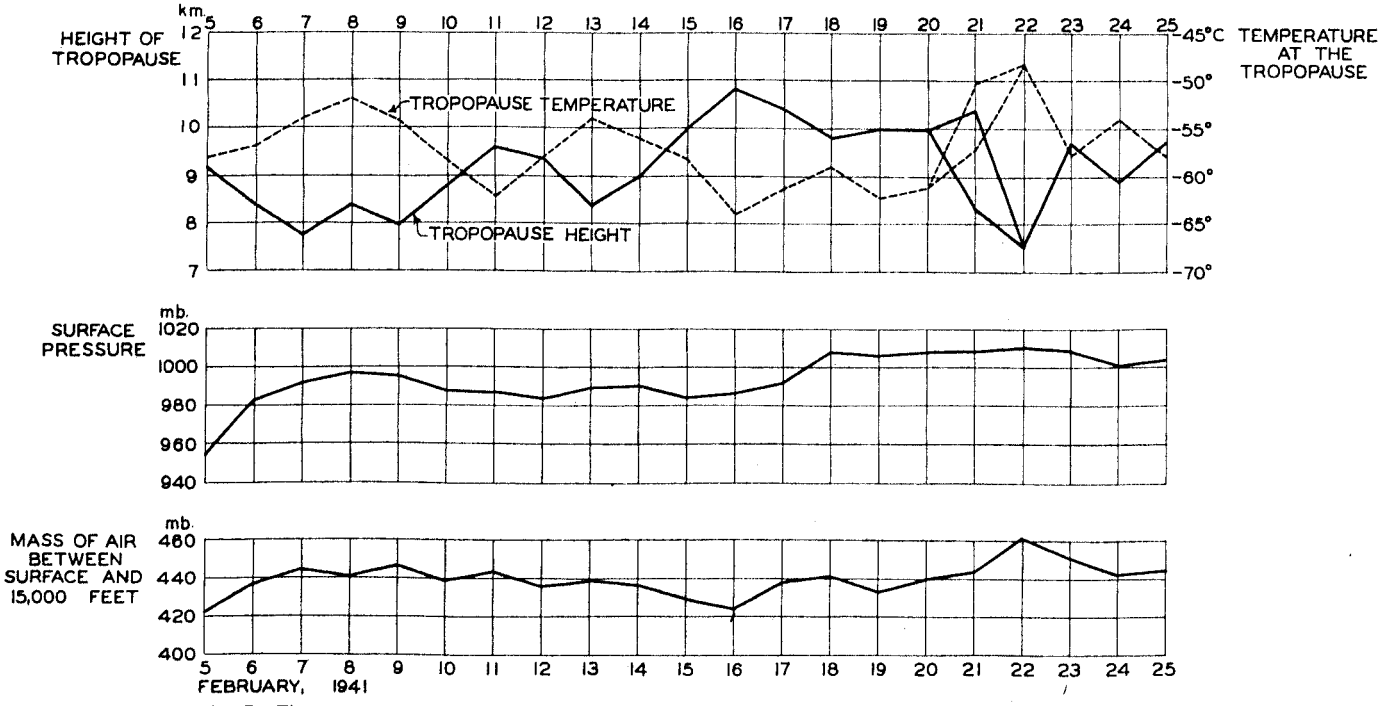

Fig. 3—Time graphs of certain aerological data for Fairbanks, Alaska during February 1941

is only partly explained by the replacement of warmer by colder air at levels below 15,000 ft. The rise of pressure at upper levels is also accompanied by the trend toward higher and colder stratosphere. It should be noted that the greatest rise of surface pressure at Fairbanks did not coincide with the greatest rise of the tropopause, because the pressure rise taking place at high levels was offset by the warming in the lower troposphere (i.e., the pressure difference of the layer between the surface and 15,000 ft. fell 15 mb., while the pressure at 15,000 ft. actually rose 7 mb. during the interval February 13-16).

These short-period fluctuations of tropopause height and temperature are superimposed upon more gradual rises which lasted from one to two weeks beginning around February 7. These long-period trends in which the shorter period variations are smoothed out, are illustrated in Fig. 5 where five-day mean values are plotted in such a manner that a point placed at February 7 indicates the mean value for the five-day period February 5-9; a

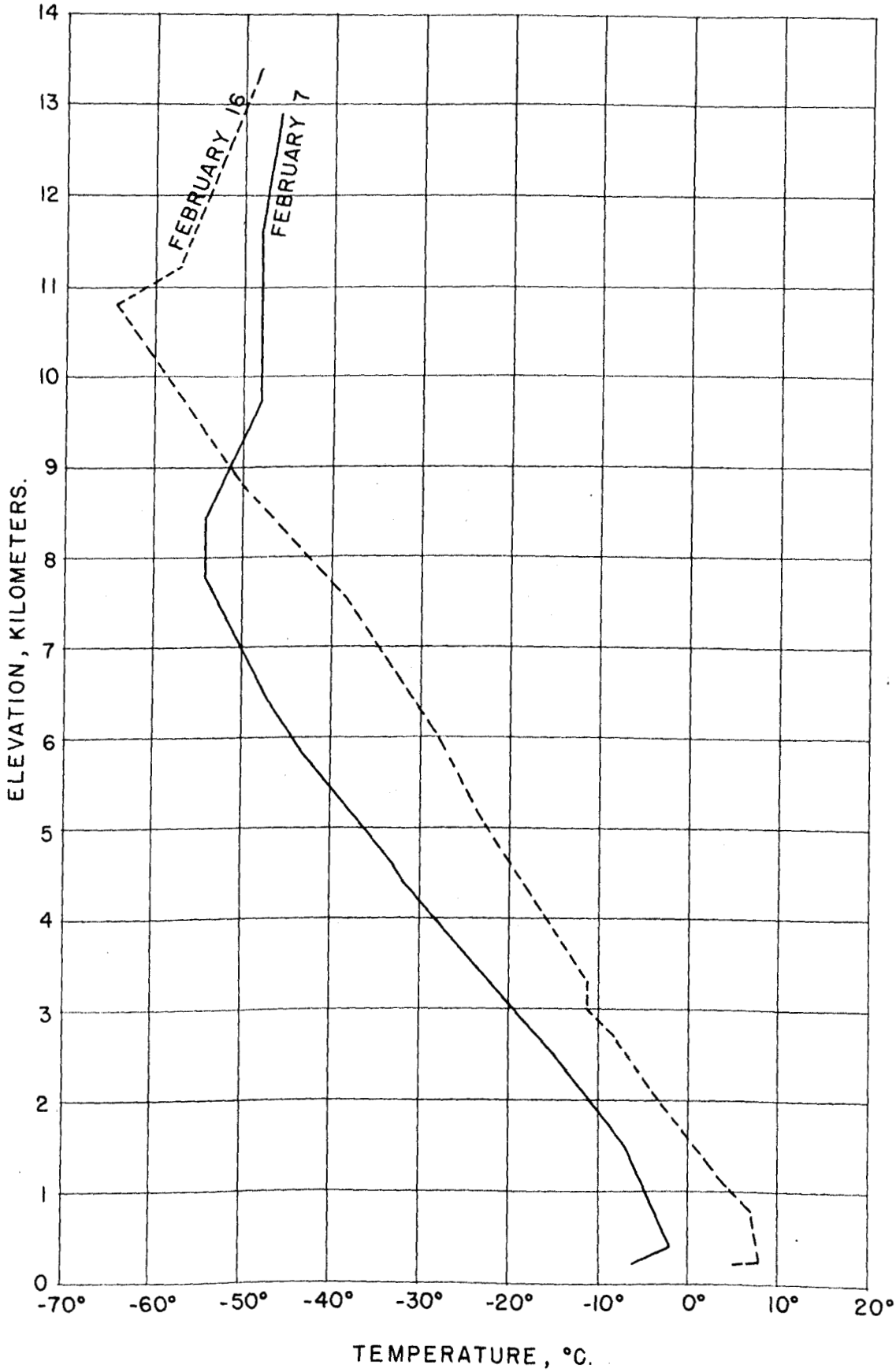

FIG. 4—Upper air soundings at Fairbanks, Alaska, for February 7 and 16, 1941

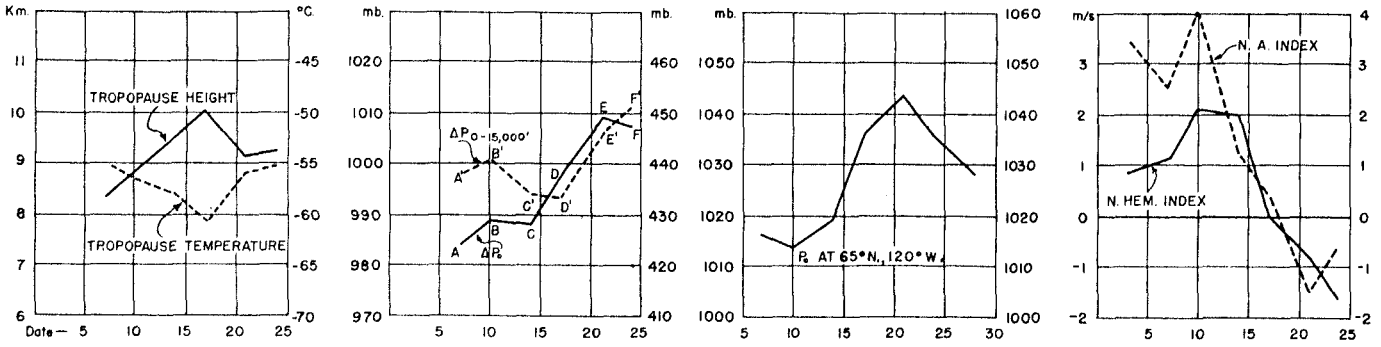

Fig. 5 — Five-day means of certain meteorological quantities for February 1941

point at February 14 represents the mean for the period February 12-16, and so on. Also shown in this figure are the behavior of the zonal index[1] for the hemisphere as a whole and for the region bounded by the longitudes 50°W. to 180°W.[2] The values plotted in this figure are mean values for five-day periods corresponding to periods of the maps shown in Figs. 10-15. Also shown are the five-day mean sea level pressures observed at latitude 65°N. longitude 120°W., a point over North America where the pressure increased much more than it did at Fairbanks, as Fairbanks was some distance west of the center of the polar high.

The gradual rising trend of the tropopause and the associated drop in temperature during the first part of February are shown in the first graph of Fig. 5. The second graph shows the variation of the surface pressure and of the pressure difference between the surface and 15,000 ft. While the five-day mean surface pressure rose 9 mb. from the period February 12-16 to the period of February 15-19 (C to D), the contribution of the lower troposphere from the surface to 15,000 ft. was actually decreased by one millibar (from C' to D'). Practically all of the rise during this period was therefore due to changes in the air structure above 15,000 ft., which were connected with the change in density of the upper troposphere and lower stratosphere. It seems that the pressure rise area appearing on the mean maps in the Pacific and moving eastward was intimately associated with the high cold stratosphere. When the center of the pressure rise moved in over northern Canada, the

[1]The average difference in pressure between latitude 35° and 55° converted by use of the geostrophic wind equation to an average zonal wind speed. In this period, data from most of Europe were not available.

[2]The index determined for this portion of the Northern Hemisphere is called the North American zonal index.

variations in surface pressure were greatest. This is shown in the second graph of Fig. 5, in which a large part of the indicated surface pressure rise may reasonably be attributed to the superimposition of the tropopause crest.

We then arrive at the fairly simple model of the development of this strong polar high. A shallow polar anticyclone forming over the polar regions is reinforced by the superimposition of a high cold tropopause, or by what we may call the crest of a tropopause wave.

We may throw further light on this hypothesis by the charts of pressure and pressure change at 10 km. These charts, also constructed for five-day periods corresponding to the periods of other charts in this report, are shown in Fig. 6, where the broken

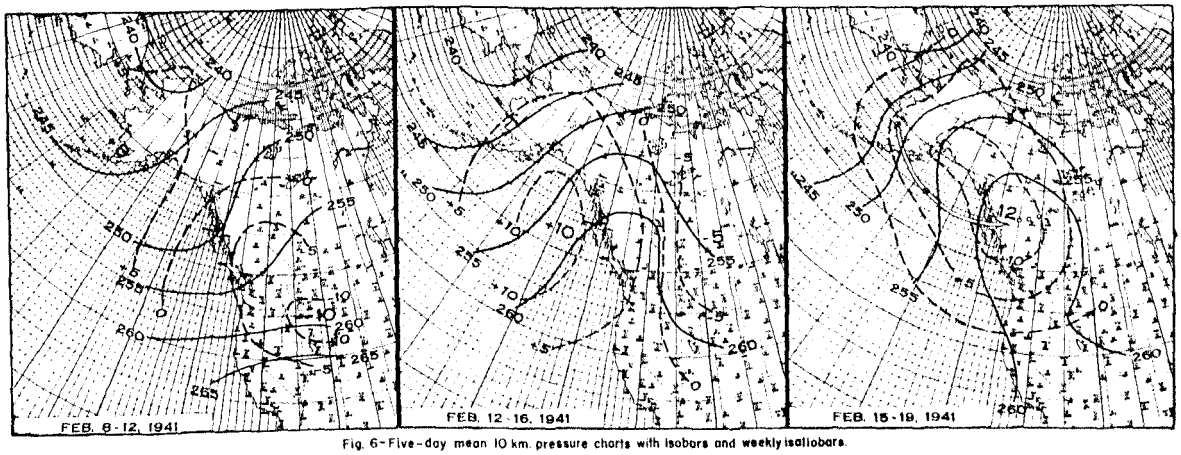

Fig. 6-Five-day mean 10 km. pressure charts with isobars and weekly isallobars.

lines are the lines of five-day mean pressure change since the preceding week's five-day mean chart. It is clear from these high-level charts that an area of rising pressure drifts eastward from the North Pacific and Alaskan area into the region where the maximum polar anticyclogenesis occurs (i.e., over northwestern Canada) The observed drift of this area is indicated by the double arrow in the chart of February 15-19, and the dotted arrow indicates its probable path, as determined by extrapolation, for the following half week, February 19-23, when the sea level pressures were highest in northwestern Canada. The lack of radiosonde data in these areas prohibits verifying this extrapolation. The pressure at 10 km. over Fairbanks (not displayed) shows an almost identical variation to the graph of tropopause height.

It seems possible that this combination of shallow polar highs and high level pressure rises occurs more frequently than we are wont to believe. The classical correlation coefficients of Dines show (2) that there is a correlation (over England) of 0.82 between the temperature at 4 km. and the pressure at 9 km., and also that an equally high correlation (0.84) exists between the height of the

tropopause and the pressure at 9 km.[1] Thus, while a high and cold tropopause usually goes with a warm lower troposphere, this correlation accounts only for perhaps $(0.82)^2$, or roughly 70% of the variation, while among the other 30% may be included the type of case with which we are concerned. This result is also in accord with recent studies by Brier (10) showing that at Fairbanks in the fall only about 50% of the variation of surface pressure can be attributed to the change in the structure of the lower troposphere below 4 km. It seems likely, then, that the upper atmosphere above 4 km. must play an important part in bringing about these large variations in surface pressure. This result is, of course, in accord with the Dines (2) and Schedler (4) coefficients, which suggest that most of the variations in pressure observed at the surface over Europe are due to excess or deficit of mass above the 9 km. level. It must be emphasized that this result does not necessarily mean that the surface pressure variations originate in the stratosphere (although Stüve (5) suggests that they do), for the stratospheric changes may result from processes originating in the lower troposphere (as brought out by J. Bjerknes and others (6)).

We will now consider the relationship between the data presented above and the variation of the zonal index. During the period of formation of the polar anticyclone there was a sharp fall of the zonal index (Fig. 5) which is in agreement with the Rossby theory (7). However, at the beginning of the period under discussion, the Aleutian low split into two distinct centers This occurred during the period February 5-9 whereas, during the period February 1-5 it was a single intense center. The zonal index increased in this interval and continued to increase for the succeeding period, February 8-12, when the Pacific low remained split into two cells. This fact at first glance seems contradictory, since, according to Rossby (7), a decreasing zonal index is supposed to be associated with a split Aleutian low. It will be remembered, however, that Rossby's theoretical analysis of the planetary flow patterns of atmospheric circulation has its starting point on the east coasts of continents where polar air flowing off to sea is rapidly heated. This heating induces changes in vorticity of the westerly flow which result in wave patterns in the upper air currents similar to those shown in Fig. 7. It seems reasonable that the continent of Eurasia, which has by far the greatest land mass in the Northern Hemisphere, might be the seat of the origin of fluctuations in zonal index; that is, the slowing down of the zonal circulation might first take place there and determine the spacing of the wave train in the prevailing westerlies. If this is true, a decrease in the index over Eurasia should precede both the splitting of the Aleutian low and the fall of the zonal index over the Northern Hemisphere.

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[1] Similar coefficients have also been determined by Haurwitz for Boston and for Canadian stations (3).

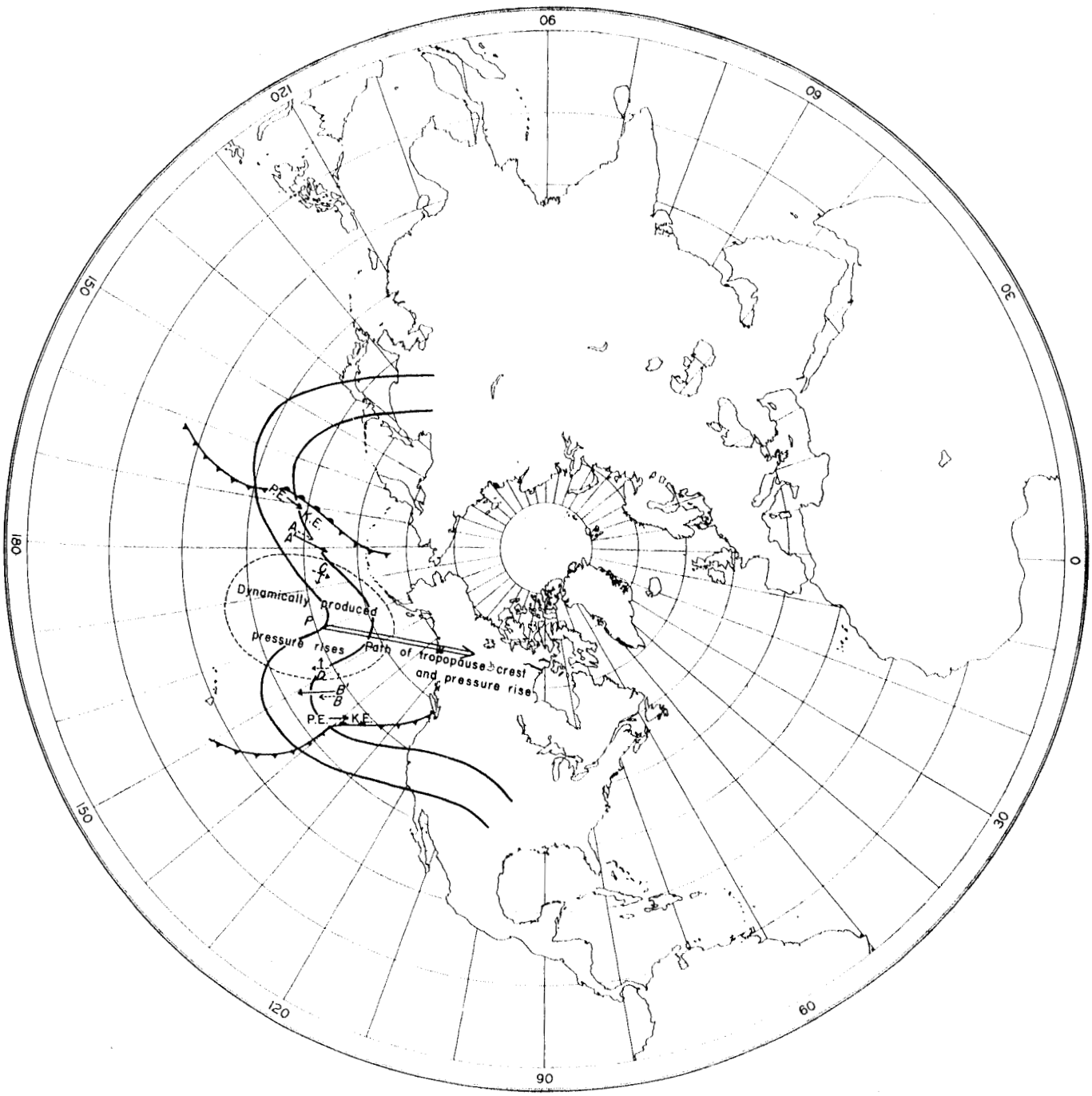

Fig. 7 – Schematic representation of developments following a fall in the Asiatic zonal index.

In the case treated above, the zonal index over Asia, as measured by the pressure difference between latitudes 45° to 65°[1] fell from +5.2 mb. for the period February 1-5 to -2.7 mb. for the period February 5-9, and to -3.9 mb. for the period February 8-12. Thus, one of the first signs of the splitting Aleutian low and the subsequent drop in the zonal index seems to be expressed in the Asiatic index. That this is not an unusual circumstance is shown by the lag correlation coefficients found by Allen (8) between indices for various sections, the particular sections he chose being shown in Fig. 8. His coefficients are repeated in Table 1.

Table 1.

Zonal Index Correlations (after Allen)

Sections	No Lag		One Week Lag		Two Weeks Lag	
	1932-33	38-39	1932-33	38-39	1932-33	38-39
Asia-Asia				0.54		
Asia-Pacific	0.49	-0.20		0.02		
Asia-America	0.03	0.06	0.28	0.24	0.42	
Asia-Atlantic	0.24	0.13	0.49	0.32		0.10

More recent correlations of a similar nature have been made by Stone and Willett (11) who, using slightly different geographical sections, obtained the values shown in Tables II and III. Table III, however, applies to the "max-min index", an index which measures the strength of the westerlies using the 20° latitude band in which they are strongest. (The zone is thus not fixed but varies from one situation to another.)

Table II.

Zonal Index Correlations (after Stone and Willett)

Sections	No Lag		One Week Lag		Two Weeks Lag	
	1932-33	35-36	1932-33	35-36	1932-33	35-36
Asia-Asia						
Asia-Pacific	0.41	-0.05	0.23	-0.43		
Asia-America	0.02	0.03	0.23	-0.16		
Asia-Atlantic	0.29	0.24	0.45	0.13		

[1] Data from latitude 35° were not available over Asia; the data were taken between longitudes 40° E. and 160° E.

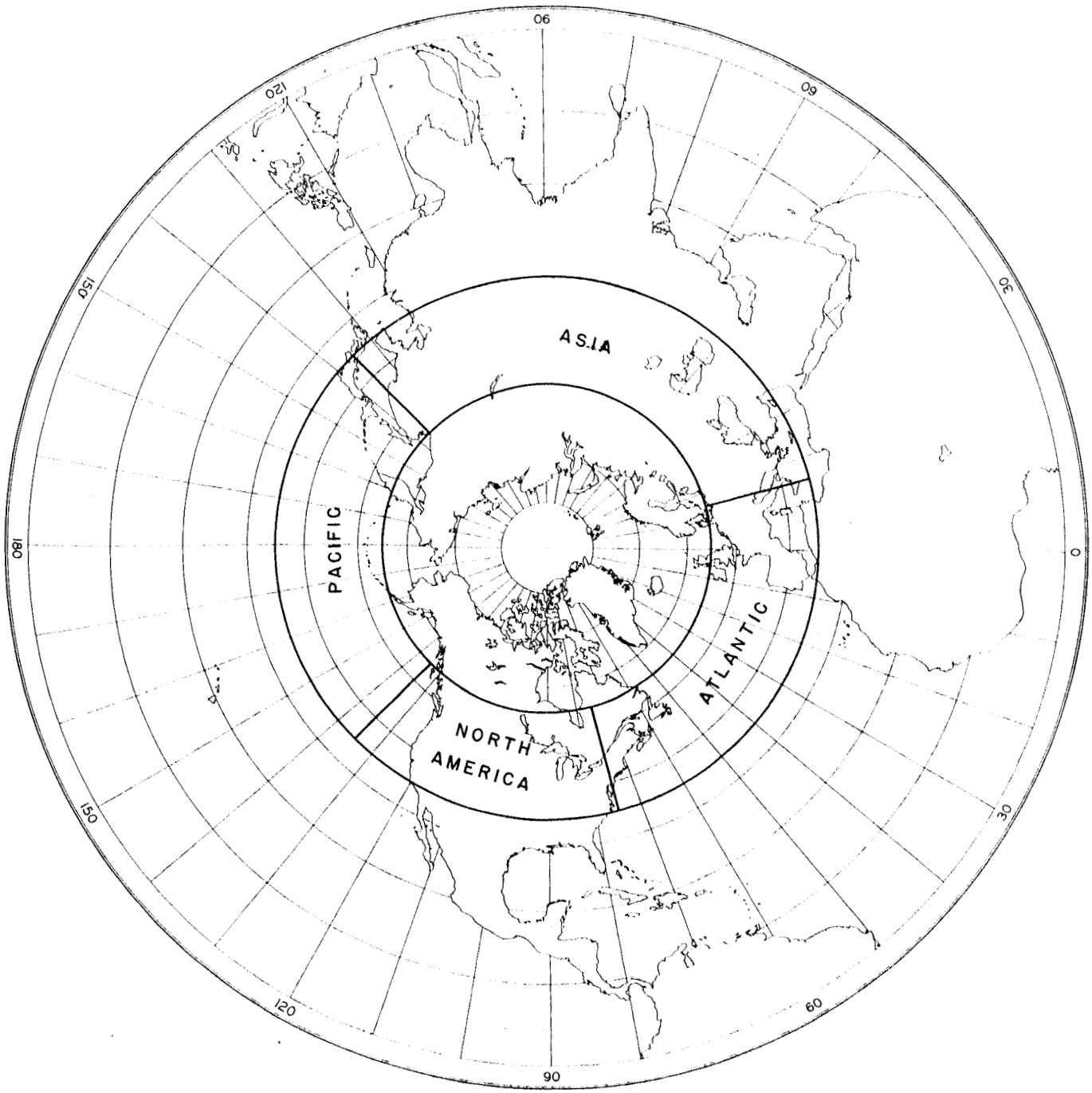

Fig. 8– Geographical regions used in computing sectional indices

Table III

Max-Min Zonal Indices (after Stone and Willett)

Sections	No Lag		One Week Lag		Two Weeks Lag	
	1932-33	35-36	1932-33	35-36	1932-33	35-36
Asia-Asia						
Asia-Pacific	0.12	0.13	0.11	0.08	0.30	0.15
Asia-America	0.19	0.16	0.42	-0.02	0.16	0.05
Asia-Atlantic	0.03	0.00	-0.17	0.31	0.17	0.05

From these data it may be seen that there are predominately positive coefficients for lags of one and two weeks, although the correlations are low and by no means conclusive. But they seem to lend some support to the hypothesis that a slowing down of the circulation over Asia is followed by a slowing down in other portions of the hemisphere. This is also indicated by the prevailingly positive correlations found by Allen (8) between the Asiatic index and the total zonal index one and two weeks later.

	1932-33	1938-39
One week lag	0.55	0.42
Two weeks lag	0.49	0.19

In part these coefficients include the well-known "blocking" effect,[1] in which sharp falls in the index over the eastern Atlantic and western Europe precede, by about a week, falls in the index over North America. It seems highly likely from Figs. 10, 11, and 12 that the initial blocking mechanism, as expressed by the distribution of pressure changes over the eastern Atlantic, has begun to operate.

One is tempted to speculate as to just how the extreme slowing down of the circulation occurs and how this may be associated with the development of the Polar high. The chronological order in which events occurred in the particular case discussed above was as follows (the periods given are when the action first began in a pronounced manner):

1. Fall in the zonal index over Asia and onset of "blocking" in the eastern Atlantic (January 29-February 2).
2. Splitting of the Aleutian low into two cells and the building up of a ridge between the two low pressure cells (February 5-9).
3. Fall of the zonal index and North American index (February 8-12).
4. Development of the polar high (February 15-19).

In order to elucidate our hypothesis, we shall refer to the schematic representation shown in Fig. 9, which starts out with Rossby's planetary flow model (7) as a basis. The generation of the two troughs leads to convergence of warm and cold air masses and, hence, two frontal systems. These systems in turn give rise to cyclone waves which transform the potential energy of mass distribution, represented by the solenoid concentration at the fronts, into kinetic energy. The resultant speed-up of certain air

[1]For a complete explanation, see (8).

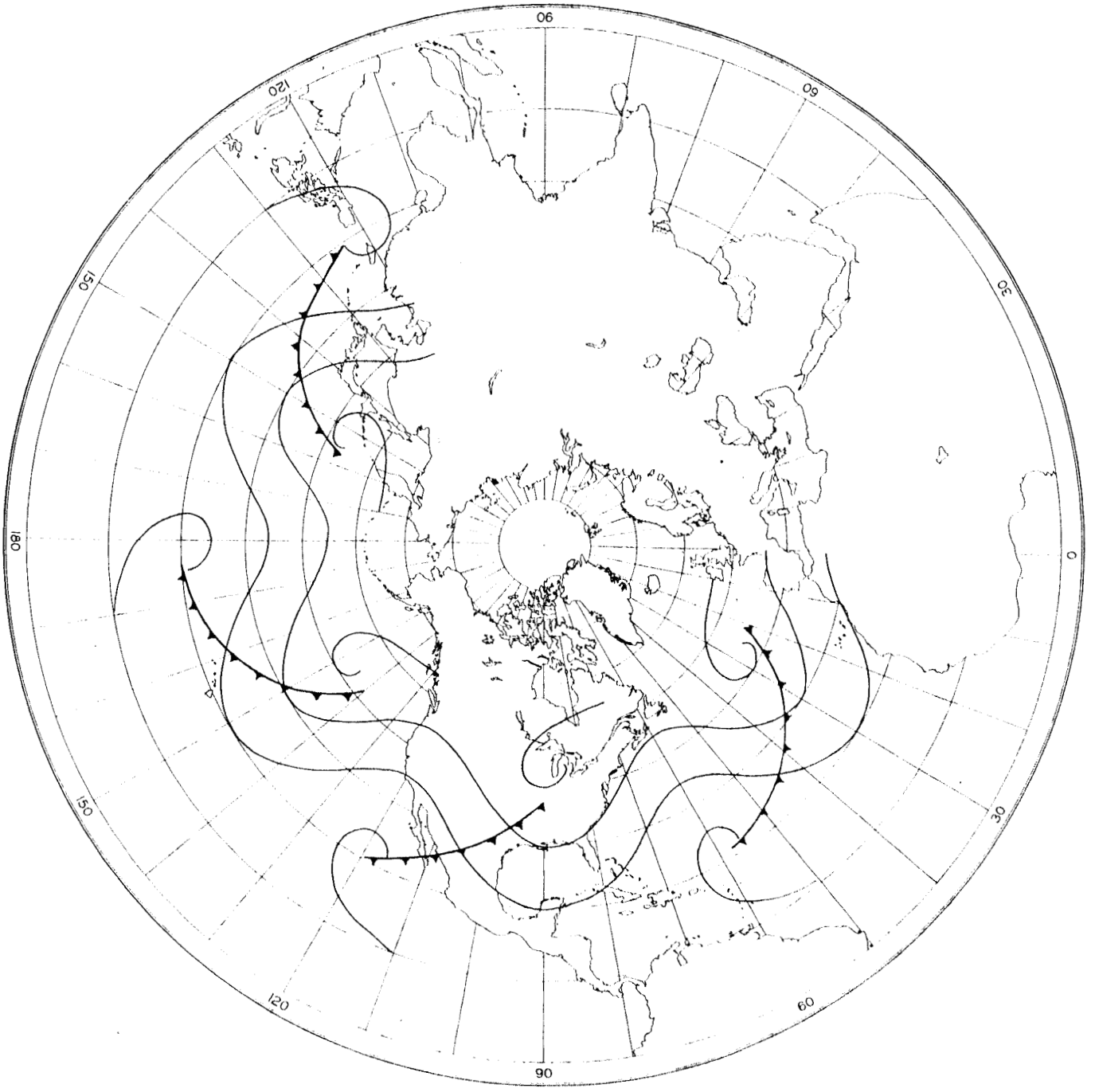

Fig.9 – Schematic representation of planetary flow pattern for the case of low index (after Rossby).

currents is indicated in Fig. 7, where velocity A becomes A' and velocity B becomes B'. These accelerated currents lead to lateral (isentropic) shearing stresses, causing supergradient winds at C and D, which are then banked to their right, tending to build up a compensating pressure gradient to balance the non-gradient motion. As a result, air is piled up at P, and the convergence leads to a pressure rise like that observed in Figs. 12, 13, and 14. The convergence presumably goes on through a deep layer[1] so that the stratosphere itself may be lifted, and in this manner a tropopause wave may be initiated. This is essentially the reverse of the divergence process suggested by Palmen (9) by means of which the tropopause is at times considerably depressed. This effect is probably superimposed upon the advective transport of southerly air with high stratosphere in advance of the trough.

The wave crest, once formed, may after a time break away and move eastward or northeastward, bringing with it pressure rises at lower levels. Finally the crest of the tropopause moves over polar regions. If it becomes superimposed on a cake of air already cold--an incipient polar anticyclone--it reinforces it, so that a very strong polar high may be developed. On the other hand, if the tropopause crest moves over relatively warm polar air, only a weak polar high is formed. Apparently this latter condition occurred during 1940 in periods November 9-13 and December 7-11.[2]

Aerological soundings show that the pressure changes appearing at the surface along the Alaskan coastal region are often associated with this high level rise or tropopause crest. In fact, the onset of large pressure rises in the Gulf of Alaska on the five-day mean sea level maps is in itself a quite effective clue to the subsequent formation of the polar high over northern North America. An examination of sea level pressure and pressure change maps for the winters of 1932-33, 1940-41, and 1941-42, indicates that the frequency of polar anticyclones in the week following the occurrence of pressure rises in the Gulf of Alaska was greater than the normal expectancy of polar highs.

Once the North American polar high is formed, the zonal index over North America falls, and it seems possible that the sequence of events which occurs in the Pacific following a drop in the Asiatic index may also occur in the Atlantic, namely, splitting of the Icelandic low with the development of a ridge between cells, making up the typical low index pattern.

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[1]Pressure change charts at the 3 km. level show that the rises are fully as great as the surface pressure rises shown between the two cells of the Aleutian low on Figs. 11, 12, 13, 14 and 15.

[2]The maps for these periods are not reproduced here.

According to this hypothesis, general falls in the zonal index might be initiated over Asia with progressive low index conditions becoming established in the general direction from west to east as well as from east to west, which may also be referred to as "blocking".

When both factors operate, namely blocking in the eastern Atlantic and a slowing down in a zonal flow off the Asiatic coast, a pronounced fall in the zonal index as a whole is indicated.

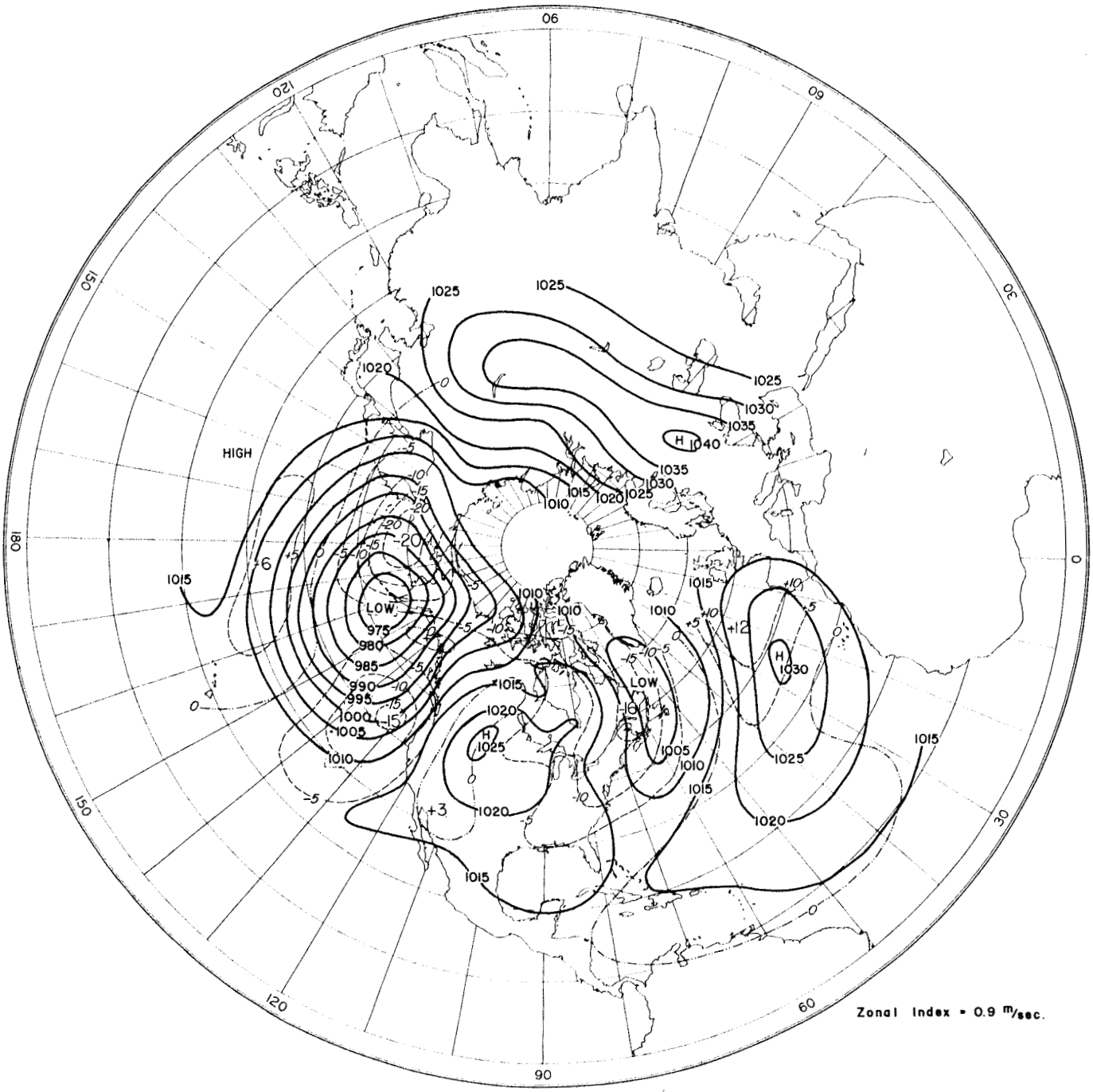

Fig.10 - Five day mean pressure chart for February 1-5, 1941, with isobars and weekly isallobars.

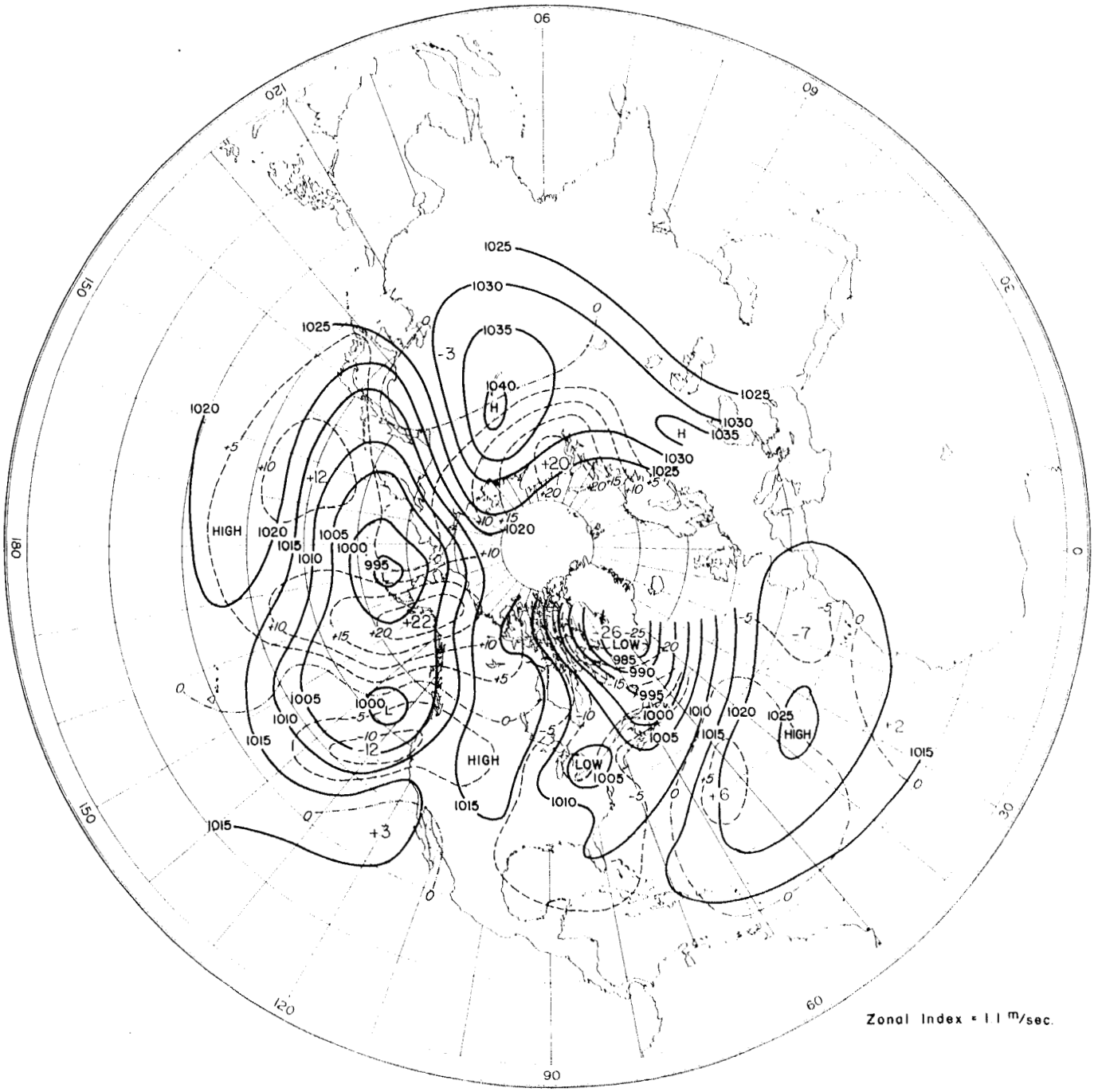

Fig. 11 - Five day mean pressure chart for February 5-9, 1941, with isobars and weekly isallobars.

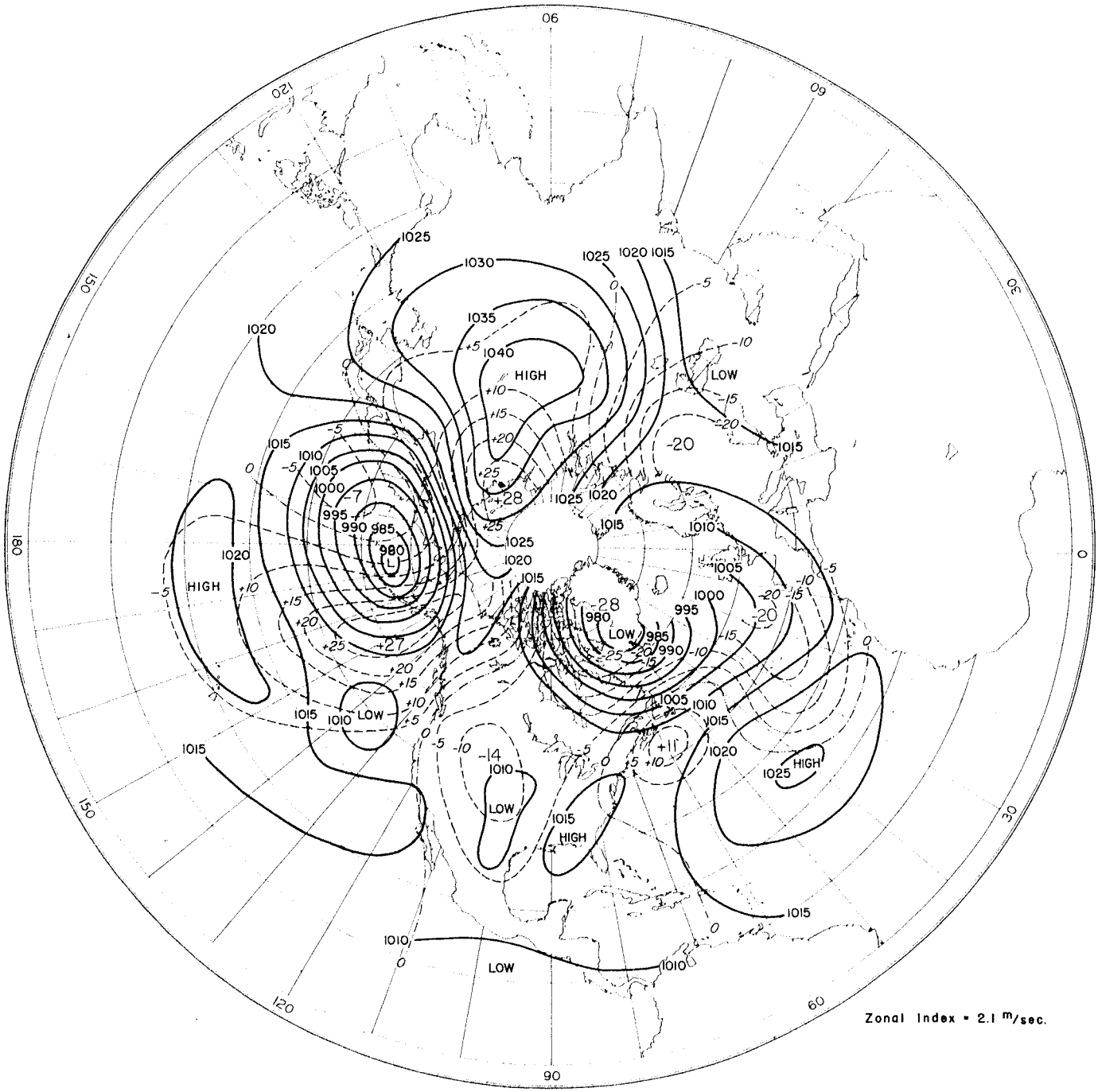

Fig. 12 - Five day mean pressure chart for February 8-12, 1941, with isobars and weekly isallobars.

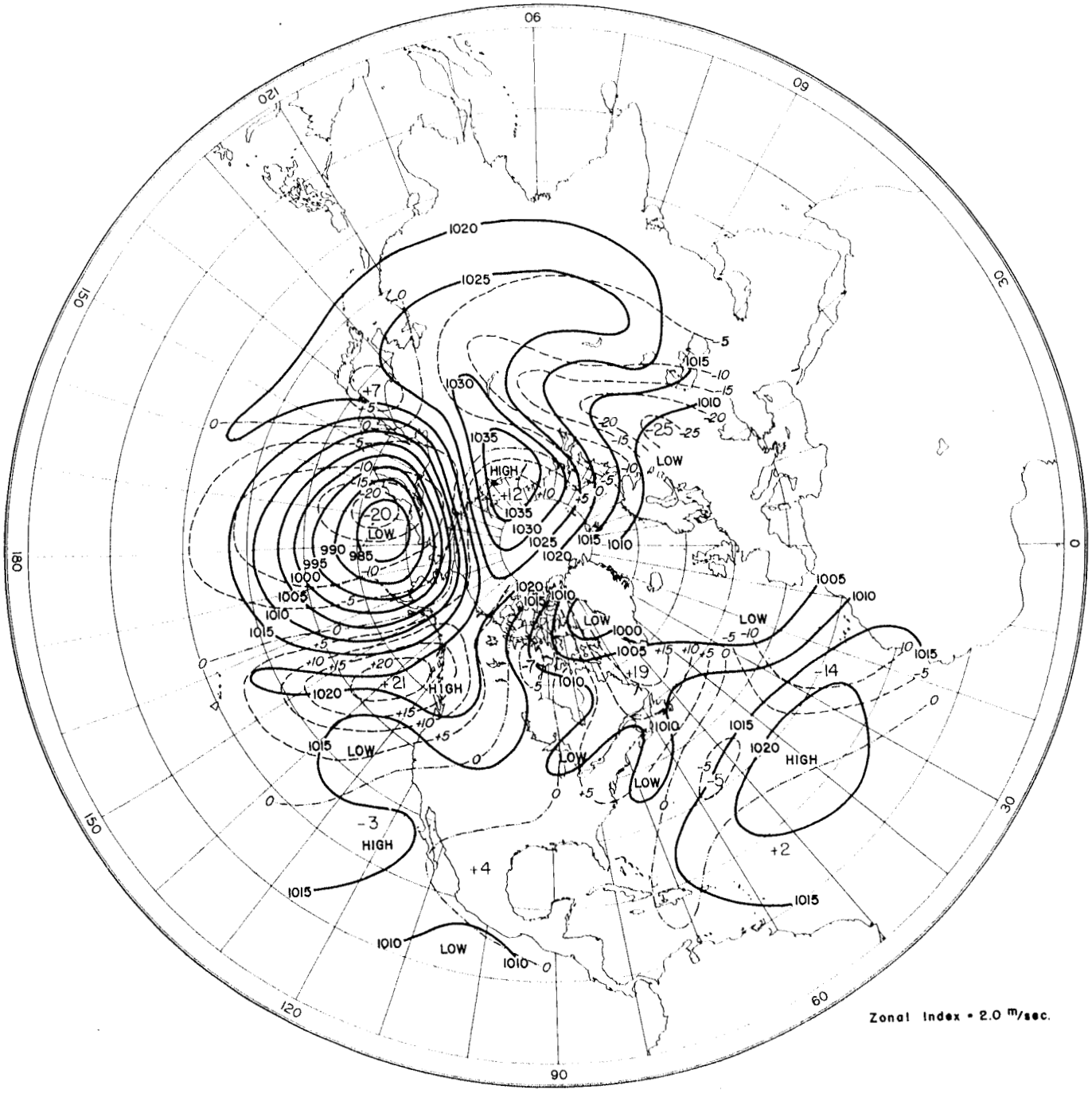

Fig. 13 - Five day mean pressure chart for February 12-16, 1941, with isobars and weekly isallobars.

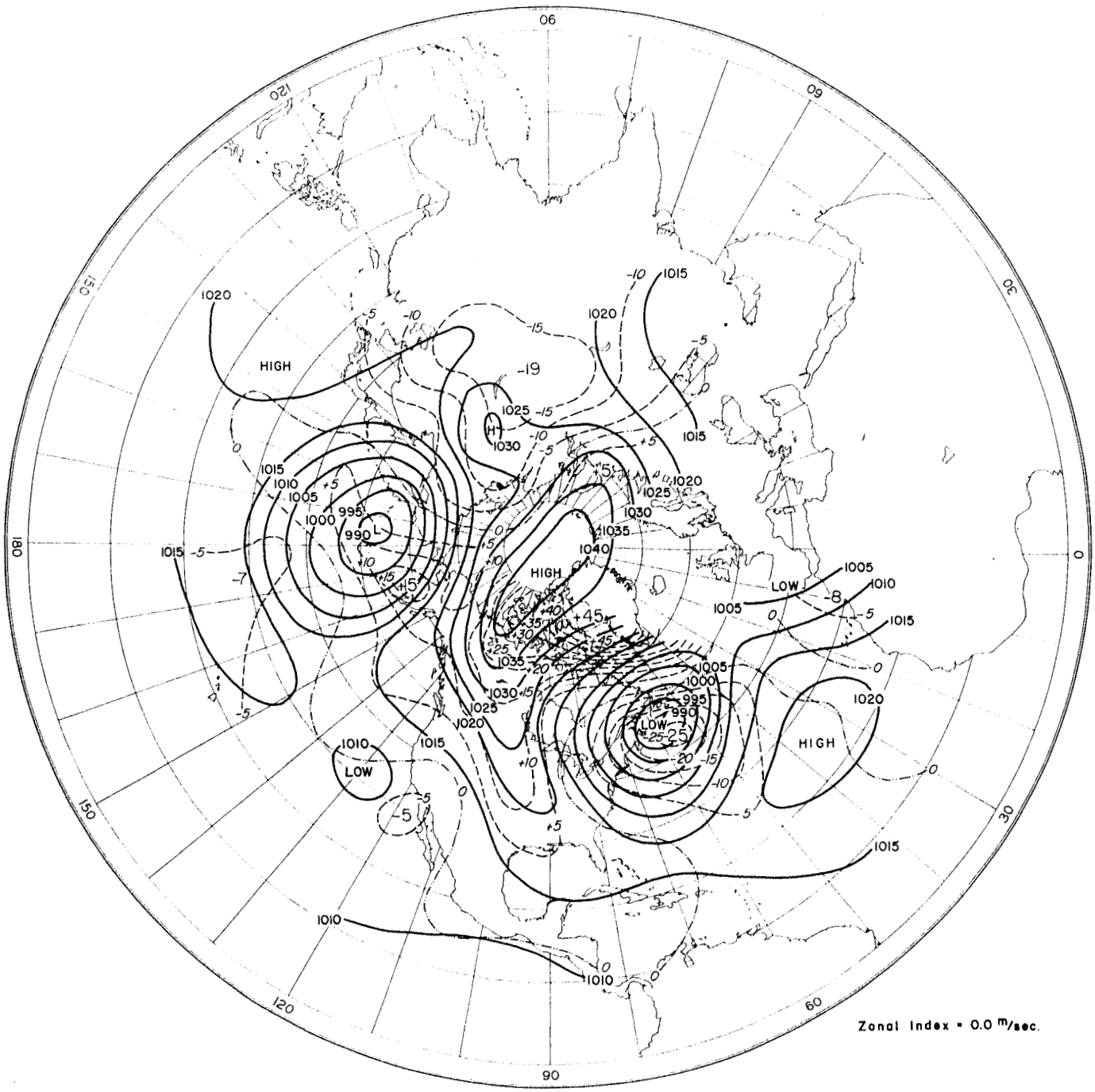

Fig.14- Five day mean pressure chart for February 15-19, 1941, with isobars and weekly isallobars.

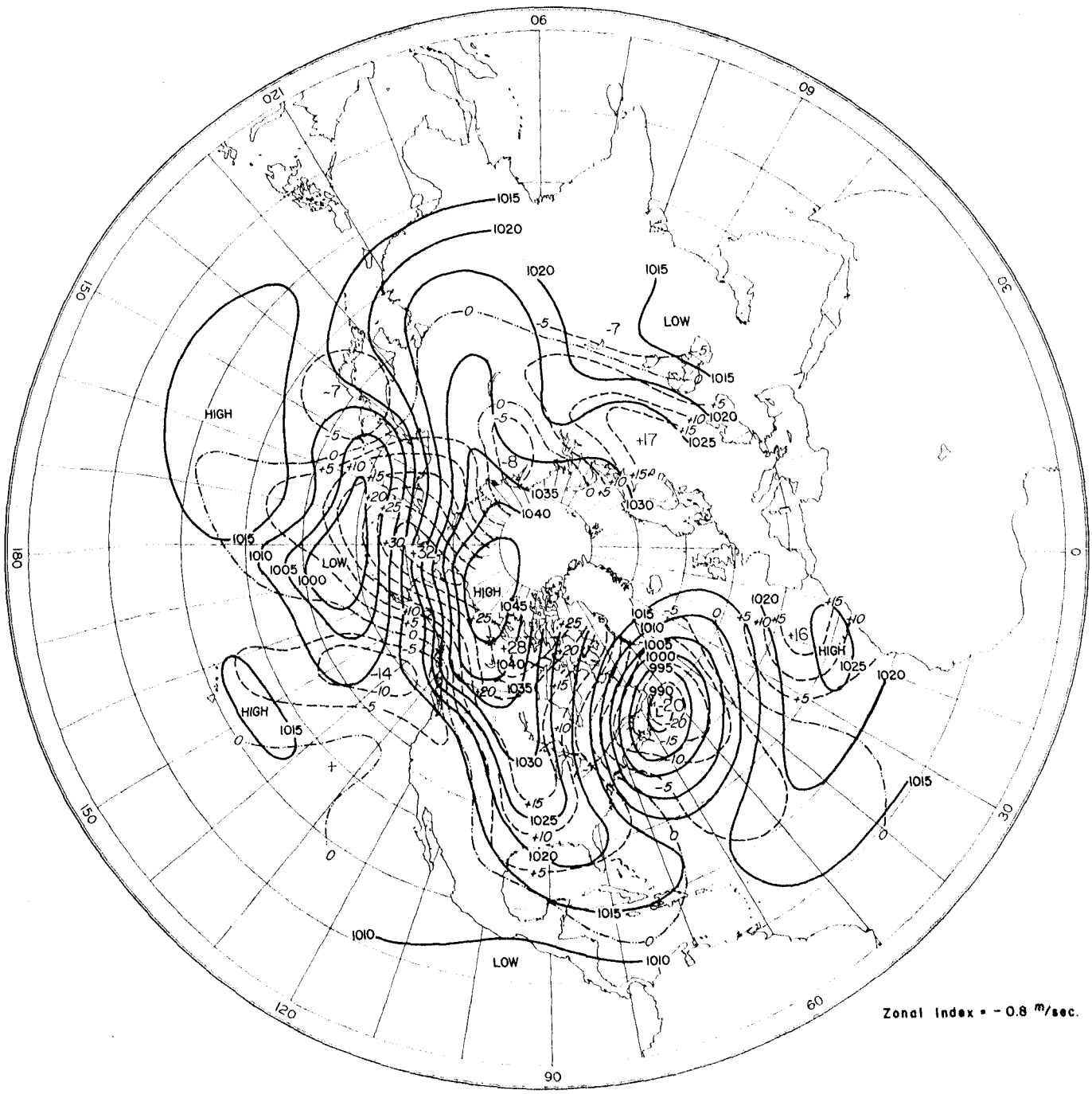

Fig. 15 - Five day mean pressure chart for February 19-23, 1941, with isobars and weekly isallobars.

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