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THE CIRCULATION OF THE ATMOSPHERE IN HIGH LATITUDES DURING WINTER

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THE CIRCULATION OF THE ATMOSPHERE IN HIGH LATITUDES DURING WINTER

By Horace R. Byers and Victor P. Starr

[U. S. Weather Bureau, Washington, D. C.]

PREFACE

The research project made possible by an allotment to the Weather Bureau under the Bankhead-Jones Act of 1935 and concerned with winter conditions in the interior of Canada and Alaska has been described in a general way in a previous paper,[1] from the preface to which the following is copied:

> The process of formation of cold continental air in the northern interior of Canada and Alaska during the winter was investigated early in 1936 by Wexler, on the basis of theoretical considerations and scattered aerological ascents. A theory of the formation of these air masses by radiational cooling of originally warmer air was advanced, but it was evident that additional data from the upper air, and measurements of nocturnal terrestrial radiation during the polar night were needed. Furthermore, a study of the formation of cold anticyclones and the release of cold outbreaks into the latitudes of the United States was considered desirable.
>
> To provide the necessary data, there was established, with funds made available through the Bankhead-Jones Act of 1935, a project for obtaining airplane soundings of the upper air, and terrestrial radiation measurements twice daily, during the winter 1936–37 at Fairbanks, Alaska. The Meteorological Service of Canada cooperated by conducting daily airplane and pilot-balloon soundings at Fort Smith, Northwest Territory. Snow-surface temperatures were also measured at these stations and at the aerological stations in the northern part of the United States. Terrestrial radiation measurements were likewise made at Fargo, N. Dak. A small research staff was assigned to the Meteorological Research Division of the Weather Bureau in Washington to analyze the data.

Additional winter sounding data were obtained at Fairbanks by continuing the aerological soundings through the winter of 1937–38 with radiosonde equipment.

Several preliminary papers and theoretical studies in connection with this project have been, or are in process of being, published.[2] The main study of the data naturally divides itself into two parts: (1) an investigation of the radiation and cooling processes in connection with the development of the continental Arctic air masses; and (2) a study of the circulation and air mass interactions in the northern Canadian and Alaskan region. The present paper is concerned with the latter phase.

In attempting to utilize the observational material to best advantage, it became apparent in the course of the investigation that the circulation and weather conditions in high latitudes over North America are intimately connected with the conditions at other latitudes of the continent, and also with the circulation in other parts of the Northern Hemisphere. This suggested an extension of the field of investigation to include most of North America, and, for certain purposes, the entire Northern Hemisphere. Other research efforts directed toward an understanding of the circulation processes in middle and low latitudes were found to be closely related to the polar air investigation, and several factors having a bearing on these were incorporated into the study.

ACKNOWLEDGMENTS

The names of those employed on this project were given in the summary of the Fairbanks data published as Monthly Weather Review Supplement No. 40. Invaluable assistance in the last stages of preparation for publication of the present report was afforded by Messrs. P. J. Harney, A. M. Marks, and V. J. Oliver in the Chicago office of the United States Weather Bureau.

FORMATION OF CONTINENTAL ARCTIC AIR

It has been shown by Wexler[3] that the formation of continental Arctic air masses[4] comes about mainly as the result of cooling of the lower atmosphere by radiation processes over the northern snow-covered continents and ice fields during the winter night. If these areas represent a true cold source, then air masses reaching there from other localities must always be at higher temperatures at first, then become Arctic in character through cooling. Since a migration of air masses from one part of the earth to another is occurring constantly, the building up of continental Arctic air from previously warmer air masses, their outbreak into lower latitudes after having achieved the low temperatures, and their replacement by new air masses which are relatively warm in the beginning but undergo the same cooling to form again more Arctic air, are continuous processes. Wexler has shown that one of the principal relatively-warm air masses involved in the beginning stage of this cycle is maritime polar air. This is particularly true in North America where the prevailing west-to-east flow brings air from the Pacific Ocean into the continental Arctic air "factory." The principal characteristic of this air is its uniform lapse rate, following closely the saturation-adiabatic corresponding to its temperature, which, at sea level, is in the vicinity of 0° C. The cooling of the air mass occurs first from contact with the frozen surface, later from radiation processes. Wexler has outlined the mechanism whereby this radiation cooling makes itself felt gradually to greater and greater heights; but since cooling from below is a stabilizing process, the air at higher levels cannot participate in this cooling by any mixing process brought about through vertical stirring. Therefore, it must remain approximately at its original temperature until the radiation processes have made themselves felt at these heights. Ordinarily the radiation cooling effects do not reach a depth beyond three kilometers, except after long periods of ideal radiation conditions, so that upward from 2 to 4 km. the air maintains the characteristics acquired

[1] Data from Aerological Soundings at Fairbanks, Alaska, During the Winters 1936–37 and 1937–38, Monthly Weather Review Supplement No. 40, 1940.

[2] (a) H. Wexler, Cooling in the Lower Atmosphere and the Structure of Polar Continental Air, Monthly Weather Review, vol. 64, April 1936. (Published prior to the beginning of the project.)
(b) H. Wexler, *Absorption of Radiation* by Water Vapor as Determined by Hettner and by Weber and Randall, Monthly Weather Review, vol. 65, March 1937.
(c) J. C. Ballard, Some Outgoing Radiation and Surface Temperature Measurements at Fargo, N. Dak., *Transactions*, American Geophysical Union, 18th Annual Meeting, April 1937.
(d) H. Wexler, Formation of Polar Anticyclones, Monthly Weather Review, vol. 65, June 1937.
(e) Another paper, by Wexler, entitled "Polar Anticyclogenesis Caused by Lateral Mixing" representing work done at the Massachusetts Institute of Technology, is in manuscript form and early publication is expected.
(f) H. Wexler, Observations of Nocturnal Radiation at Fairbanks, Alaska, and Fargo, N. Dak., Monthly Weather Review Supplement No. 46, in press.

[3] *Op cit.*, footnote 2a.

[4] For definitions of continental Arctic and other air masses in North America see Showalter, A. K.: Further Studies in American Air-mass Properties, Monthly Weather Review, vol. 67, pp. 204–218. 1939.

during its maritime sojourn. With the few ascents at his disposal during the formulative stages of the project, Wexler was led to a picture of the vertical structure of this air as consisting of a sharp temperature inversion next to the ground and above that a nearly isothermal layer extending to the maximum height of radiation effects with a moderate lapse rate hence to the tropopause. The observations taken at Fairbanks and Fort Smith have shown that Wexler's picture is essentially correct, although there are frequent complications in the structure.

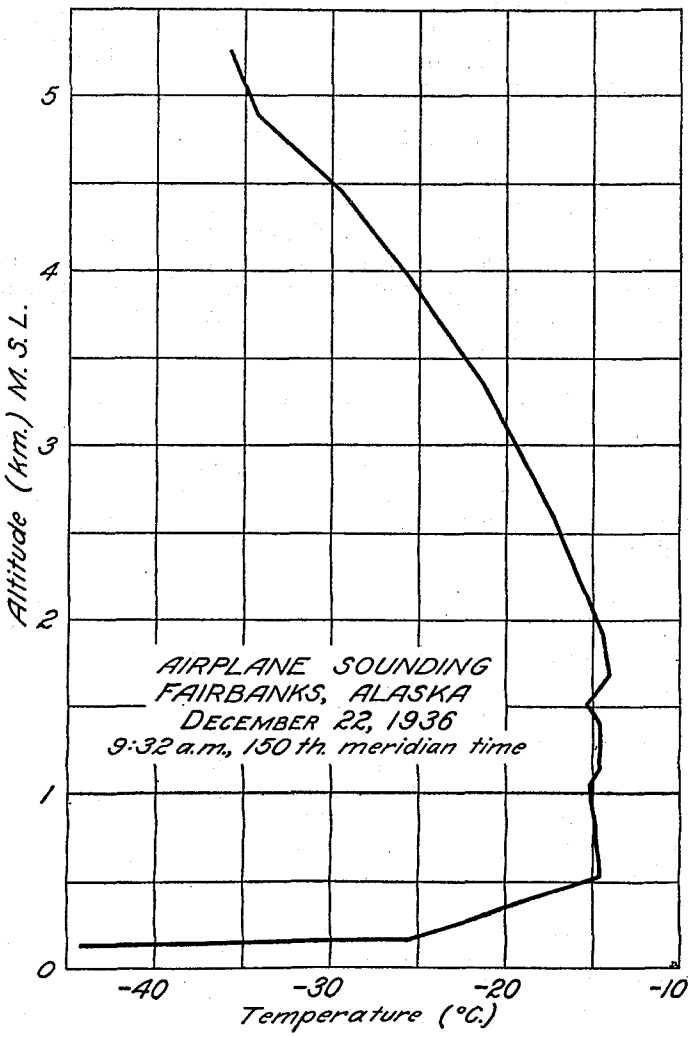

FIGURE 1.—Temperature-height diagram of a sounding representing ideal relationship between snow-surface temperature and vertical temperature distribution in the overlying air.

The curve in figure 1 represents a sounding taken at Fairbanks on December 22, 1936, which Wexler chose as typical of the vertical temperature structure resulting from the processes described by him. A large number of similar soundings can be gleaned from the records of Fairbanks and Fort Smith for the winter months. Naturally, some modifications of this temperature structure due to mechanical turbulence, frontal activity, invasions of new air masses and other factors are found. During the period of record it was shown that, even in midwinter, air masses that definitely are not of true Arctic character, sometimes even tropical air masses, can invade these areas. However, for the most part, particularly at Fort Smith, real continental Arctic conditions prevailed and it was possible to treat the air-mass manufacturing process as consisting of radiation action only. An analysis of the radiation in relation to the thermal structure of the air is being covered by Wexler in another report (footnote 2 (*f*)).

One of the principal factors serving to upset the radiation balance and thus to produce a vertical temperature distribution that does not agree with that predicted by the theory is the occurrence of high-wind velocities. Mechanical turbulence then causes mixing which tends toward equalizing the potential temperature throughout the turbulent layer, resulting in an increase of the temperature in the low levels. Without taking into consideration the character or trajectories of the air masses, a plot was made of wind velocity and temperature at the level of 500 meters above sea level over Fort Smith during December 1936, January and February 1937. A "scatter" diagram, reproduced in figure 2, resulted. Each dot shows the relationship between the temperature and wind velocity at 500 meters for a given sounding. At

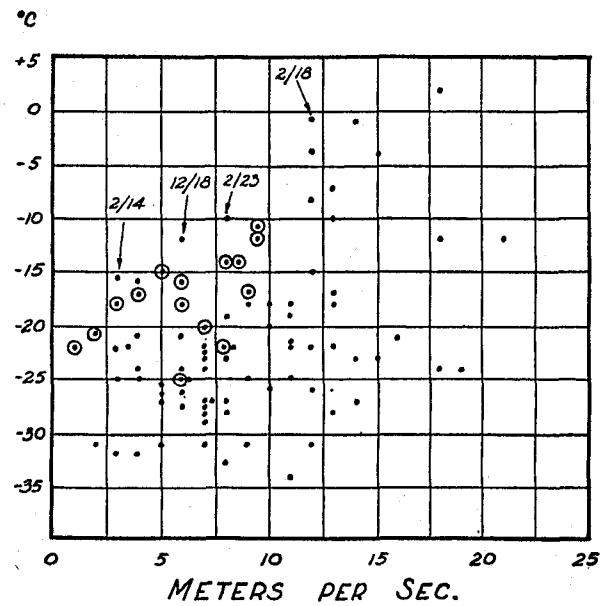

FIGURE 2.—Relationship between wind velocity and temperature at 500 meters in winter soundings at Fort Smith.

velocities of less than 10 meters per second, the cloudiness (overcast or clear) was considered, and cases of complete overcast are indicated by the dots enclosed in circles. At higher velocities, the presence or absence of clouds did not materially affect the temperature because then the turbulence apparently was of overwhelming importance. A few cases in which air almost of tropical origin was at the station were noted, and these are indicated by the dots labeled with dates (2/14, 12/18, 2/23, 2/18). It will be noted from the diagram that there is a correlation between the simple facts of high temperature and high-wind velocity and that this relationship becomes more definite if days of overcast conditions or of abnormally warm air-mass occurrences are not considered. This demonstrates the effect of just one factor in determining the lapse rate near the ground.

MEAN LAPSE RATES

It is of interest to examine the mean vertical temperature distribution at Fairbanks and Fort Smith in order to obtain some idea of the prevailing temperatures and lapse rates. Temperature-pressure curves of the means of all soundings by months are reproduced in figure 3 for Fairbanks; and in figure 4 the data for Fort Smith in

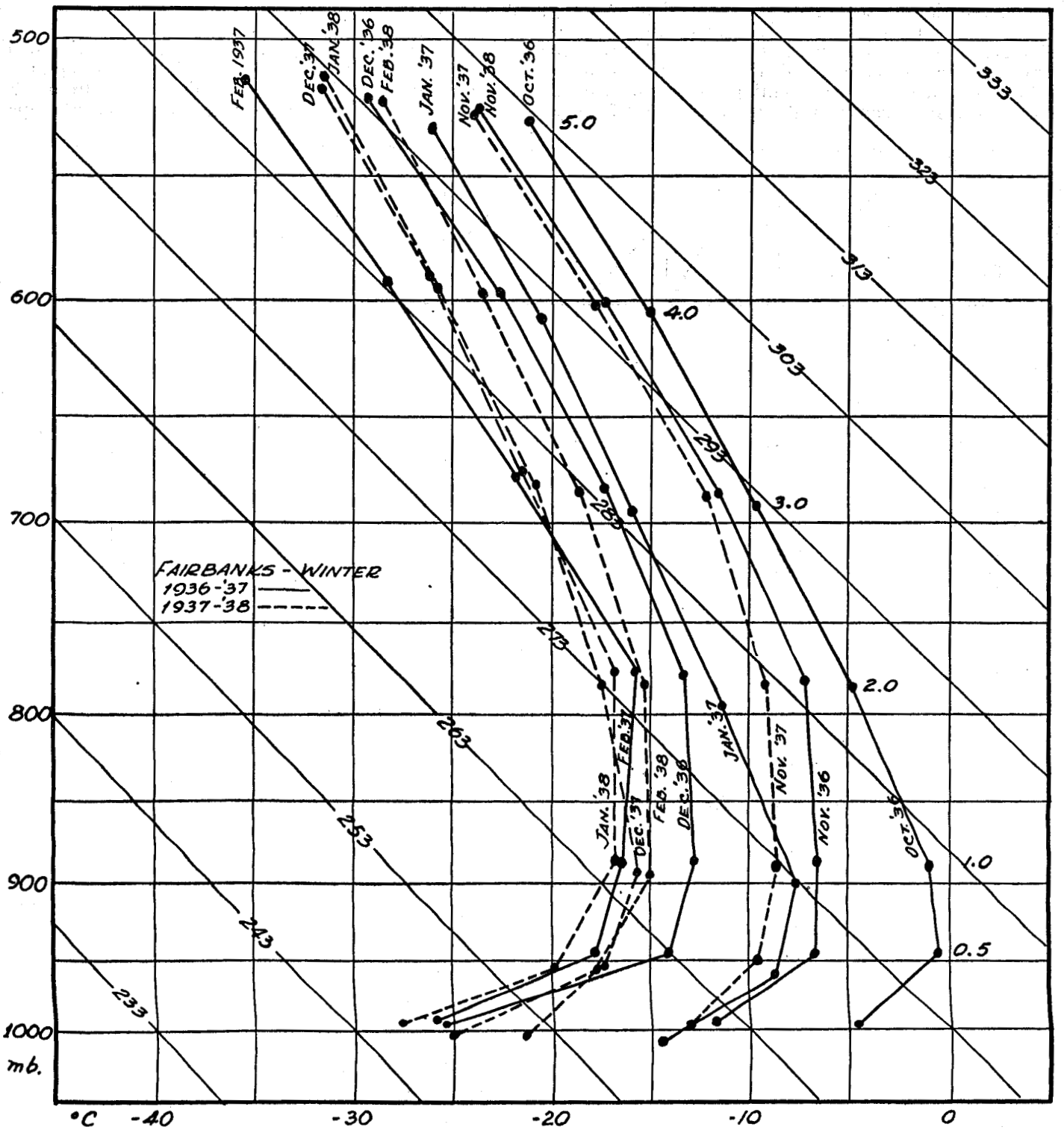

FIGURE 3.—Monthly mean free-air temperatures at Fairbanks.

February 1937 are given. It will be noted that there is a considerable variation in the monthly mean temperatures between the various months. At Fairbanks the month of January 1937 stands out as being especially warm. This month was unusual in many respects throughout most of North America, characterized by flood rains in the Ohio Valley, record winter warmth on the Atlantic coast and in Alaska and record low temperatures in California.

The monthly mean temperature curves, even though representing in some cases a large number of flights in non-Arctic air masses, all types of weather conditions, cloudiness and wind, still show the marks of the principal process that has acted upon the lower atmosphere, namely, terrestrial and atmospheric radiation. The temperature inversion next to the ground is there, although not so well marked as in the ideal case because there are many situations included where high surface winds tended to destroy it. The nearly isothermal layer of the ideal case is suggested, but it is smoothed out due to (1) the variety of heights at which it prevails in individual cases and (2) therefore also the varied lapse rates at a given level near

the upper or lower part of its mean position. Finally, the region of moderate lapse rate lying above the extremely stable layers is apparent in the curves. In ~~figure 5~~ the average vertical temperature distribution during January 1940 at Juneau, Alaska, representing the character of the air that enters the continental Arctic air-mass "factory" is plotted with the January 1937, 1938, and 1940 data of Fairbanks, the January 1937 data of Fort Smith and five Januarys at Fargo, N. Dak. The similarity of the continental and Juneau curves at high levels shows that the creation of continental Arctic air operates from below. However, the upper air at Juneau shows higher tempera-

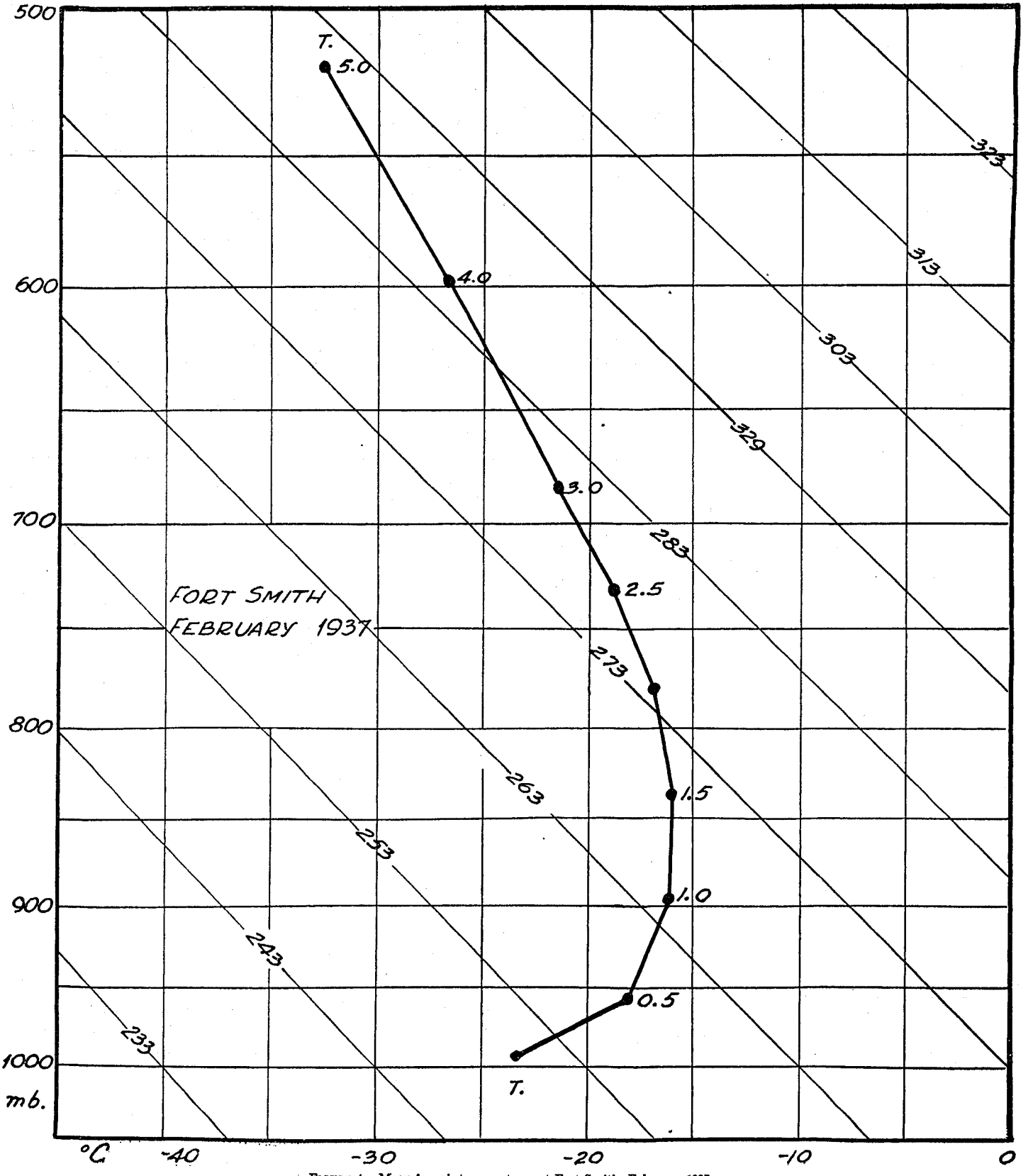

FIGURE 4.—Mean free-air temperatures at Fort Smith, February 1937.

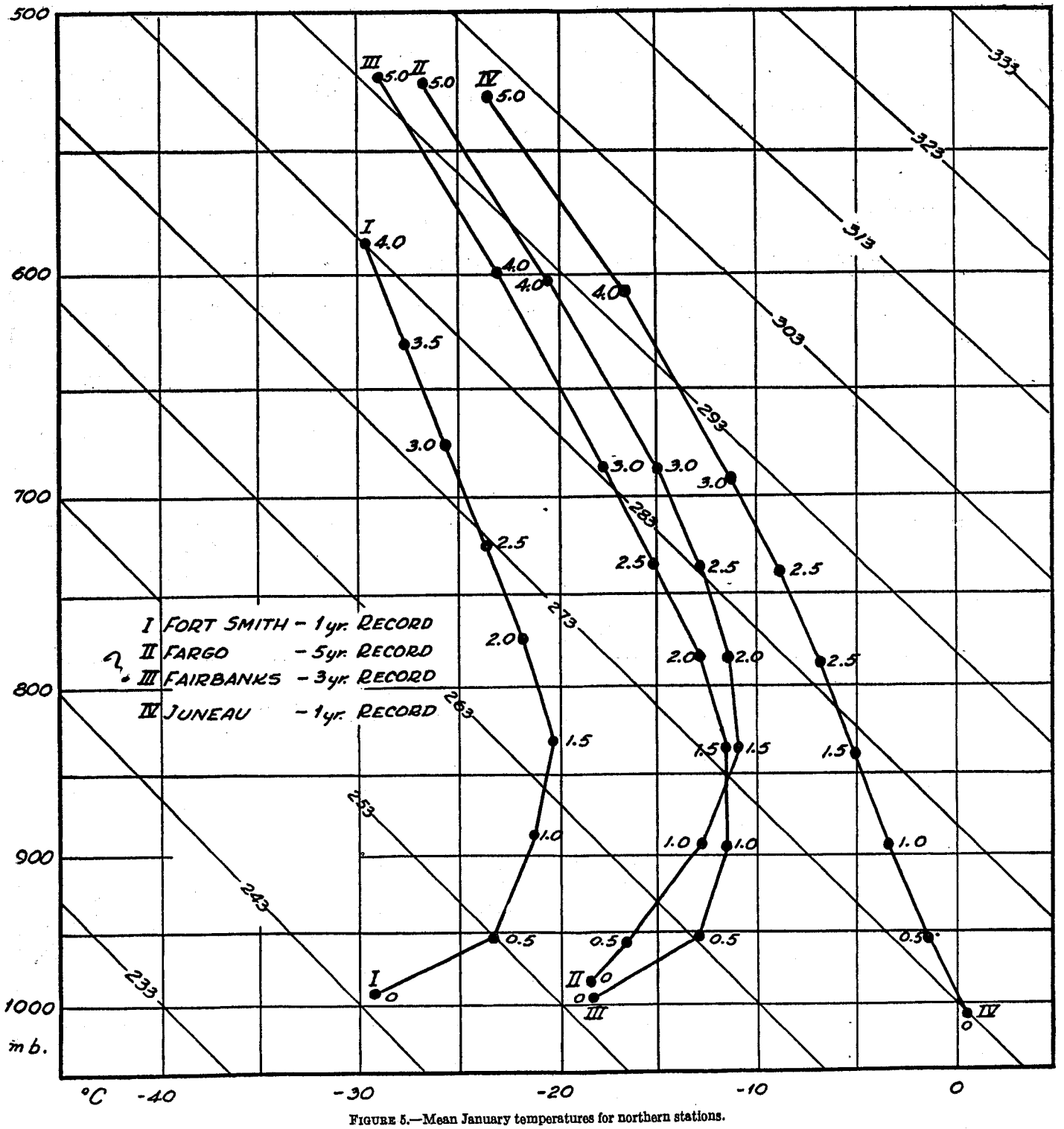

FIGURE 5.—Mean January temperatures for northern stations.

tures that at any of the continental stations. This probably means that, included in the air brought over the continent during the month, are currents not having a trajectory over the Gulf of Alaska, but coming directly from Siberia, the Arctic Sea ice, or the vicinity of Greenland. At Forth Smith the lower high-level temperatures are particularly noticeable. The curves indicate that Wexler's original simplified picture of the manufacture of maritime polar air into continental Arctic needs some modification. However, it should be pointed out that the one January of record at Juneau might have been abnormally warm or at Fort Smith unusually cold.

It is not immediately clear from theoretical reasoning as to exactly how the extreme cold at such a station as Fort Smith is achieved, but it is probably reasonable to suppose that after a long Arctic sojourn, cooling of the air even at high levels without a direct connection with ground radiation or surface cooling may be accomplished.

Other high-latitude continental regions of the earth show even more greatly reduced temperatures in the upper troposphere. In four soundings at McMurdo Sound in Antarctica, the extremely low temperatures noted in figure 6 were found. The four flights may not represent typical winter conditions, however. The Fort Smith

soundings compare closely with those of Spitzbergen and Kiruna (Lapland) (fig. 7), except that the inversion at these two stations is less pronounced as a result of recent heating from below over ice-free seas. A striking fact brought out in figure 5 is that at Fargo, N. Dak., the temperatures are about the same as at Fairbanks, in spite of more than 15° difference in latitude. Continentality is much more of a factor than latitude in determining temperatures in these latitudes in winter.

The soundings in figure 6 are presented here merely for comparison purposes. The Amundsen Expedition flights (curve II) were taken in the Arctic Sea near the North Siberian shelf (76° N., 155–175° E.). They show temperatures generally about 5° C. lower than those of the February mean at Fort Smith. The Weddell Sea ascents, at 69° S., near the Antarctic continent (curve III) represent conditions only slightly colder than at Fort Smith. The four flights at McMurdo Sound (77.6° S.,

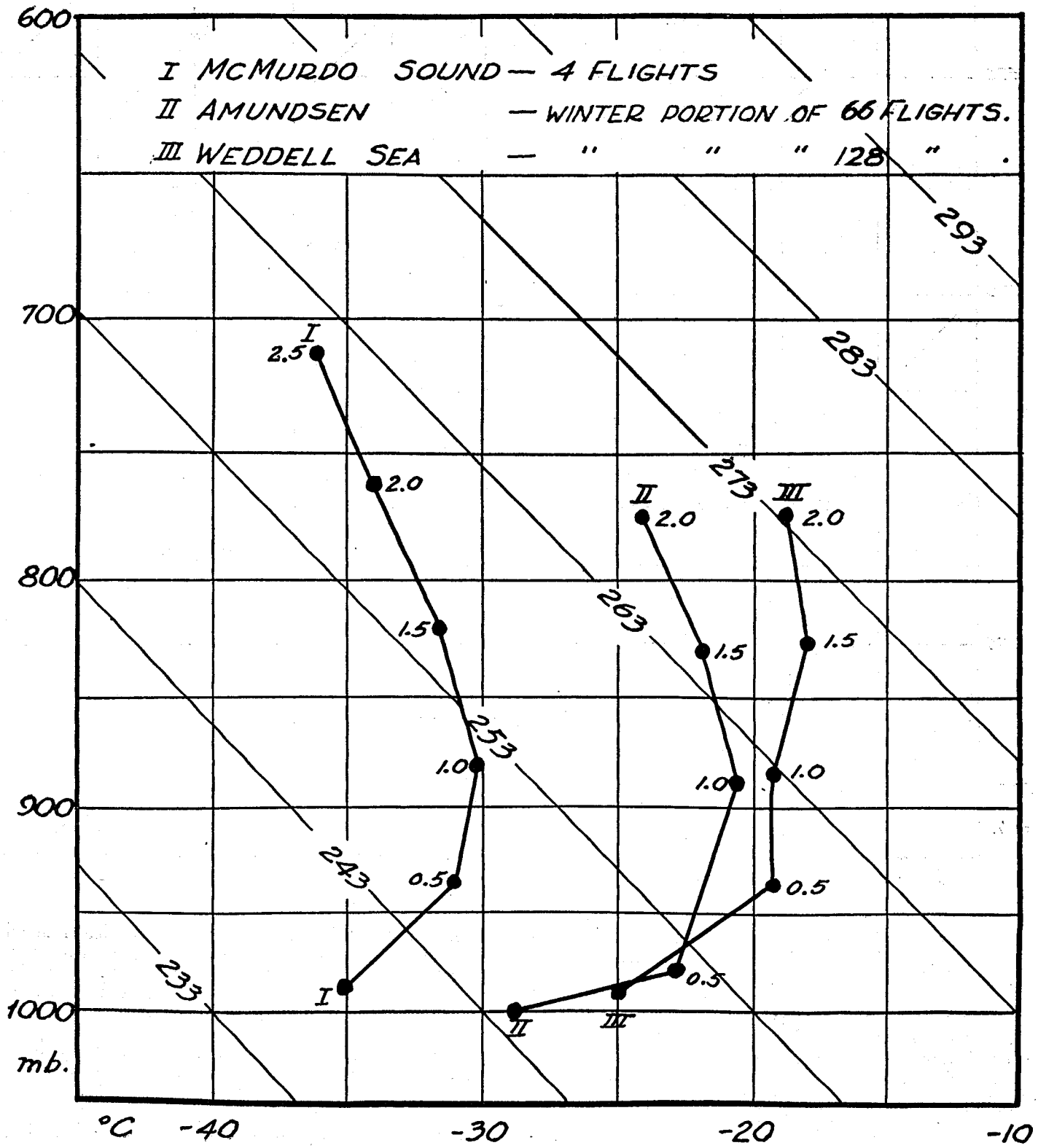

FIGURE 6.—Vertical temperature distribution at polar stations in winter.

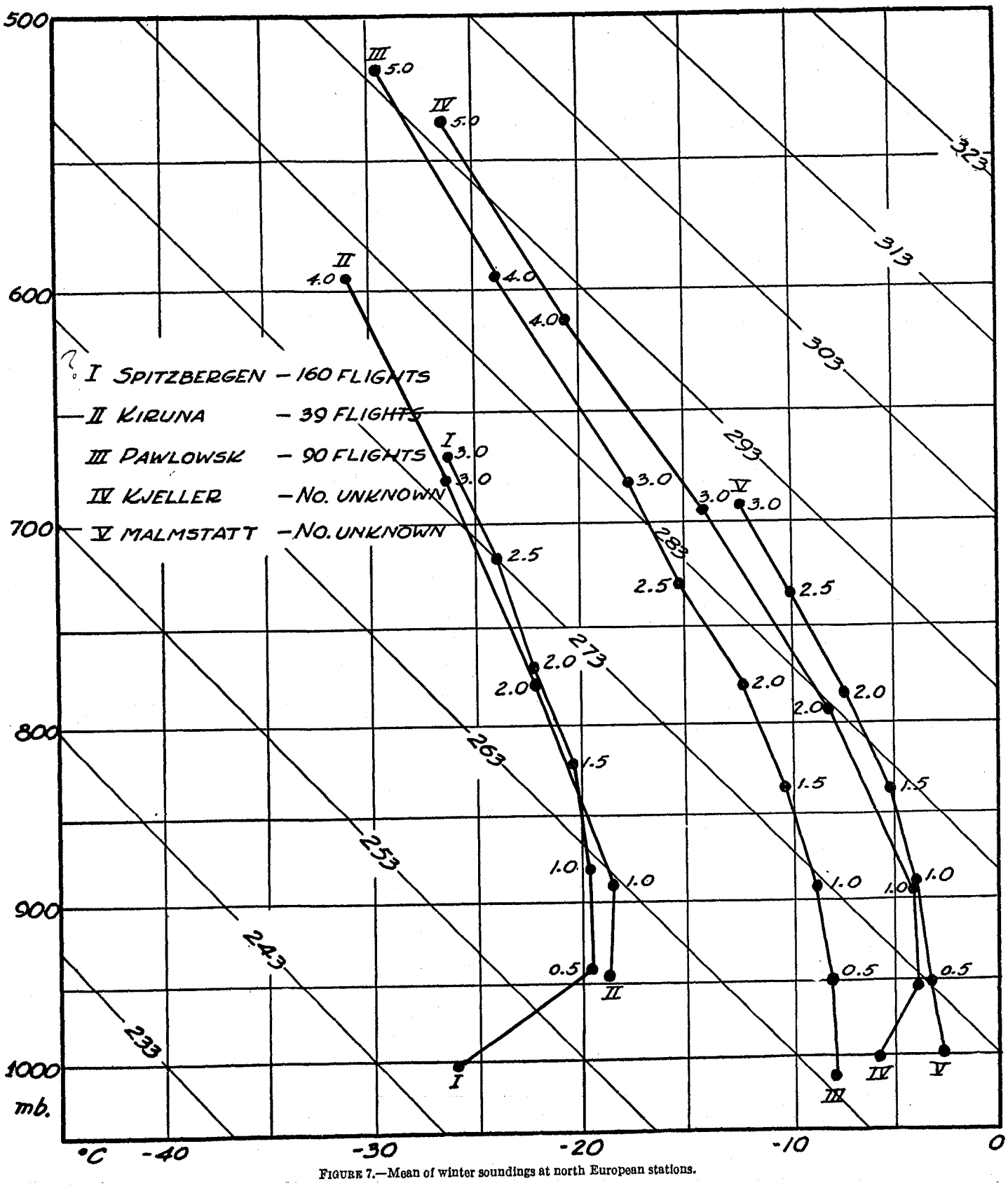

FIGURE 7.—Mean of winter soundings at north European stations.

166.5° E.) (curve I) probably represent extreme rather than average conditions. At Spitzbergen and Kiruna (67°50′ N., 20°15′ E.) (fig. 7) the temperatures also are similar to those at Fort Smith, except that at Kiruna the pronounced stability near the ground is not present. Pawlowsk (39°41′ N., 30°26′ E.), Kjeller (59°58′ N., 11°2′ E.) and Malmstatt (58°25′ N., 15° 32′ E.) do not show the effects of continentality to the extent of the North American interior stations, even those at rather low latitudes; however, stability up to 2 km. is apparent.

In figure 8 typical western European data are shown, including Munich, Lindenberg (near Berlin), Breedene à

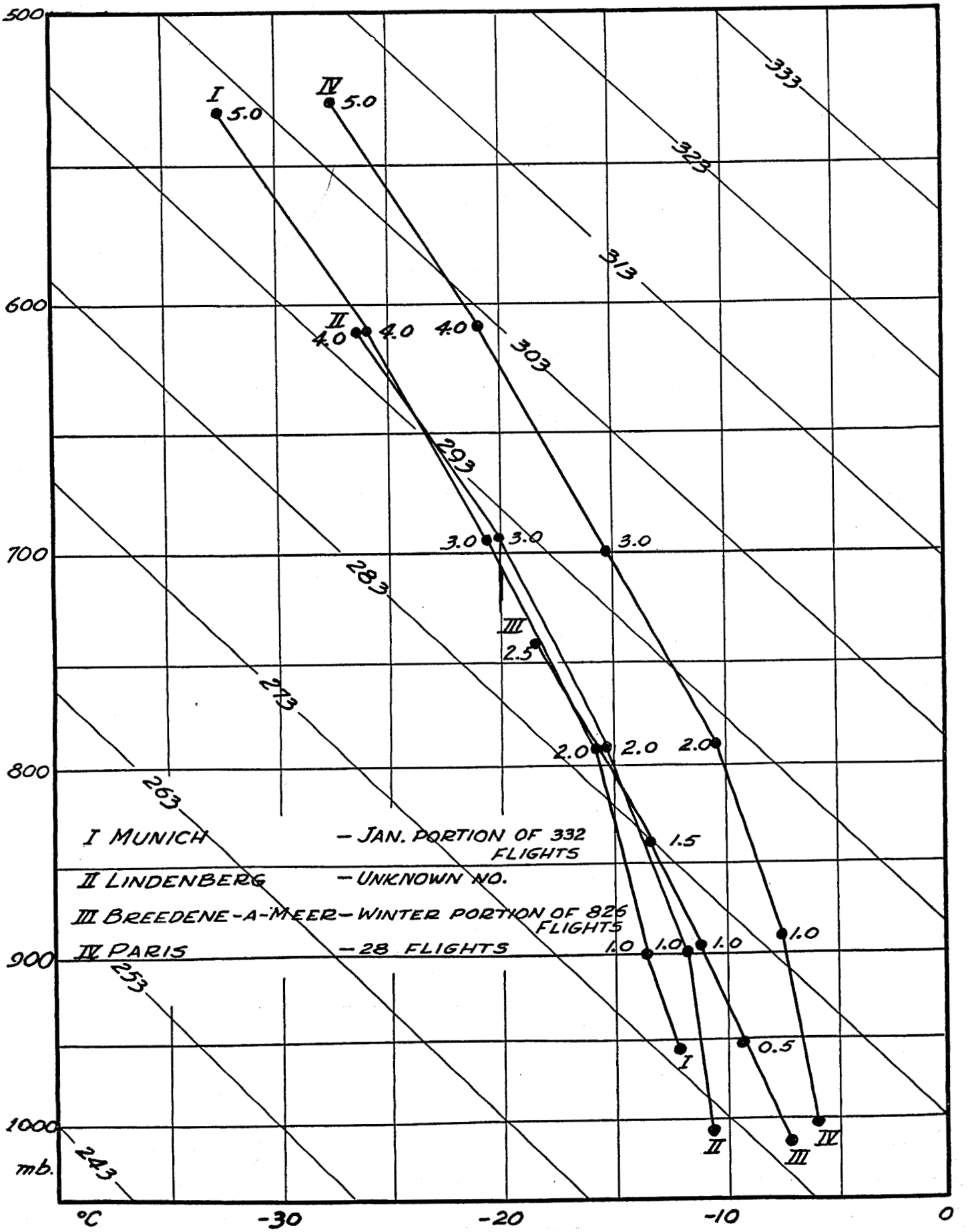

FIGURE 8.—Mean winter soundings in western Europe.

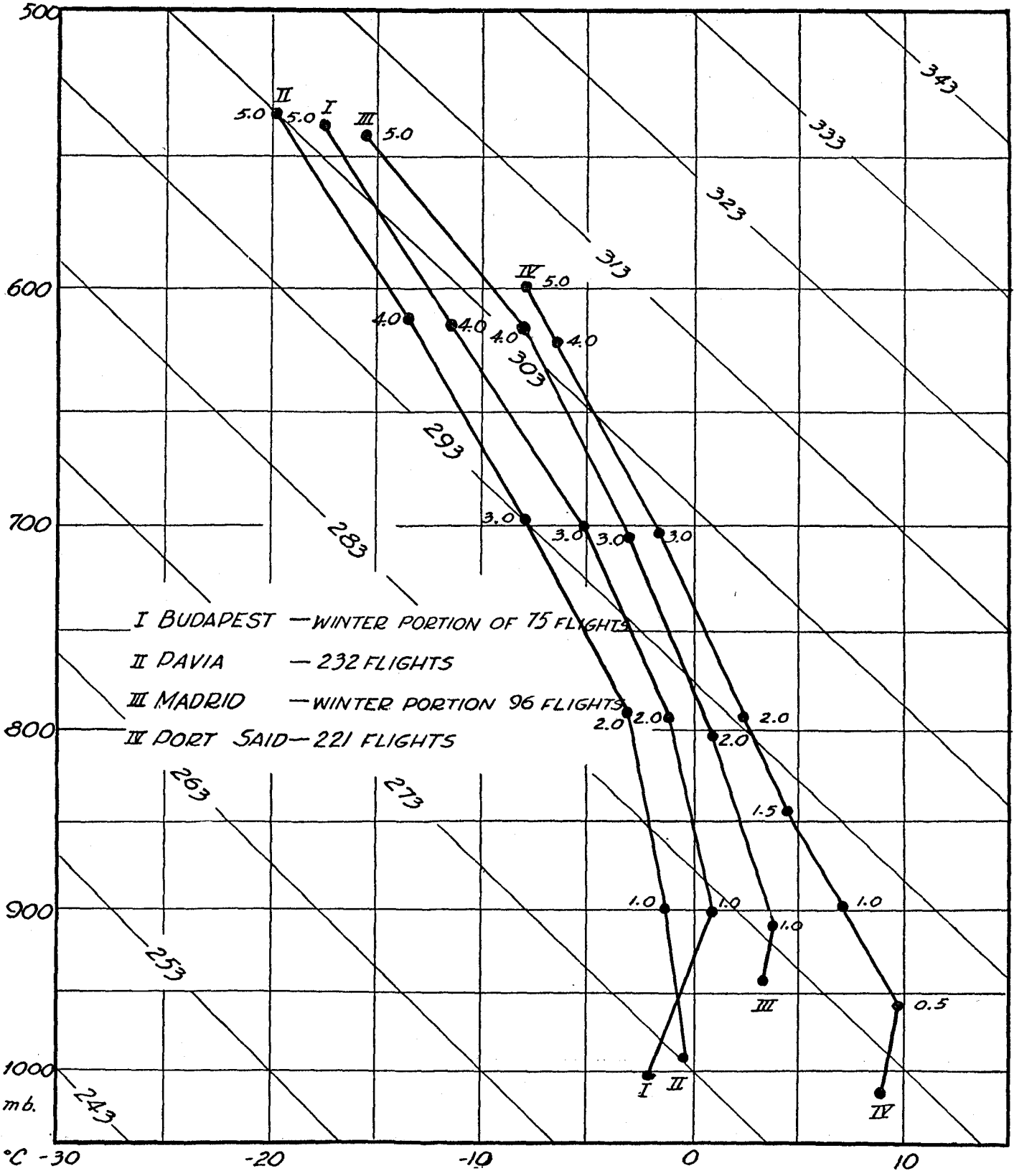

FIGURE 9.—Mean of winter soundings in southern European and Mediterranean stations.

Meer in Belgium, and Paris. Only slight stability appears in the low layers, but it is definitely present. European stations of more southerly latitudes are represented in figure 9. These stations show even greater stability in the low levels than is the case at the stations farther north, such as Paris and Lindenberg. At Budapest, the typical continental characteristics are beginning to appear. Even at Port Said, the stability is pronounced, although the time of day of the flights may enter into the result to a considerable extent.

Northeastern continental conditions are represented by the curves in figure 10. The domination of cyclonic

activity presumably accounts for the fact that these lapse rates are less stable than at such stations as Fargo (fig. 5) and Omaha (fig. 11) which are in about the same latitudes as Sault Ste. Marie and Boston, respectively. The curve for Peiping, China, results from a few soundings specifically selected as representative of a fresh continental-Arctic air outbreak, with strong winds. The records at Sault Ste. Marie and Boston include many similar flights. It is worthy of note that at these stations in the eastern parts of the continents, while the temperatures below 2 km. are higher than at the mid-continental stations, they are about the same or slightly

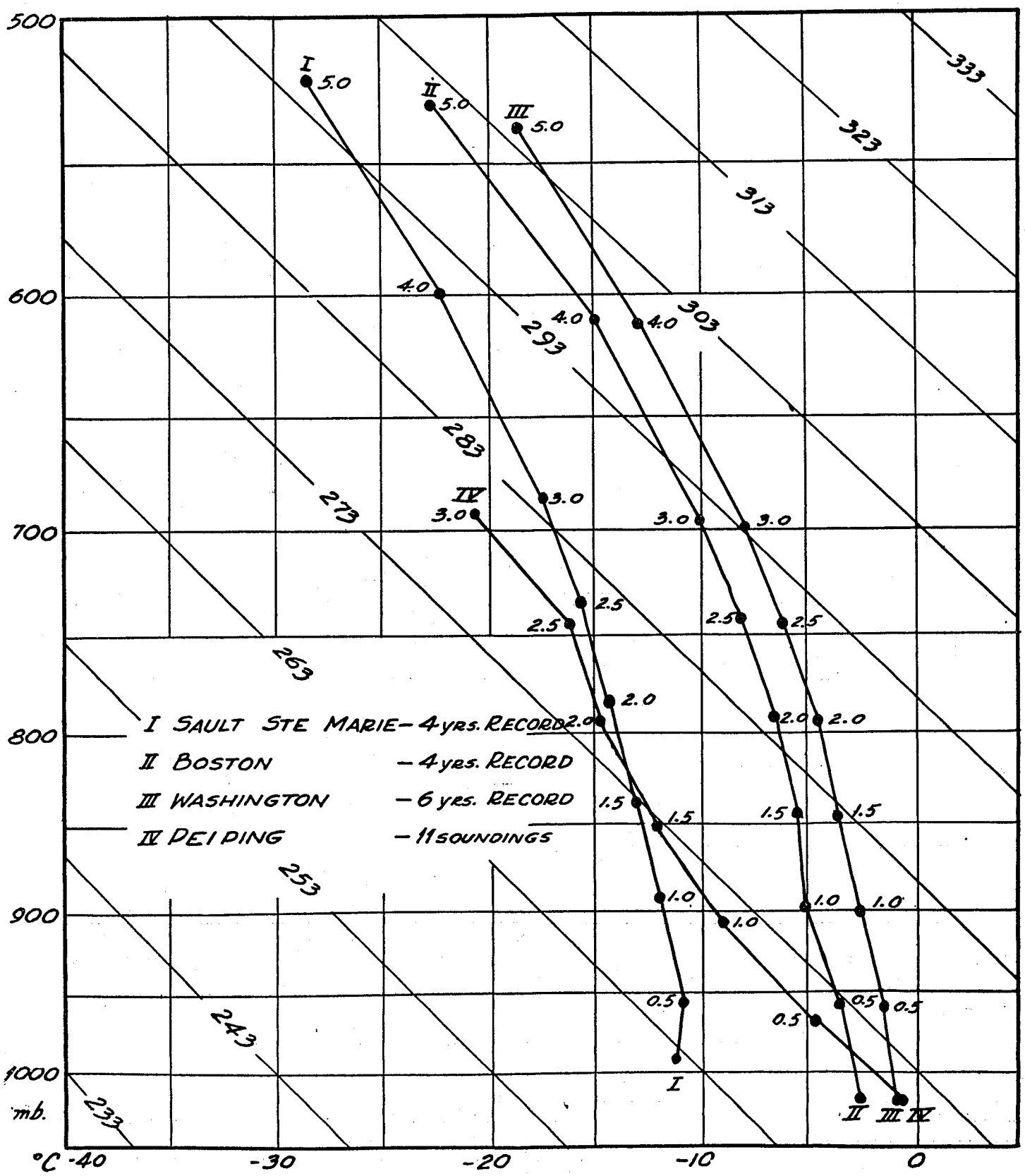

FIGURE 10.—Winter soundings at northeastern continental stations.

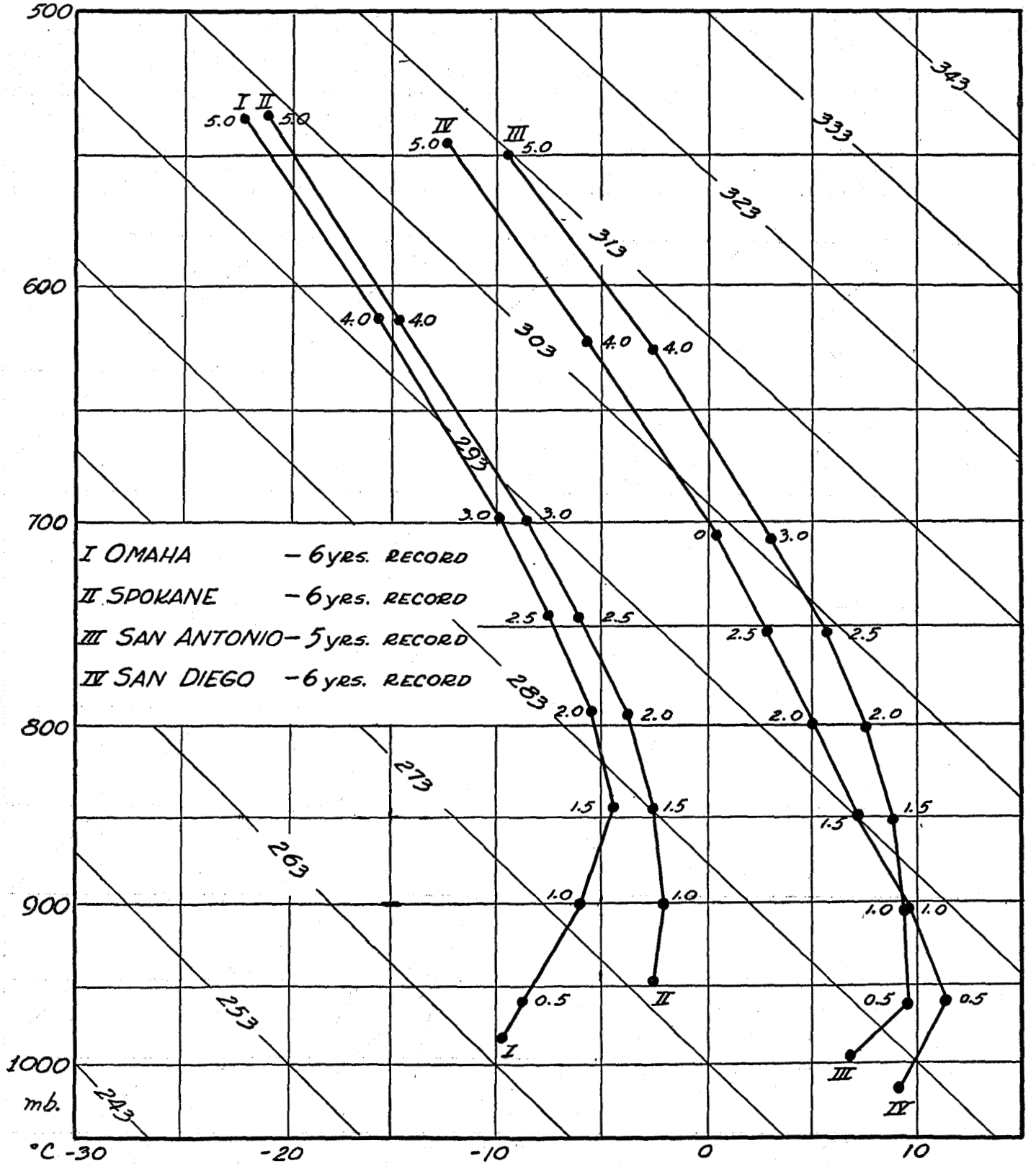

FIGURE 11.—Mean free-air temperatures at selected United States stations in January.

lower above that height. For example, at 3 km. at Fargo the mean January temperature is −15° C., at Sault Ste. Marie, −17° C.; at Omaha it is −10° C., which is the same as at Boston. Another striking fact is that at San Antonio, in spite of the subtropical latitude, pronounced continental stability is shown. This stability is greater than at the southern European and Levantine stations shown in figure 9. Although San Antonio has lower temperatures near the ground than Port Said, at 3 km. it has a temperature 5° C. higher, which is comparable to the temperature at that height over Agra (fig. 13).

The normal curves for three southeastern United States stations and Coco Solo, C. Z., are entered in figure 12.

Nashville, above 2 km. exhibits about the same temperature distribution as Madrid (fig. 9) but below that level the temperatures and lapse rates are less, in response to the effects of continental cooling. At Pensacola are noted conditions similar to those at San Antonio, except that the continental effect is less pronounced. As we go toward Miami, located on a peninsula reaching out into warm seas, the effects of the continent are disappearing and nearly tropical conditions prevail, comparable to those of Pearl Harbor, T. H., and Manila (fig. 13). At Coco Solo, real tropical temperatures are found, comparable to those at Batavia (fig. 13). The lower temperatures at high levels at Batavia as compared with Coco Solo may be a result of the small, perhaps unrepresentative number of observations at Batavia. The soundings were made during May, June, and July. The Manila flights show higher temperatures aloft, which are in close agreement with those of Coco Solo. Tropical continental conditions are represented by the soundings at Agra where, apparently due to the protection from continental

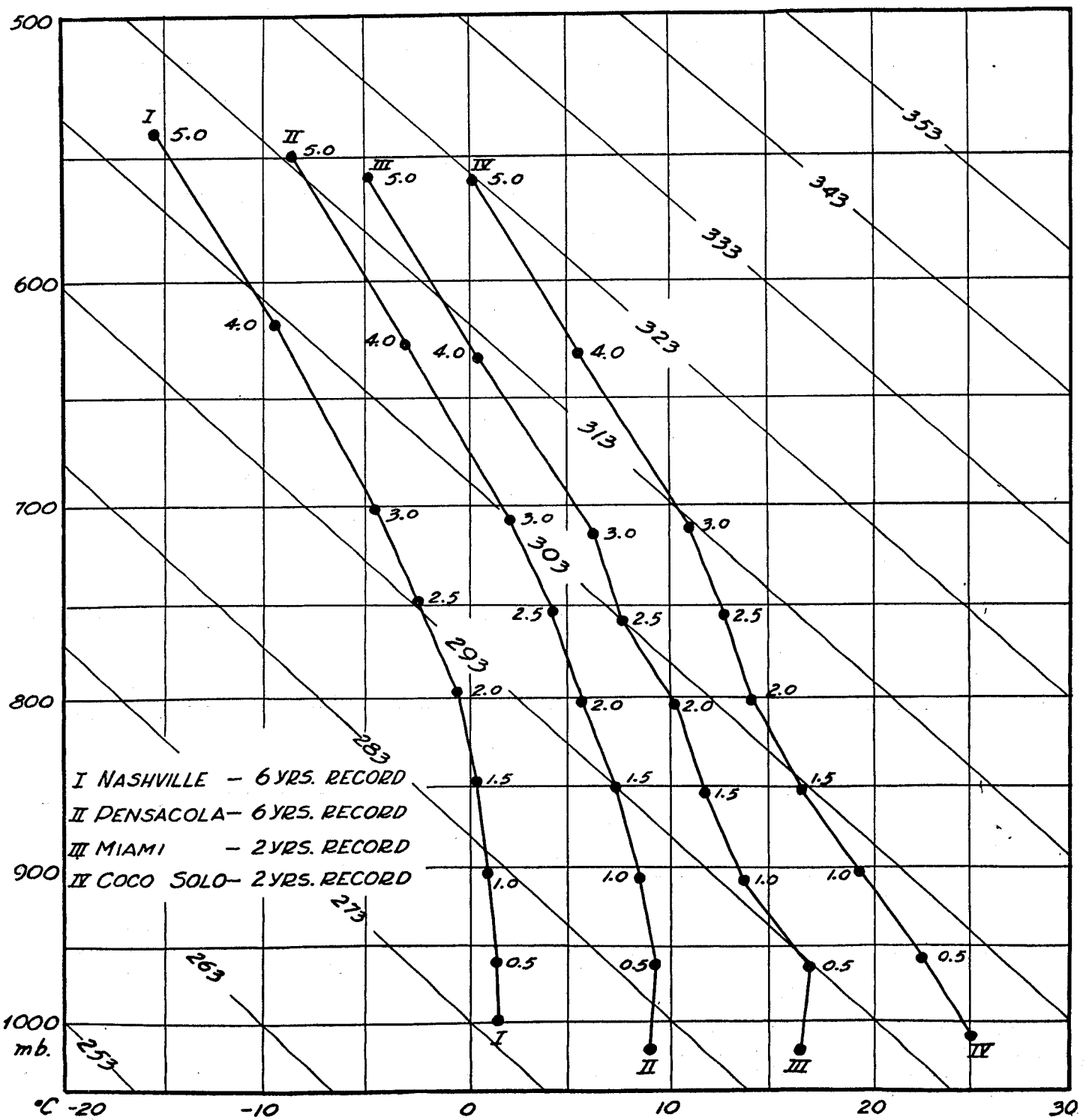

FIGURE 12.—Mean free-air temperatures in January at low latitude American stations.

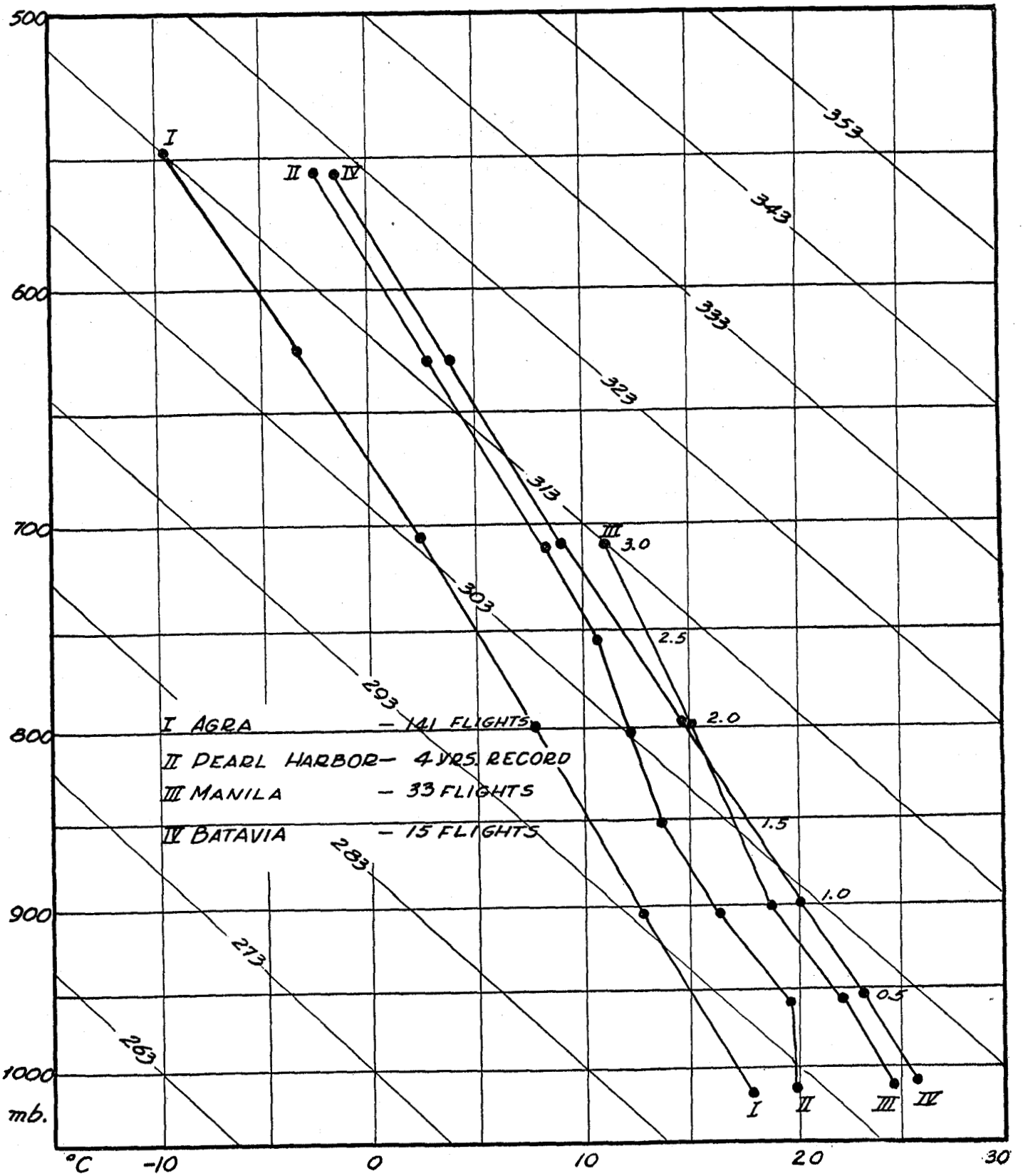

FIGURE 13.—Mean of winter soundings at tropical stations.

coldness afforded by the Himalayas, the temperatures in the low levels are considerably higher than at Pensacola, its American counterpart.

JANUARY UPPER-AIR PRESSURES

The findings concerning the average temperatures and vertical temperature lapse rates over the northern continental regions in winter suggest a revision of the picture meteorologists have had of the normal pressure distribution at upper levels in the atmosphere at this season. The problem of drawing charts showing the normal upper-air isobars has been treated by several meteorologists, notably by Teisserenc de Bort and by Sir Napier Shaw. The general line of attack used by these investigators

has been to arrive at the desired pressures by assuming a probable mean temperature lapse rate, uniform for the entire globe, and applying hypsometric formulae, starting with the known mean values of pressure and temperature at the surface. For example, Shaw's charts were based on the assumption of a mean lapse rate of 5.0° C. per km. up to 2 km. and 5.5° C. per km. from 2 to 4 km. The charts obtained in this way have formed the basis of meteorologists' ideas of the circulation at these upper levels and they have been copied and used quite generally.[5] Over oceanic areas, and also over land surfaces during the warm seasons, this method can probably be improved upon but little, except for the substitution of data obtained from actual soundings where such information has become available recently. It is well known, however, as Shaw has pointed out, that during the winter over continental areas, especially in the polar regions and higher middle latitudes, large inversions of temperature are usually found immediately above the surface, making it difficult to apply this method.

Wexler[6] has shown that there exists a maximum value for these inversions which may be found under favorable conditions, determined by the nature of the radiative balance between the surface and the air above. If these theoretical inversions were often realized, this fact would furnish a clue to the distribution of temperature aloft, since according to Wexler's theory the size of the in-

[5] See, e. g., Shaw, Manual of Meteorology, vol. 2, 1936; Bjerknes, et. al., Physikalische Hydrodynamik, pp. 637–640, 1933 (July charts only used).

[6] *Op. cit.* in footnote [3](z).

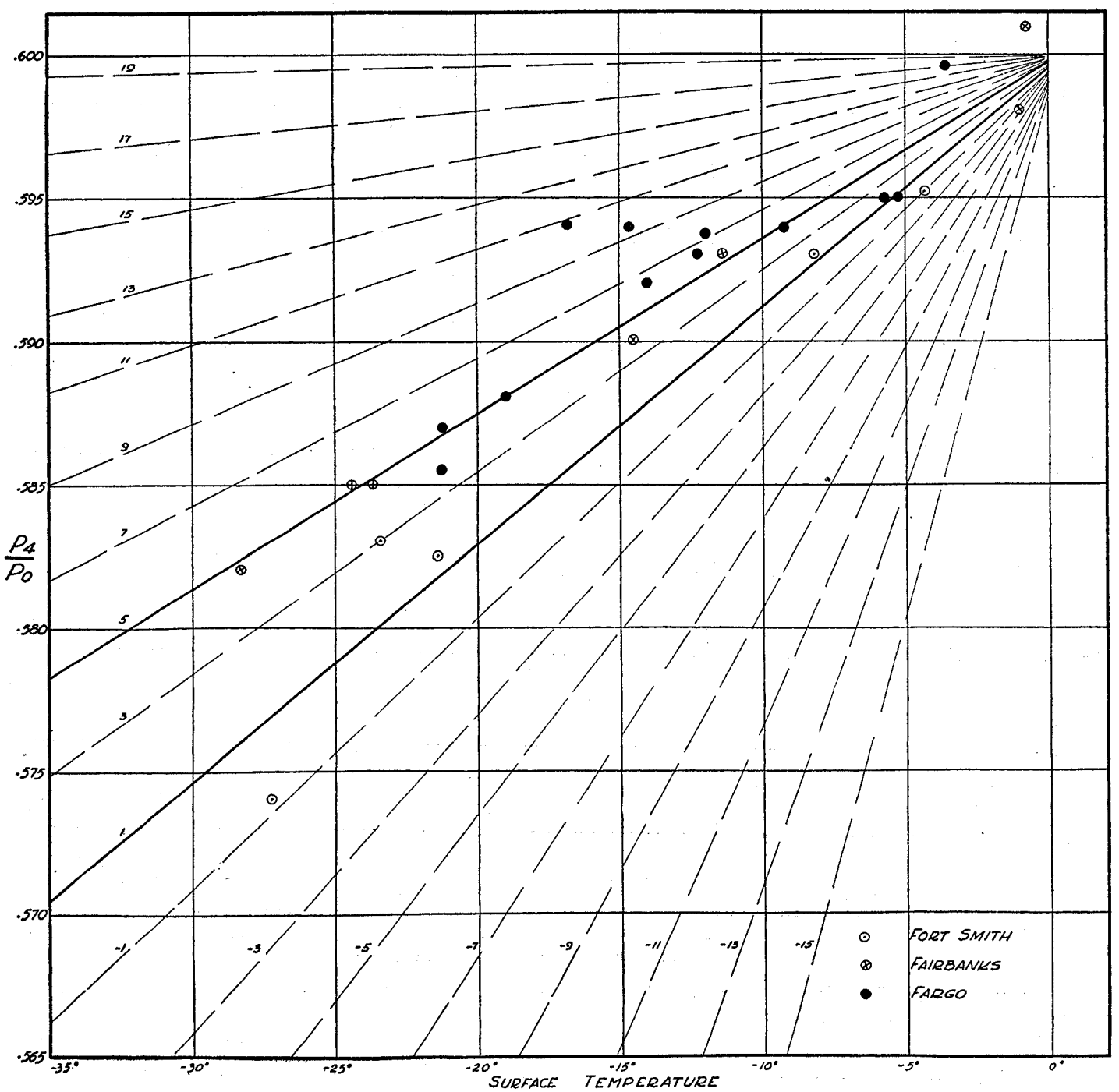

FIGURE 14.—Diagram for obtaining pressure at 4 km.

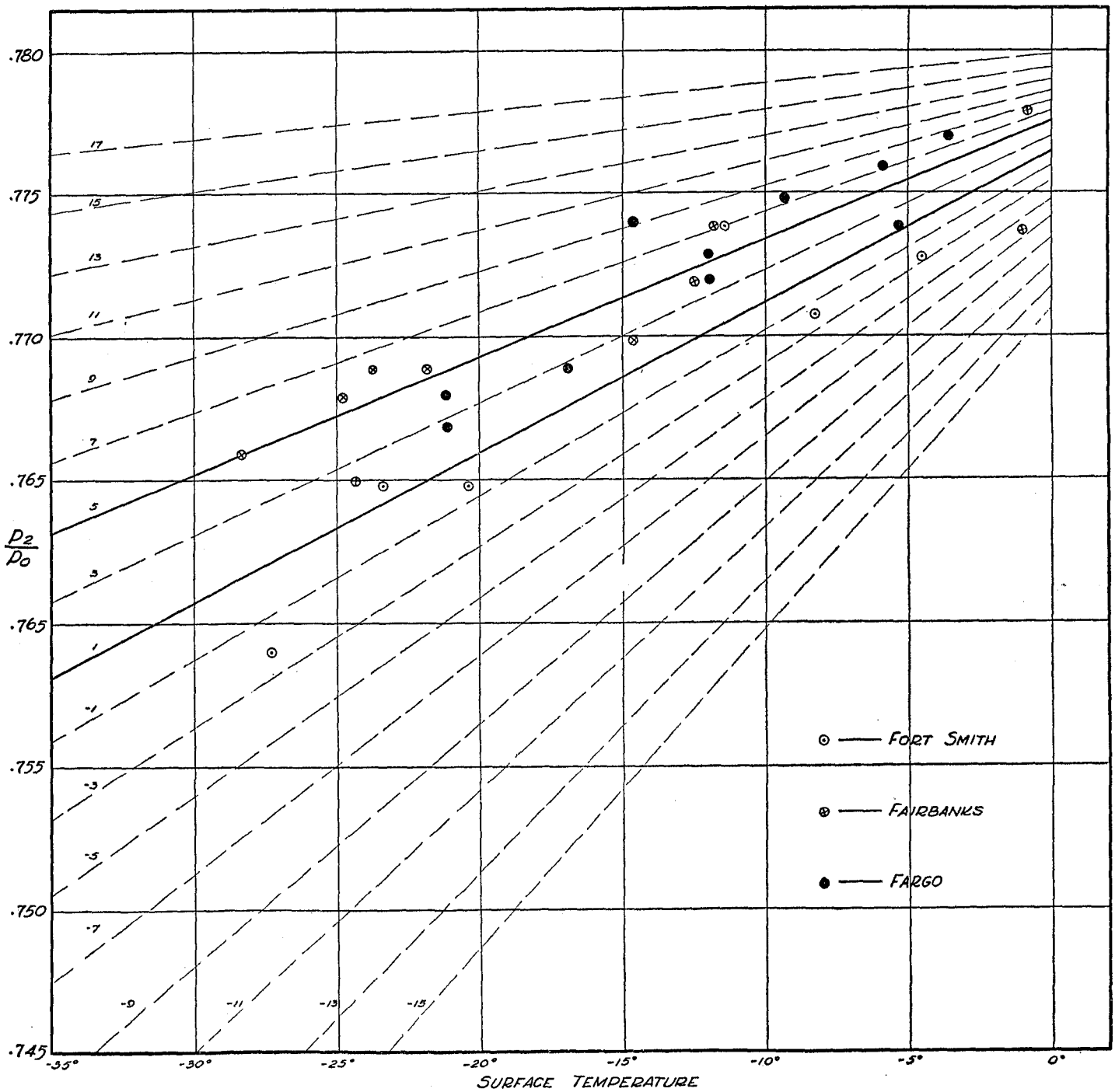

FIGURE 15.—Diagram for obtaining pressure at 2 km.

version is uniquely fixed by the surface temperature alone. Unfortunately, an examination of the mean curves of temperature distribution at Fairbanks and Fort Smith shows that this is not the case. The discrepancy is probably brought about by the partial destruction of the theoretical inversions by wind action, so that no rational approach to the problem appears to be at hand.

It seems, nevertheless, logical to suppose that the data obtained from the soundings at Fairbanks and Fort Smith should lead to some empirical approach to the problem of computing the value of pressure at upper levels in other similar regions during the winter months Such an endeavor is made below, although in order to base the method on a larger amount of data use is also made of soundings taken at Fargo, N. Dak. The general plan is to formulate a scheme for computing the upper level pressures from these three sets of soundings, and then to check the computed results with observed figures for several additional stations in the United States and northern Europe and Asia before applying the method to other regions.

In studying the monthly mean pressures at 4 kilometers at Fairbanks, it was found that there exists an approximately linear relation between the ratio of these pressures to the sea-level pressures and the climatological mean surface temperatures for individual months; that is, if p_4 indicates the pressure at 4 km., and p_0 the pressure at sea level, then the quantity $\frac{p_4}{p_0}$ when plotted against the mean surface temperature for various months as in figure

14 produces a scattering of points which range themselves roughly along a straight line. Here the data for Fairbanks are represented by the symbol ⊕ and the upper of the two solid slanting lines is taken as a mean curve. The months used are October to March, inclusive.

The same system of plotting the data in the case of Fort Smith produces a scattering of points as shown by the symbols ⊙ in the diagram. The lower of the two solid lines is taken as a mean curve of these points. Also, in plotting points for Fargo, the distribution is given by the symbols ●. Discounting to some extent the two months having abnormally high values of $\frac{p_4}{p_0}$, one might then represent the data at Fargo approximately by the same line as for Fairbanks.

In order to use these data as a basis for determining pressures aloft from surface conditions, it is next necessary to devise some objective criterion for determining how the upper level pressure characteristics of a given station compare with the above. It is clear that whatever means for doing this is adopted, surface data alone can be used for the purpose. In performing this step, it is assumed that conditions at any particular station can be represented by one of the dash lines similar to the two solid lines already referred to, converging to the same point, as illustrated in the diagram. Each line is now assigned

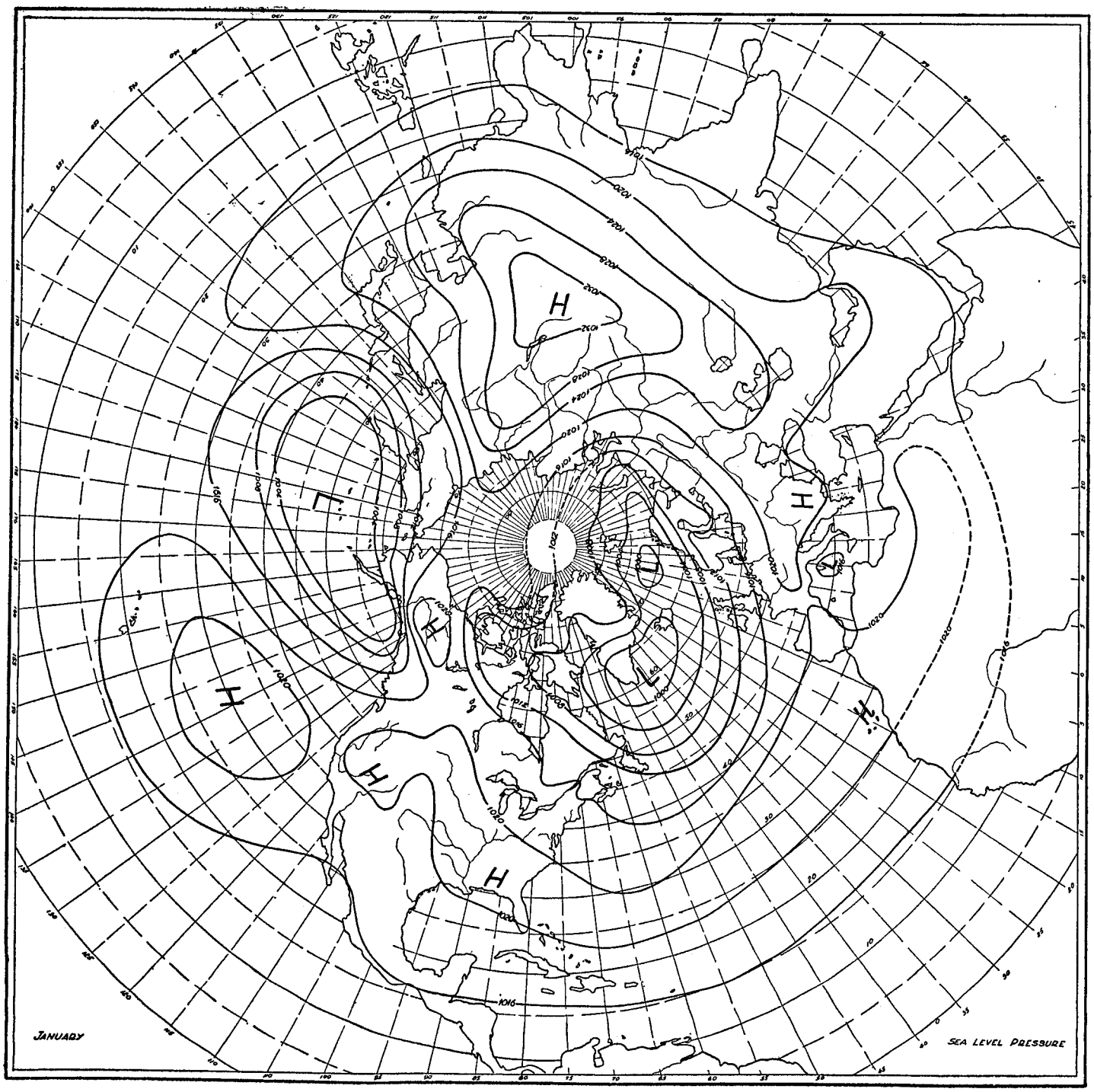

FIGURE 16.—Normal January sea-level pressure in northern hemisphere taken from Shaw's Manual of Meteorology, vol. II, and the Köppen-Geiger Handbuch der Klimatologie.

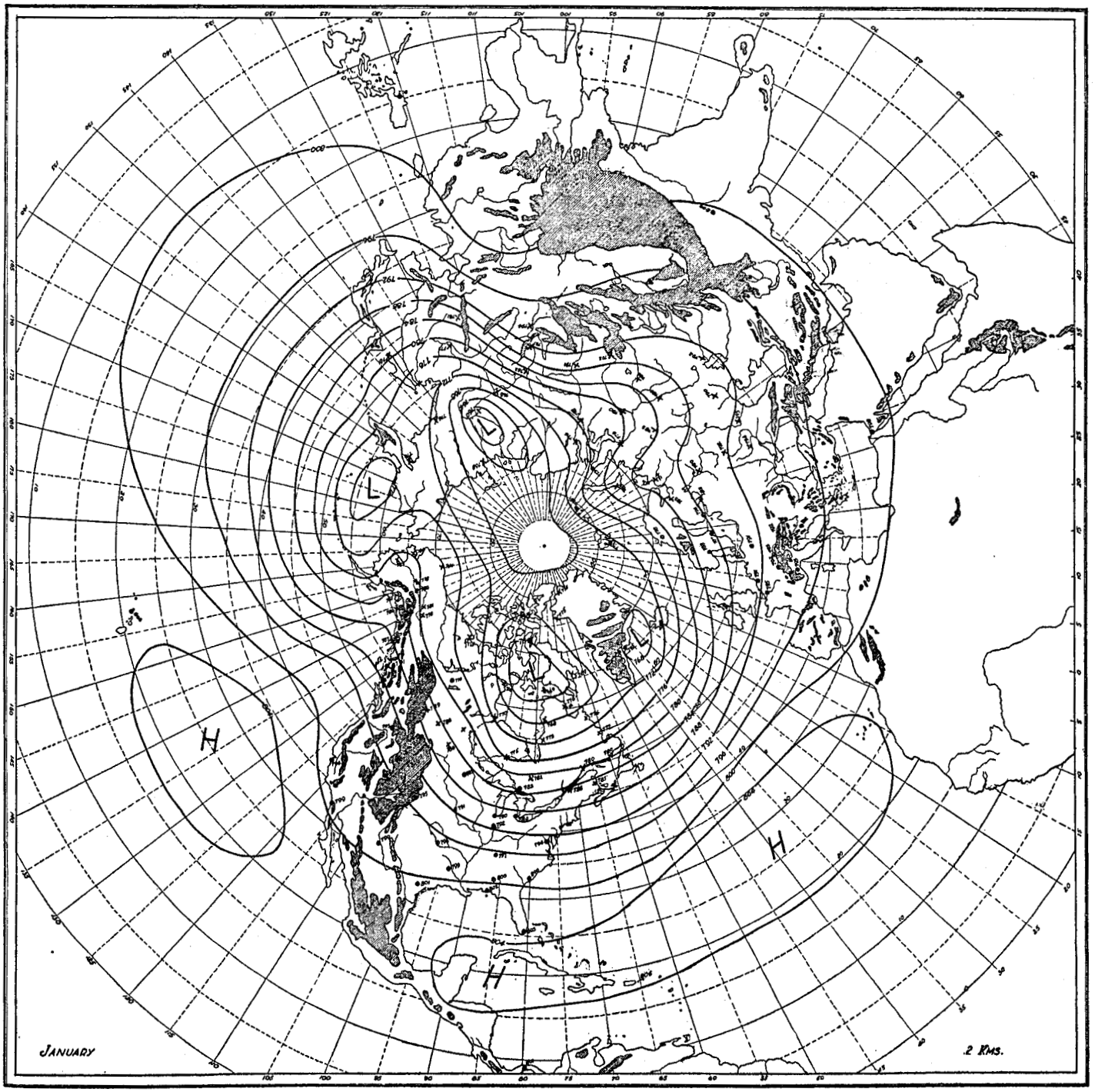

FIGURE 17.—Normal January pressure at 2 km.

an "index number" based on the arbitrary assumption that the value of this quantity is five at Fairbanks and Fargo, and one at Fort Smith. These index numbers are shown in the figure at the left.

The determination of the index values from surface data is accomplished as follows: It is assumed that the index is determined jointly by the mean monthly temperature at the surface, the mean monthly sea-level pressure, and the latitude. In the absence of any rational theory, it is then assumed that variation of the index is linear with respect to each of these items, so that it may be said that the index I can be represented by the equation,

$$I=A_1\ T+A_2\ P_0+A_3\ L, \qquad (1)$$

in which T is the temperature in degrees C., P_0 is the sea-level pressure in mb., L is the latitude in degrees, and A_1, A_2, A_3 are arbitrary constants. If now the appropriate data for each of the three above stations be substituted into (1) it is possible to determine the values of A_1, A_2 and A_3. When this is done (1) can be rewritten as

$$I=0.794\ T-0.0157\ P_0+0.628\ L \qquad (2)$$

From these values of the constants it is seen that the contribution of the variations of the sea-level pressure to the variation of the index is only slight, but it will be retained for the sake of completeness.

In view of the fact that the scheme outlined above is purely empirical, it must be used with caution, and preferably be checked first insofar as is possible for stations for which upper-level pressure observations are available.

Such a comparison of computed and observed pressure values is given in the table below, which is based on data for the month of January. However, some of the observational data used for verification include observations taken during other winter months, but in each case the pressures at upper levels are based on mean sea-level pressures for January as a starting point. The table includes also a comparison of actual pressures at 2 km. with computed data. The calculation of the pressures at this level was carried out in the same general manner as for 4 km., using the same index numbers. The graph of $\frac{p_2}{p_0}$ against T is shown in figure 15.

Since the method has been based on data from inland stations where large inversions of temperature are apt to exist, it should not be expected that it will give very good results in oceanic regions where steep lapse rates are found. The lack of agreement between calculated and observed figures at Boston, Helsinki, and Oslo may be due to this cause. At Sault Ste. Marie a similar condition may be attributed to the presence of the Great Lakes. The discrepancy at Malmstatt, Sweden, however, cannot readily be explained.

TABLE 1

Station	L	T	P_0	I	Observed P_2	Calculated P_2	Observed P_4	Calculated P_4	Number of flights and remarks
Boston	43	−24	1,018	9.1	788	791	606	611	170 winter airplane flights.
Helsinki	60	−6	1,012	17.2	794	790	----	609	366 winter kite ascents to 2 km., no surface inversion.
Joliet [1]	42	−11	1,020	−.9	786	785	603	600	31 radiosonde flights January 1940.
Lindenberg	52	0	1,017	16.4	791	792	608	609	44 January soundings over long period, kind unknown.
Malmstatt	58	−1	1,015	19.8	787	792	604	609	Winter kite ascents, number unknown.
Minneapolis [1]	45	−15	1,024	.6	787	788	602	601	31 radiosonde flights January 1940 (cold winter).
Omaha	41	−6	1,021	5.2	791	792	610	609	178 January airplane and radiosonde flights.
Oslo	60	−4	1,016	18.3	788	792	604	609	80 January airplane flights.
St. Louis [1]	39	−10	1,024	.3	790	790	607	606	31 radiosonde flights January 1940 (cold winter).
Sault Ste. Marie	47	−10	1,017	5.3	783	786	599	604	116 January airplane and radiosonde flights.
Spokane	48	−2	1,020	12.5	793	793	612	611	148 January airplane and radiosonde flights.
Strasburg	48	0	1,020	13.9	793	795	611	612	Series of kite flights for January, number unknown.
Dickson, northern Siberia.	73	−28	1,013	7.6	773	766	588	586	Not more than 7 winter radiosonde flights.

[1] The observed data for sea-level and upper-level pressures and temperatures represent conditions for only 1 month and cannot therefore be considered as representing normal conditions.

In view of the fact that the results for the remaining eight stations are fairly satisfactory, considering the number of observations available, use is made of the method as an aid in the drawing of normal upper-level pressure maps for the Northern Hemisphere. The maps constructed are for the 2 and 4 km. levels for the month of January. Since the drawing of upper-level pressure maps involves the use of sea-level data as a starting point a chart of the normal sea-level pressure for January in the Northern Hemisphere is also included in figure 16. In the main, this is a reproduction of the sea-level map given by Shaw for the month of January, except in certain regions where slight departures exist. In northern Asia the pressures were obtained from surface data published in the *Handbuch der Klimatologie* by W. Köppen and R. Geiger. The sea-level reductions were made on the basis of an assumed mean temperature equal to the normal surface temperature published in the same source. Over Europe the configuration of the isobars is the result of a combination of a chart by Gorczyński, and a similar chart by Birkeland and Foÿn, both of these being taken from the above publication. Likewise, the portion over the North American continent is an adaption of a map by C. F. Brooks, A. J. Connor, and others, while over the pole the conditions are assumed to be given by a map by Sverdrup. These maps are also to be found in the handbook of Köppen-Geiger.

The chart of normal pressures at the 2 km. level for January is given in figure 17. The sources of the data are as follows: Over the ocean areas, the isobars are an adaptation of a map given by Shaw in his *Manual of Meteorology*, volume II, except near the continents where some changes are necessary to secure a reasonable agreement with the pressure distribution used over the land areas. A considerable amount of observational data in the form of soundings is incorporated in drawing the isobars. The stations for which such information is available are indicated by dots on the map, and a brief description of the data is given in table 2.[7] Stations for which the pressures were calculated from surface data are indicated by small crosses. The shaded portions of the map include areas at an elevation above 2,000 meters.

TABLE 2

NORTH AMERICAN STATIONS

Station	Length of record	Type of sounding
	Years	
Boston	4	3 years airplane, 1 year radiosonde.
Cheyenne	4	Airplane.
Chicago	4	3 years airplane, 1 year radiosonde.
Coco-Solo	5	Airplane.
Detroit	2	Do.
El Paso	3	2 years airplane, 1 year radiosonde.
Fairbanks	3	Do.
Fargo	5	4 years airplane, 1 year radiosonde.
Fort Smith	1	Airplane.
Juneau	1	Radiosonde.
Lakehurst	5	Airplane.
Miami	2	1 year airplane, 1 year radiosonde.
Montgomery	2	Airplane.
Nashville	6	5 years airplane, 1 year radiosonde.
Oakland	3	2 years airplane, 1 year radiosonde.
Oklahoma City	4	2 years airplane, 2 years radiosonde.
Omaha	6	4 years airplane, 2 years radiosonde.
Pensacola	6	Airplane.
Salt Lake City	2	Do.
San Antonio	3	2 years airplane, 1 year radiosonde.
San Diego	6	Airplane.
Sault Ste. Marie	4	2 years airplane, 2 years radiosonde.
Shreveport	6	Airplane.
Spokane	6	5 years airplane, 1 year radiosonde.
Washington	6	Airplane.

NON-AMERICAN STATIONS

Agra, India	Winter averages of a series of 141 observations.
Angmagsalik, Greenland	Not more than 3 winter airplane observations.
Breedene a Meer, Belgium	Winter kite observations from a total of 826.
Dickson, North Siberia	Not more than 7 winter radiosonde observations.
Kiruna, Sweden	39 flights in February and March.
Kjeller, Norway	80 airplane flights in January.
Lindenburg, Germany	44 flights for January over a long period.
Malmstatt, Sweden	Unknown number of winter kites.
Manila, P. I.	33 January airplane observations, 1931–32.
Madrid, Spain	Unknown number of winter obs. out of 96 obs.
Munich, Germany	January portion of 332.
Nova Zemlia, Siberia	Unknown number winter radiosonde observations.
Oslo, Norway	See Kjeller.
Paris, France	28 January observations.
Pavia, Italy	January portion of 232.
Pawlowsk, U. S. S. R.	90 January soundings.
Pearl Harbor, T. H.	5 years airplane.
Pieping, China	11 winter kites with N., NE., or NW. winds.
Port Said, Egypt	January portion of 221 airplane observations.
Spitzbergen	160 winter observations.
Strassburg, Germany	Unknown number of January observations.
Vienna	January portion of 197 observations.

[7] For a fairly complete list of published aerological data, the reader is referred to Shaw's *Manual of Meteorology* (cited in footnote 5) and to the section on climatology of the free atmosphere in the Köppen-Geiger *Handbuch*.

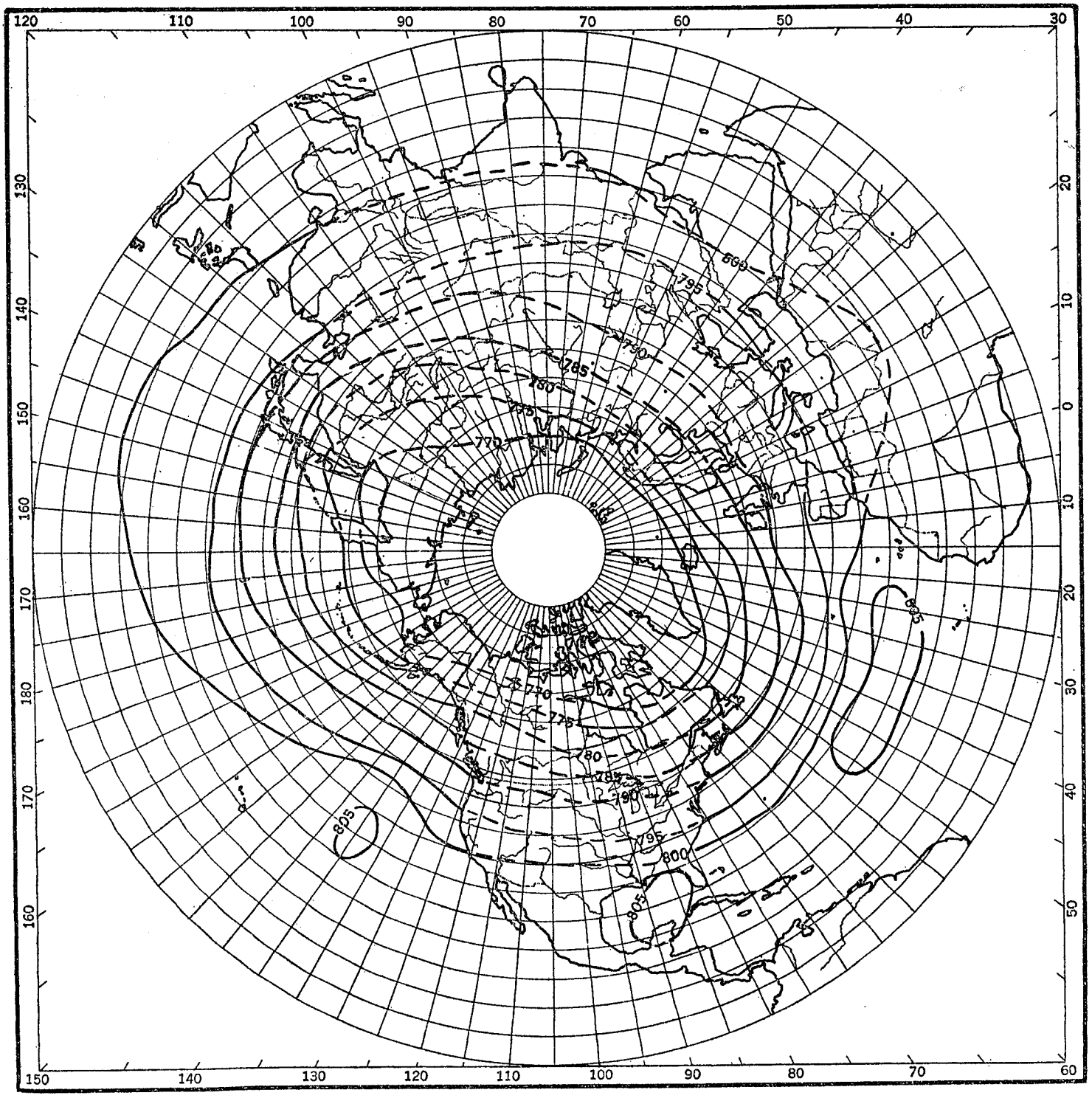

FIGURE 18.—Shaw's 2 km. pressure map.

In drawing the isobars, observed values are given preference unless it is clear that such data are in error. The computed and observed values of the pressure are entered upon the chart for each station in order that the reader may judge as to whether insufficient or excessive weight has been placed upon the figures. The calculation of the pressures at more numerous stations in the polar regions is impracticable because of the lack of information concerning surface temperatures.

An interesting feature of the map is the absence of any single center of low pressure at the pole. Rather, two major centers of low pressure are present, one in northern North America at about latitude 67° N., and another slightly deeper centered over eastern Siberia at about the same latitude. For purposes of comparison, a reproduction of Shaw's map is given in figure 18. It must not be forgotten, however, that Shaw does not claim that the dashed portions of his isobars over the continents represent true conditions.

A normal pressure map for the 4 km. level, constructed in the same manner as the 2 km. chart, is shown in figure 19. The data for the oceanic areas in this case are an adaptation of a chart constructed by Teisserenc de Bort and reproduced by Shaw. A copy of Teisserenc de Bort's

map is given in figure 20. It will be noticed that the isobars over the Pacific, off the west coast of the United States and Mexico, have been altered. This has been done on the supposition that the presence of an inversion at moderate elevations in this vicinity was not taken into account by Teisserenc de Bort, because observational evidence of this condition has become available only recently. The shaded portions of the map include areas at an elevation above 4,000 meters.

As on the chart for 2 km., two deep centers of low pressure are found, one over Siberia and the other over northern North America. The calculated data seem to suggest that each is closed, with somewhat higher pressure at the pole, so that no single polar vortex is indicated. The ridge of high pressure shown by Teisserenc de Bort to the northwest of the Scandinavian Peninsula is displaced quite far to the east. This may indicate a transport of relatively warm air to the northeast over Europe. The conditions noted over Asia indicate that although an extremely large land area is involved here, the center of continental low pressure is localized to a relatively small region in the eastern portion. This suggests that the low pressure may be produced to some extent by large scale dynamic processes rather than by radiational cooling and other thermal effects alone.

NORTH AMERICAN WINTER WEATHER

In attempting to obtain a picture of the weather phenomena during the North American winter, particularly those associated with the release of "cold waves" from

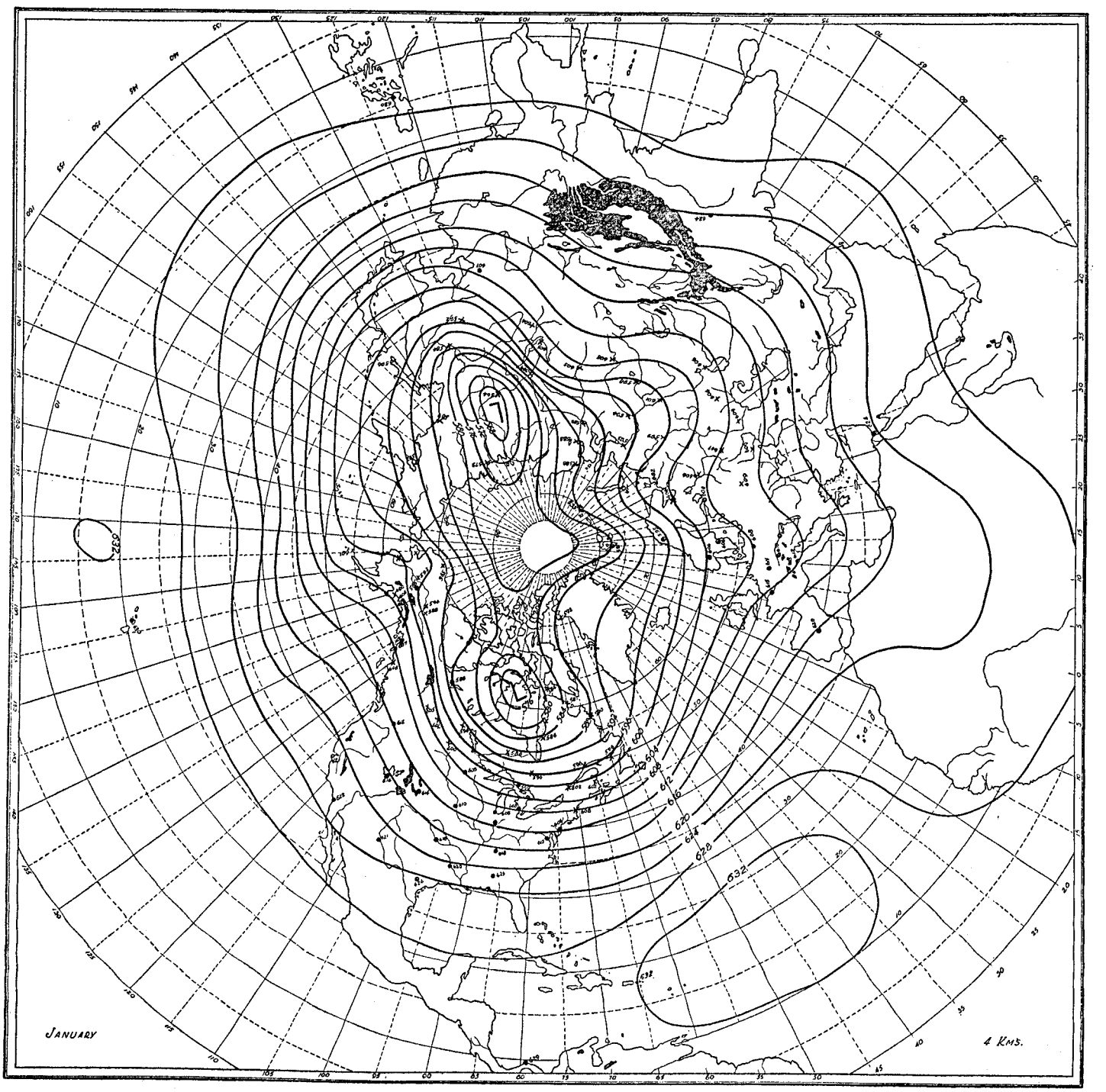

FIGURE 19.—Normal January pressure at 4 km.

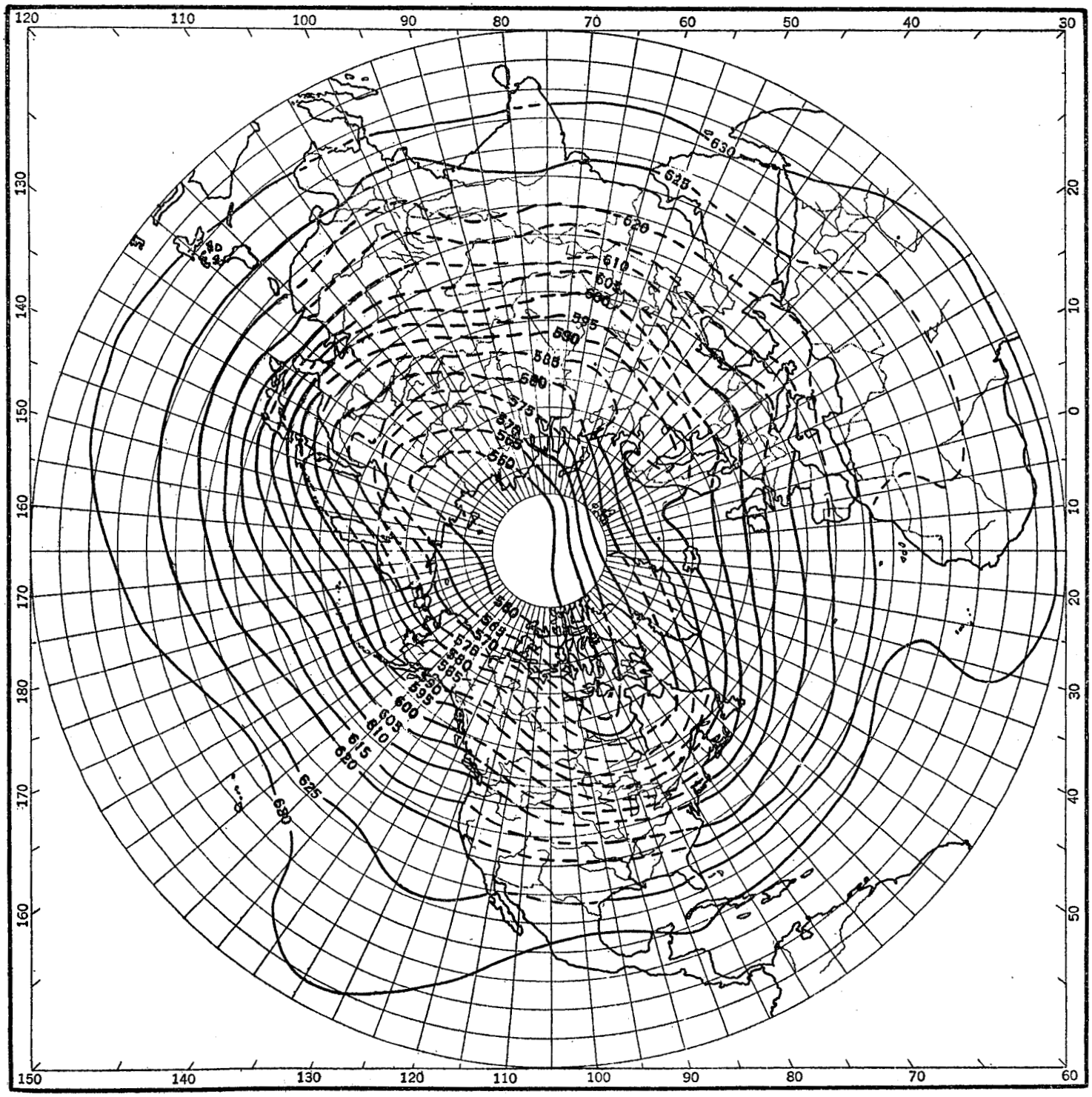

FIGURE 20.—Shaw's 4 km. pressure map, adapted from Teisserenc de Bort.

Canada and Alaska into the United States, vertical cross sections of the atmosphere based on the Fairbanks, Fort Smith, and northern United States soundings were constructed for every day that data were available. An approximately straight-line section was possible by making use of the Fairbanks, Fort Smith, Sault Ste. Marie, and Washington soundings—a section more than 3,000 miles in length extending diagonally across Canada from interior Alaska into the northeastern United States. These charts were analyzed in conjunction with the four-times daily synoptic weather maps, including twice daily coverage of the eastern Pacific Ocean, prepared currently in the Research Division of the Weather Bureau Central Office. Cross sections extending from Fort Smith to Fargo, Omaha, Oklahoma City, and San Antonio were also constructed, and many temperature-pressure plots of the soundings as well as pilot-balloon data were studied. These detailed analyses represented a prodigious amount of work in proportion to the amount of forecasting information obtained from them. Those experienced in synoptic meteorology and forecasting will appreciate the great mass of experience and analysis necessary to obtain even fragments of new forecasting clues.

It might be suggested that there be published herewith

all of the surface and upper-air analyses, which cover some 110 days of winter weather. The obvious expense of such a publication is not the only deterrent. Many of the analyses were incomplete or doubtful, due in some cases to missing upper-air data occasioned by unflyable weather, in some cases to insufficient knowledge of conditions approaching from the Pacific or Arctic, in others simply due to inability to obtain a correct picture from stations so widely scattered as Fairbanks, Fort Smith, and Sault Ste. Marie. It is considered better merely to set down some of the weather characteristics that appeared repeatedly in the analyses.

During the course of the winter there was ample evidence of the usefulness of the Alaskan and Canadian free-air soundings in forecasting cold-air outbreaks. One especially noteworthy factor was the role of cold fronts aloft. Their importance in North America has been recognized for several years, having been treated by Lichtblau,[8] Holzman [9] and Byers.[10]

Cold outbreaks penetrating deeply into the United States start from perturbations on the Arctic front, which separates the coldest air of northern Canada and Alaska (Arctic air) and air from the Pacific or generally modified air of high-latitude origin. When the wave perturbations on this front are of a simple type not associated with disturbances lying within the polar air to the south, extensive outbreaks of cold air usually do not occur. A cyclonic disturbance coming inland from the Pacific Ocean approaching the relatively stationary northwest-southeast lying Arctic front usually is the releasing mechanism for the cold outbreak, and an upper-air cold front is the usual accompaniment of it. The cyclone from the Pacific typically is forming a warm-type occluded front, sending ahead of its surface position at upper levels a cold front which rides over the Arctic air, forming the disturbances in the front which later will push the Arctic air into the rear portion of the cyclone that is to the south.

The weather of December, January and February 1936–37 may be briefly summarized as follows:

December 1 to 2.—The continuation of the conditions prevailing during most of the preceding month, beginning on November 7. A series of low pressure centers developing around waves on the Arctic front moved from the northern Gulf of Alaska across northern Canada to Hudson Bay, producing over a period of 26 days the variable weather conditions to be expected with frontal activity.

December 3 to 8.—A well-developed Canadian anticyclone west and northwest of Fort Smith and extending into the United States. Very cold air over Fort Smith, but not so cold in the vicinity of Fairbanks. Cyclonic centers entered the continent in the vicinity of Vancouver Island and Puget Sound, moving southeastward as waves along the Arctic front, developing further in the center of the United States, and either moving around or breaking through the high pressure area in that region.

December 9 to 20.—Another series of intense cyclones similar to that occurring in the latter part of November. High pressure over the eastern United States and some cyclonic activity in the southern Pacific Coast region.

December 21 to 27.—A return to the type prevailing from December 3 to 8, the cyclonic activity being mainly along the Canadian and United States border with a well-developed anticyclone in northwestern Canada.

December 28 to January 7.—The principal cyclonic developments were in fairly low latitudes, the main cyclonic path being from California to Colorado and New England, except for a system that passed through British Columbia and the Canadian prairies on January 3 to 5. There was secondary frontal activity in Alaska and northwestern Canada.

January 8 to 17.—Conditions very similar to December 3 to 8 with marked cyclonic development in the eastern and southeastern United States.

January 18 to 20.—One important cyclone moving from California to New England.

January 21 to February 4.—Another return to the type of weather prevailing January 8 to 17.

February 4 to 8.—Cyclones moving from California to Colorado and New England were the dominating characteristic with some secondary activity in northwestern Canada and in Alaska.

February 9 to 18.—Cyclones along the Arctic front in high latitudes, most of the cyclonic systems passing just south of Fort Smith. One moderately intense cyclone developed in the California region.

February 19 to 24.—Cyclone developing in the Gulf of Mexico moved and deepened rapidly to form an intense low in northeastern United States and southeastern Canada, which became retrograde and remained in the Great Lakes-to-Hudson Bay region. A large high pressure center occurred to the west, and no new cyclones moved into the continent from the Pacific Ocean or the Gulf of Alaska.

February 25 to 27.—Another California-to-Colorado development followed by a shift of activity to the Canada and Alaska region on the 28th.

From the above summary it appears that four main circulation types occurred during this period as follows:

I. Cyclonic centers coming through British Columbia following a counter-clockwise path southeastward, then northeastward, accompanied by extremely cold air over Fort Smith and a well-developed Canadian anticyclone. The periods December 3 to 8, December 21 to 27, January 8 to 17, and January 21 to February 4 fall in this category.

II. Frontal and cyclonic activity in high latitudes along the Arctic front, extending from Alaska to Hudson Bay. This was characteristic of the weather of November 7 to December 2, December 9 to 20, and February 9 to 18.[11]

III. Cyclones entering in the vicinity of California and moving toward Colorado and New England, usually with some secondary activity in northwestern Canada and Alaska. The weather of December 28 to January 7, January 18 to 20, February 4 to 8, and February 25 to 27 was of this type.

IV. A large stationary or retrograde cyclone in the Great Lakes-to-Hudson Bay region. This was characteristic of the 5 days, February 19 to 24.

Considering the duration of these different types, it is noted that during the period in question Type I occurred on 34 days (mainly in January); Type II on 22 days, not counting the long duration of this type during November; Type III on 18 days; and Type IV on 5 days. The pronounced period of Type I weather, lasting from January 8 to February 4, except for a 2-day interruption of Type III, was associated with the flood rains in the Ohio Valley during that period. This represents the most prolonged period of any one type of weather during that winter.

The characteristics of the different weather types in relation to conditions observed in the upper air in Canada and Alaska are of interest. Some of these relations are given herewith:

TYPE I

December 1 to 8.—Unusually low temperatures were noted at Fort Smith extending to great heights. A study of the cross sections showed that most of Canada was in a homogeneous cold air mass and that the temperatures at Fairbanks were at nearly all levels from 8 to 10° warmer than those at Fort Smith. The following data are given concerning the temperatures and winds at Fort Smith:

Date	*Temperature at 5 km.*	*Wind*
3	−47°	Strong NNW. winds all levels.
4	−46°	Strong N. winds.
5	−42°	NW. to 2 km. Fresh to strong NE. above.
6	−37°	Southerly winds below 5 km. W. above.
7	−35°	Southerly winds below 3 km. W. above.
8	−41°	Moderate to strong northerly winds all levels.

[8] Lichtblau, S. Upper-Air Cold Fronts in North America. MONTHLY WEATHER REVIEW, vol. 64, pp. 414–426. 1936.

[9] Holzman, B. Synoptic Determination and Forecasting Significance of Cold Fronts Aloft. MONTHLY WEATHER REVIEW, vol. 64, pp. 400–414. 1936.

[10] Byers, H. R. *Synoptic and Aeronautical Meteorology*, p. 146. 1937.

[11] Data on the intensity of the zonal circulation, being studied by Roger A. Allen of the Weather Bureau, indicate that all except Type II were associated with a weak zonal circulation.

During this period light easterly winds prevailed in the low levels at Fairbanks. The relative warmth and high moisture content of the air at high levels there suggest an ocean source.

December 21 to 27.—During this period it was moderately cold at Fort Smith and Fairbanks with easterly winds in the low levels and westerly winds aloft at both places.

January 8 to 17.—Temperatures ranging from −35° to −40° at 5 km. were observed at Fort Smith. Many flights were missed during this period at Fairbanks, but the few which were made showed temperatures ranging from −30° to −35° at 5 km. At Fort Smith the winds were strong north to west, while at Fairbanks easterly winds prevailed near the ground.

January 21 to February 4.—There were many temperatures below −30° or −35° at 5 km. at Fort Smith, the temperatures being generally about 5° higher at Fairbanks. The winds were between north and west at both stations.

TYPE II

December 9 to 20.—This period was characterized at both stations by considerable cloudiness, high temperatures and ice deposits. The winds were variable, as would be expected under conditions of cyclonic activity. A feature in sharp contrast to the conditions of Type I was the fact that the temperatures at Fairbanks were considerably lower than at Fort Smith. The following comparisons of the temperatures at 5 km. are given:

Date	*Fairbanks*	*Fort Smith*
9	>−20°	−31°
10	>−33°	(?)
11	−33°	−29°
12	−35°	−29°
13	−32°	−28°
14	−35°	−30°
15	?	−28°
16	−35°	−22°
17	−32°	−21°
18	−36°	>−35°
19	−41°	−33°
20	−35°	−35°

February 9 to 18.—The similarity between this and the other example of Type II weather is striking. The temperatures at Fairbanks during this period were extremely low at high levels, as the following table for 5 km. indicates.

Date	*Fairbanks*	*Fort Smith*
12	−45°	−35°
13	−45°	−29°
14	−40°	−33°
15	−43°	−31°
16	−47°	−38° (?)
17	−47°	−36° (?)
18	−35°	(?)

TYPE III

December 28 to January 7.—Low temperatures aloft prevailed at both Fairbanks and Fort Smith, particularly the latter. There was considerable variation, however.

January 18 to 20.—During this period it was very cold aloft at Fort Smith (−40° or lower at 5 km.), but not particularly cold at Fairbanks. Northerly winds of high velocity were noted in the upper air at Fort Smith.

February 4 to 8.—Considerable activity in the Fairbanks-to-Fort Smith region. (See cross sections reproduced in figs. 22 et seq.)

February 25 to 27.—Conditions similar to those in other cases, except somewhat colder aloft at Fairbanks.

TYPE IV

February 19 to 24.—Upper-air winds at Fort Smith were between north and east, and a gradual warming-up aloft at Fort Smith toward the end of the period suggests the transport of air around the low pressure center from the Atlantic. The following temperatures were observed at this station at 3 km.:

Date	*Temperature*	*Date*	*Temperature*
19	−22°	22	−20°
20	−21°	23	−19°
21	−22°	24	−11°

In noting the upper-air conditions over Canada and Alaska in these weather types, one is struck by the contrasting characteristics of Types I and II: the first is dominated by extreme low temperatures aloft over Fort Smith and temperatures eight to ten degrees higher at Fairbanks; in Type II, the high-level temperature gradient between these two stations is the reverse, Fairbanks generally showing considerably lower temperatures than Fort Smith.

The possibility of a characteristic sequence of weather types as represented by the transition from one type to another is suggested. No clear-cut trend was observed during the period under consideration: Type I changed to Type III on three occasions and to Type II once; Type II changed to Type I twice and once to Type IV; Type III changed twice each to Types I and II. This suggests a sequence from Type II to I to III and back again in a reverse sense, or in a repetition. Actually, however, there was not a single occasion when the sequence was from Type II to Type I to Type III. Although the individual parts of this sequence occurred separately, the complete change did not occur in order.

Another striking feature is the tendency for the development of a weak Type II activity when Type III is dominant, and also the reverse tendency, namely, the development of cyclonic systems in the California region when there are marked perturbations on the Arctic front in the far north. This suggests a relationship involving the dimensions of the areas between cyclonic centers of action. It would appear that a north-to-south dimension similar to the distance between northwestern Canada and California is common.

Neither the intensity and depth of the cold air, nor the intensity of the cyclone, nor the upper-air winds in northern Canada determine the extent and severity of the cold-air outbreak. More important, apparently, are the *dimensions* of the perturbations. Wave disturbances on the Arctic front coming in rapid succession are never to be associated with extensive cold-air invasions. A cyclone that develops when no new disturbance is near at hand is the type to be identified with marked southward air transport. During Type II weather, although the temperatures, particularly aloft, are extremely low at Fairbanks, no appreciable southward displacement of Arctic air occurs. This was demonstrated during the two periods December 9 to 20, 1936, and February 9 to 18, 1937, and during most of November 1936. Similarly, during Type I, when extreme cold prevails at Fort Smith, only certain parts of the United States may be affected by these Arctic conditions. These facts suggest that greater attention should be paid to the dimensions of perturbations. With a careful study over a longer period of time, criteria by means of which critical wavelengths can be determined should be developed.

In the vicinity of Fort Smith there were noted on several occasions tendencies toward breaking down of cold fronts that had appeared as rather strong ones in passing Fairbanks. The great sea of cold air in the Canadian interior causes the cold air coming from the west to appear warm by comparison or to show no temperature discontinuity whatsoever. Even warm fronts from the west occasionally fade due to peculiarities in the circulation over Canada brought about by the presence of the cold air. An example of this is seen in the cross section for February 7, 1937 (fig. 27), where typical slopes indicating warm-front action between Fairbanks and Fort Smith have no significance because easterly winds prevail at upper levels at the latter station.

A somewhat surprising result were the strong north-to-south components found in the free-air winds over Fort Smith. These are explained by the presence of a high-level cyclone east of Fort Smith under normal winter conditions, as shown in the 2- and 4-km. isobars of figures 17

and 19. Long-continued northerly winds often resulted in a gradual warming instead of cooling of the air, but under certain circumstances marked cooling occurred with northerly winds. The air trajectories rather than the directions at a point determined the temperature characteristics: If the path brought the air from the northwest before it turned directly southward, then cold air could be expected, but if the trajectory was from the east or northeast originally, then high temperatures, characteristic of Atlantic air, were to be expected. An example of the warming with north to northeast winds was given above in describing the weather regime of February 19 to February 24.

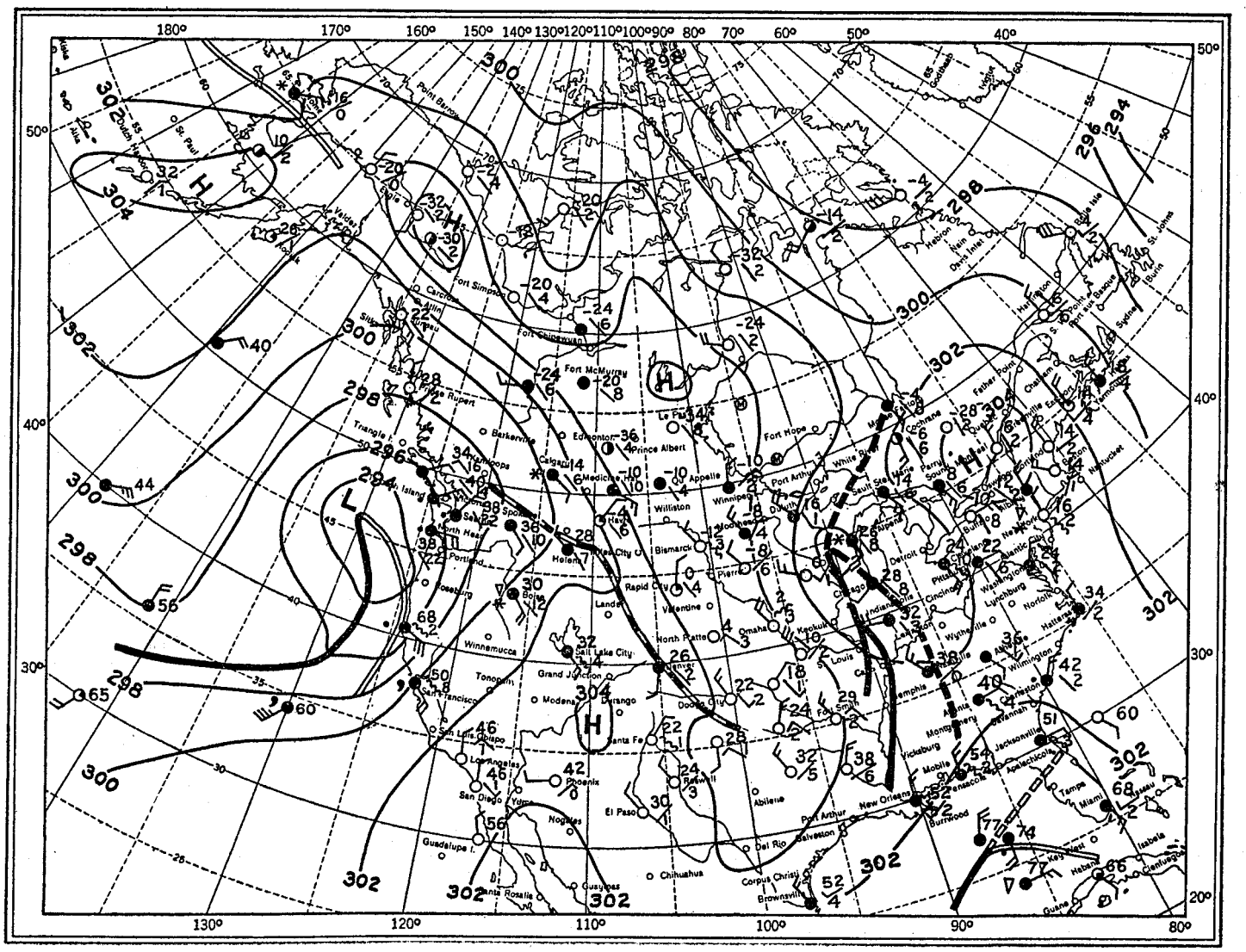

FIGURE 21.—Synoptic chart, 7:30 a. m., E. S. T., February 4, 1937.

EXAMPLES OF CROSS SECTIONS

Vertical cross sections running from Fairbanks to Fort Smith to Sault Ste. Marie to Washington, covering 6 days from February 4 to 9, inclusive, of 1937, are reproduced in figures 21 to 32, together with the synoptic weather charts for each day. The various entries on the charts are as follows:

Data are entered for significant levels at the airplane-sounding stations with temperature (°C.) and relative humidity left of the vertical line and potential temperature and mixing ratio (g. per kg.) to the right. Wind arrows are entered with velocities represented by barbs in terms of the half-Beaufort scale, south being at the bottom, north at the top, east to the right, and west to the left. The 24-hour temperature changes are entered for each whole kilometer in large figures near each sounding station, the + sign representing warming and the − sign cooling. Cloud layers are indicated by horizontal lines at their upper and lower limits, where known. The symbol E means estimated and U means direction unknown. The term "abmax" means that the clouds are above the maximum height attained by the airplane. "Bemax" indicates an undetermined height below the maximum reached. Layers of turbulence and ice formation are indicated.

Only the potential-temperature lines and the fronts are drawn on the sections, the former in intervals of 5°. Cold fronts are indicated by heavy, solid lines and warm fronts by lighter, double lines. The vertical scale is exaggerated about 275 times.

On the surface maps, the wind and weather entries are of the usual type, with wind velocities indicated on the half-Beaufort scale. The figures represent the temperature in Fahrenheit degrees and the 3-hour pressure tendency in hundredths of an inch of mercury. Warm and cold fronts are represented in the same way as on the cross sections. Occluded fronts are represented by alternate dots and dashes, stationary fronts by alternate segments of warm and cold, upper-air cold fronts by heavy dashed lines, and upper-air warm fronts by dashed light, double lines. Cold frontogenesis is indicated by a heavy chain of dots.

The series starts on February 4 with a relatively weak warm front approaching Alaska from the Bering Sea (fig. 21) in such a way that Fairbanks is at the southeastern end of the front. The slope of the front in the cross section is negligible, as noted in figure 22. At Fairbanks it appears with a shift of wind from light

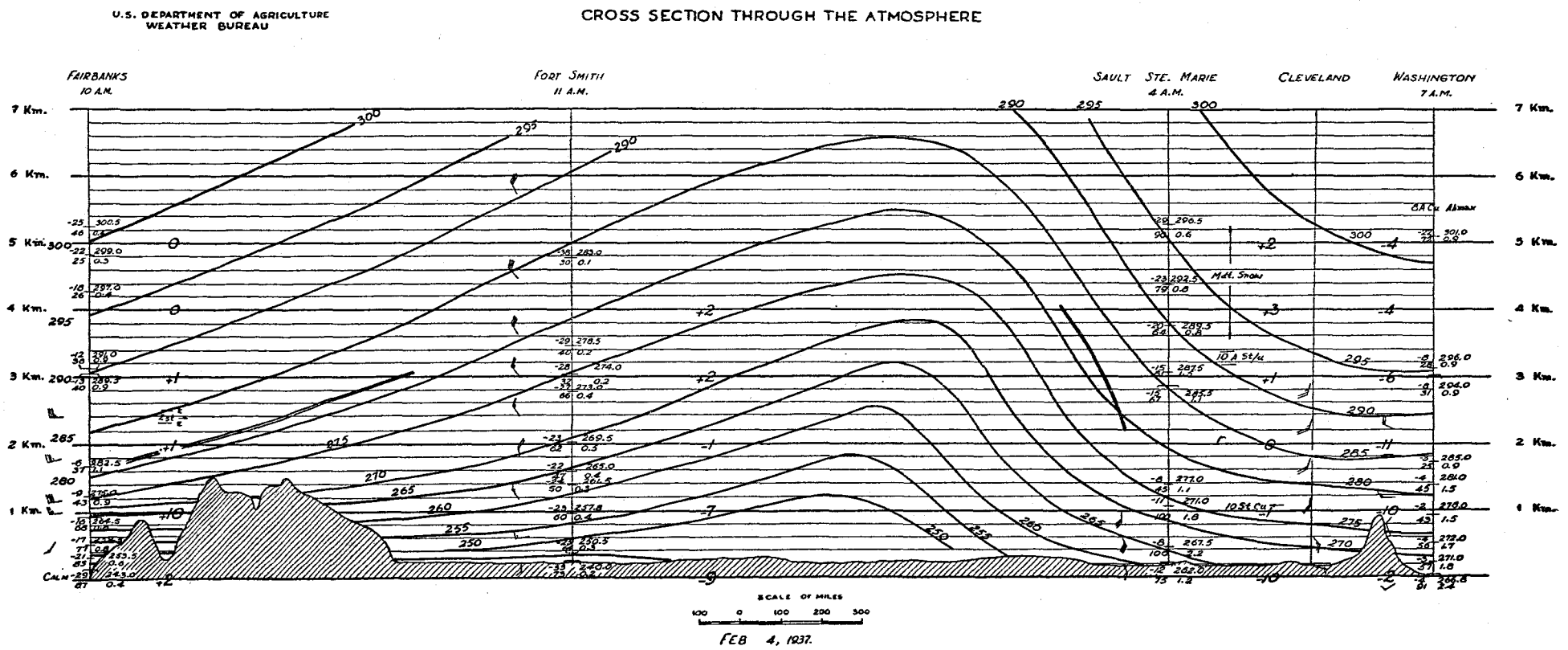

FIGURE 22.—Cross section, February 4, 1937.

southerly to fresh westerly and a pronounced temperature and moisture inversion. Although the isentropic surfaces slope upward toward Fort Smith, there is no good indication of a warm front comprising this slope, although a temperature inversion just above 3 km. may be taken to signify a weak front. This inversion occurs at a slightly lower potential temperature than the inversion at Fairbanks. Sault Ste. Marie is near the center of a large cyclone with unusually warm air to the east. This results in a steep slope of the isentropic surfaces downward toward the southeast in that region to produce the semblance of an upper-air cold front, accompanied by some cloudiness and snow. A cold front cannot be entered at the surface because the gradient would then call for a westward displacement, and it is known that the cold air is advancing eastward.

On the following day, February 5, 1937 (figs. 23 and 24), the warm front that was approaching Alaska has moved inland. The cross section indicates a perfectly horizontal inversion from the western margin to near Forth Smith, then an appreciable slope in the inversion. This inversion is the warm front. The detailed surface analysis indicated that this front must have an appreciable slope only near Fort Smith because it was only near there that large pressure falls were occurring. The decreasing depth of the cold air by advection accounts for these pressure tendencies, while to the west there would be a constant depth of the cold air regardless of the speed of advective transport. The front is rather diffuse at Fort Smith, being marked by a broad zone of small temperature inversions or isothermal layers. At Sault Ste. Marie there is indication of the deepening of the cold air. An upper-air cold front is approaching Fairbanks and Fort Smith from the north, but does not appear as yet on the cross section.

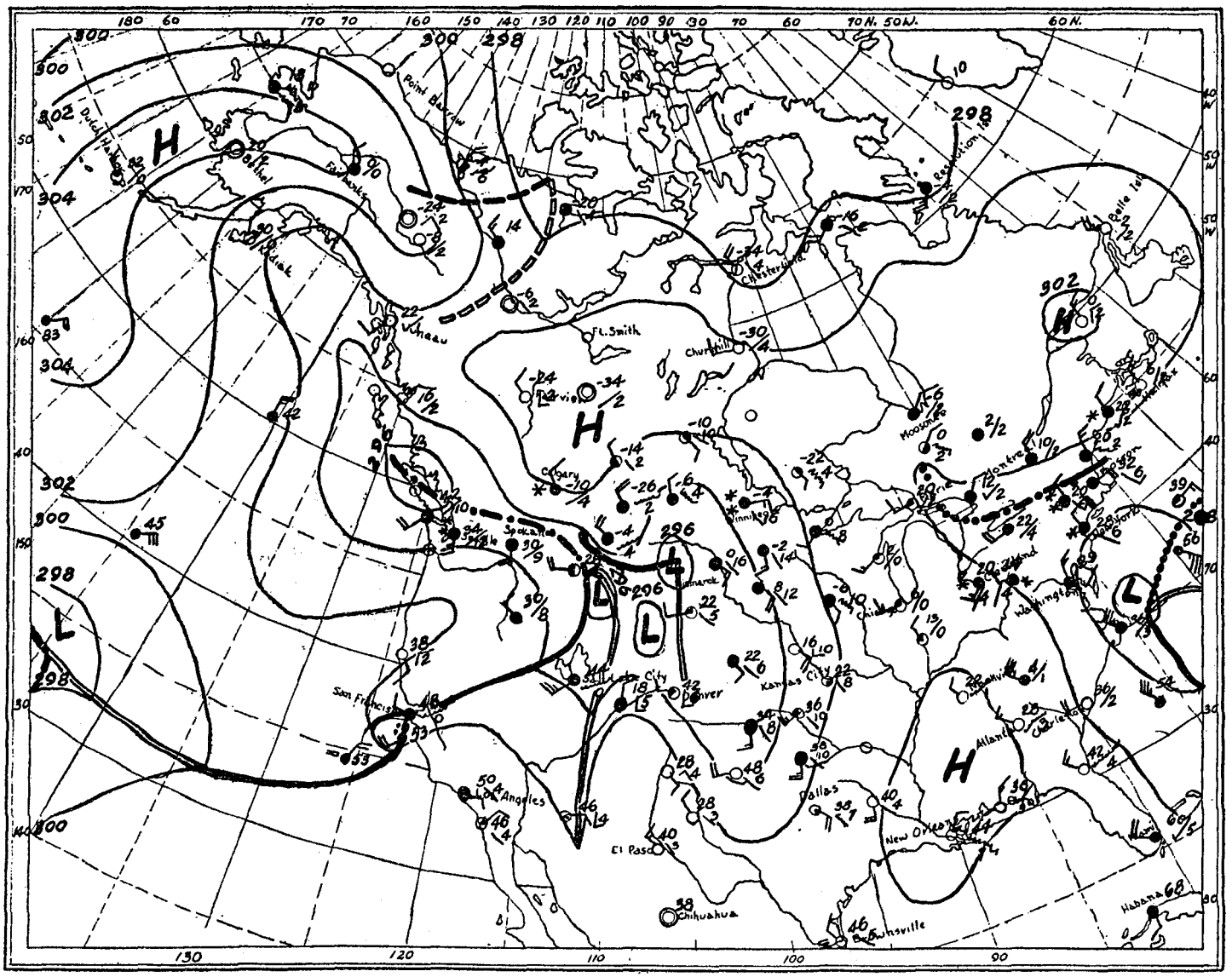

FIGURE 23.—Synoptic chart, 7:30 a. m., E. S. T., February 5, 1937.

On the following day, February 6 (figs. 25 and 26), the soundings suggest that the upper-air cold and warm fronts of the day before have formed an occlusion in the vicinity of Fort Smith. The cold front portion of this occluded front appears on the cross section at Fort Smith. The wind has shifted to northerly and the front is marked as the top of a layer of great stability. In the 24 hours there has been a cooling at the ground, not much change at intermediate levels. Meanwhile a new warm

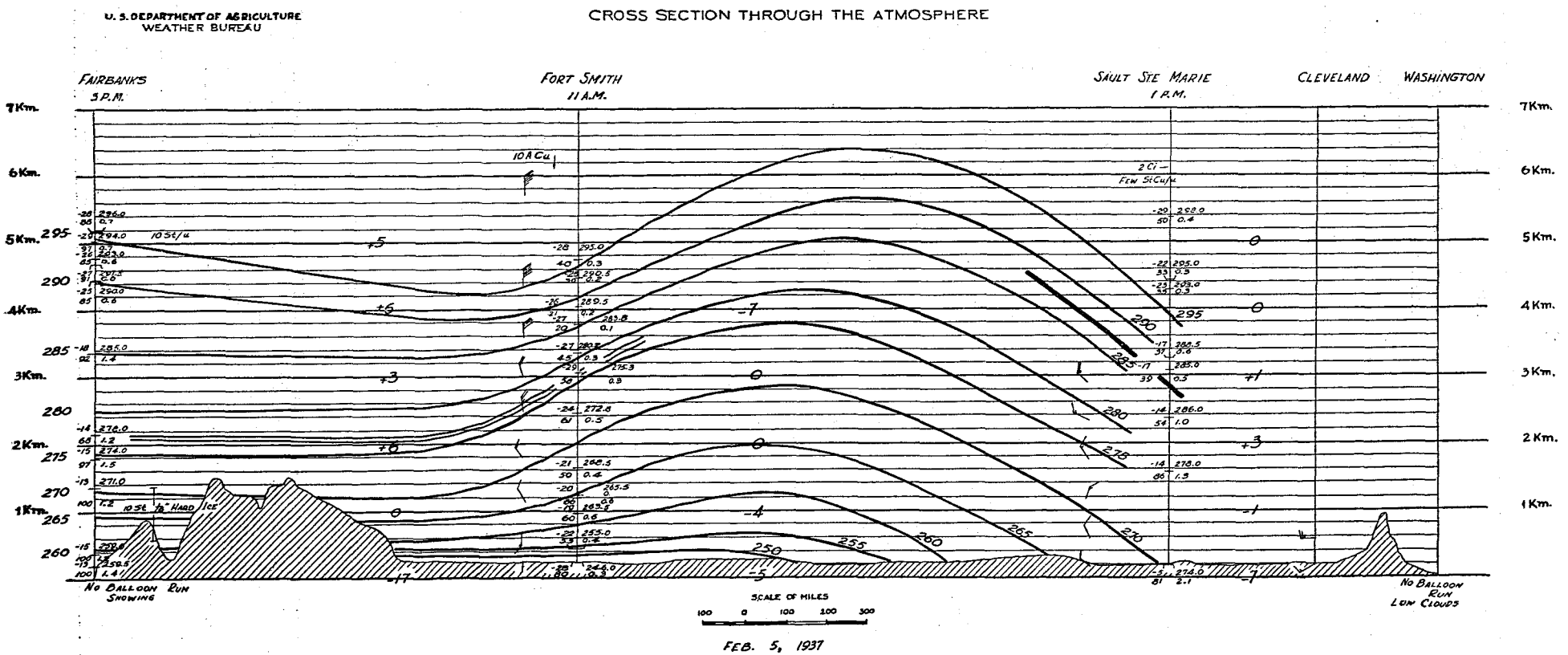

FIGURE 24.—Cross section, February 5, 1937.

front is approaching Alaska, located in a broad transition zone at Fairbanks between 2 and 3 km. where temperature inversions are noted.

The charts for February 7 (figs. 27 and 28) show that the warm front approaching Alaska the day before has been occluded by a cold front which now is east of Fairbanks (the sounding was made three hours later than the weather map observations). The warm front does not follow through to Fort Smith, and it is rather surprising banks, with a temperature of −40° at 5 km. The warm front portion should be approaching Fort Smith, but there is no significant appearance of it. At about 3,500 meters there is a nearly isothermal layer, and the wind changes from south to west and northwest. That is probably what is left of the warm front portion.

On February 9 (figs. 31 and 32), the Fort Smith sounding is at 11 a. m., and by that time the occluded front has passed eastward and the station is beginning to have a

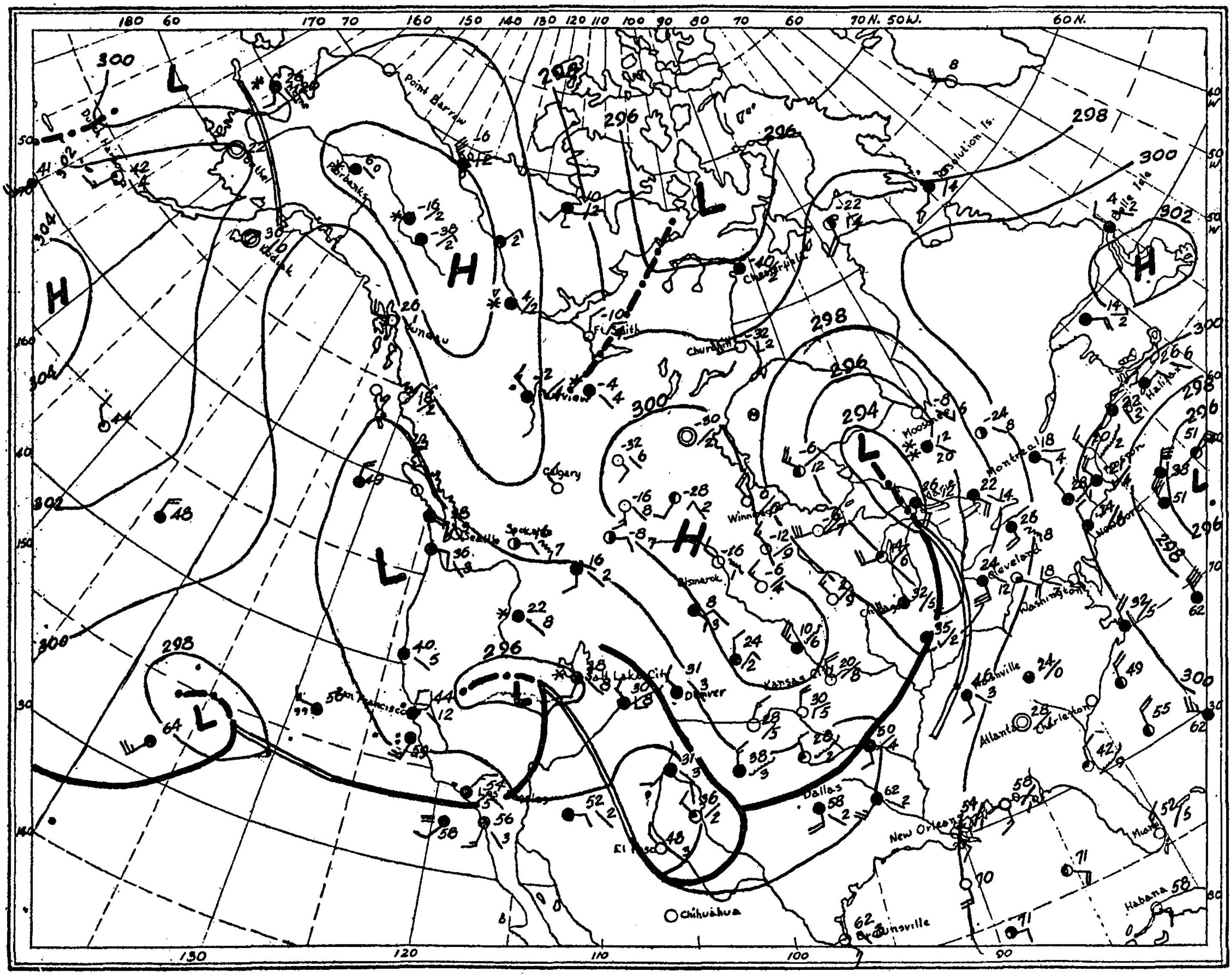

FIGURE 25.—Synoptic chart, 7:30 a. m., E. S. T., February 6, 1937.

to find easterly winds at high levels there. The occluded front of the previous day near Fort Smith has entirely disappeared and new cold air has occupied the lower levels. The cold fronts at the southeastern end of the cross section have developed behind the cyclone over northern New England.

Only the Fairbanks and Fort Smith airplane observations were obtained on the following day, February 8 (figs. 29 and 30). They show that the occluded front has made further progress; the cold portion has progressed to produce cooling well above the top of the climb at Fair- deep cold air mass over it. Fairbanks is still considerably colder than Fort Smith, as the latter is not far from the warm sector. The warm front makes a good connection with the cold front in the eastern part of the United States. In general, the fronts follow the isentropic surfaces reasonably well.

It will be noted that the series described above represents weather that has been classified as Type III—most of the disturbances entering through the southern Pacific coast of the United States but with some lesser activity in northern Canada and in Alaska.

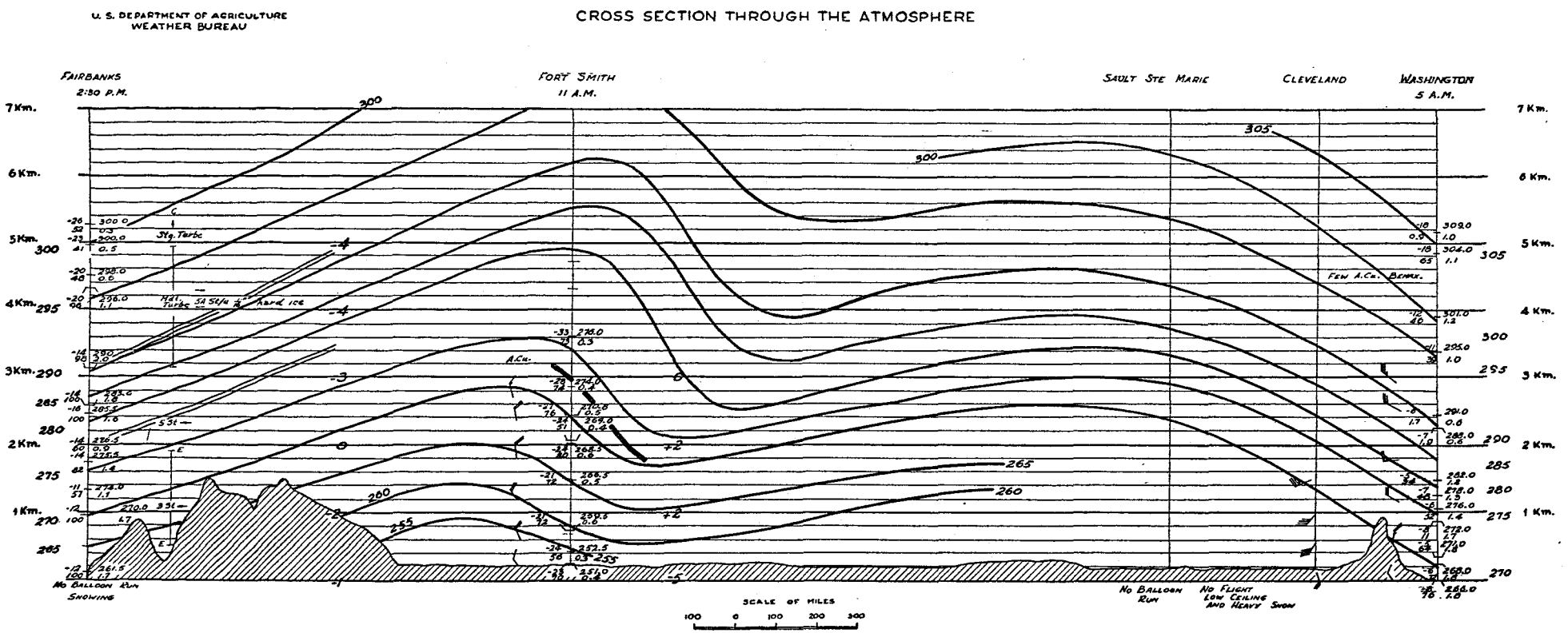

FIGURE 26.—Cross section, February 6, 1937.

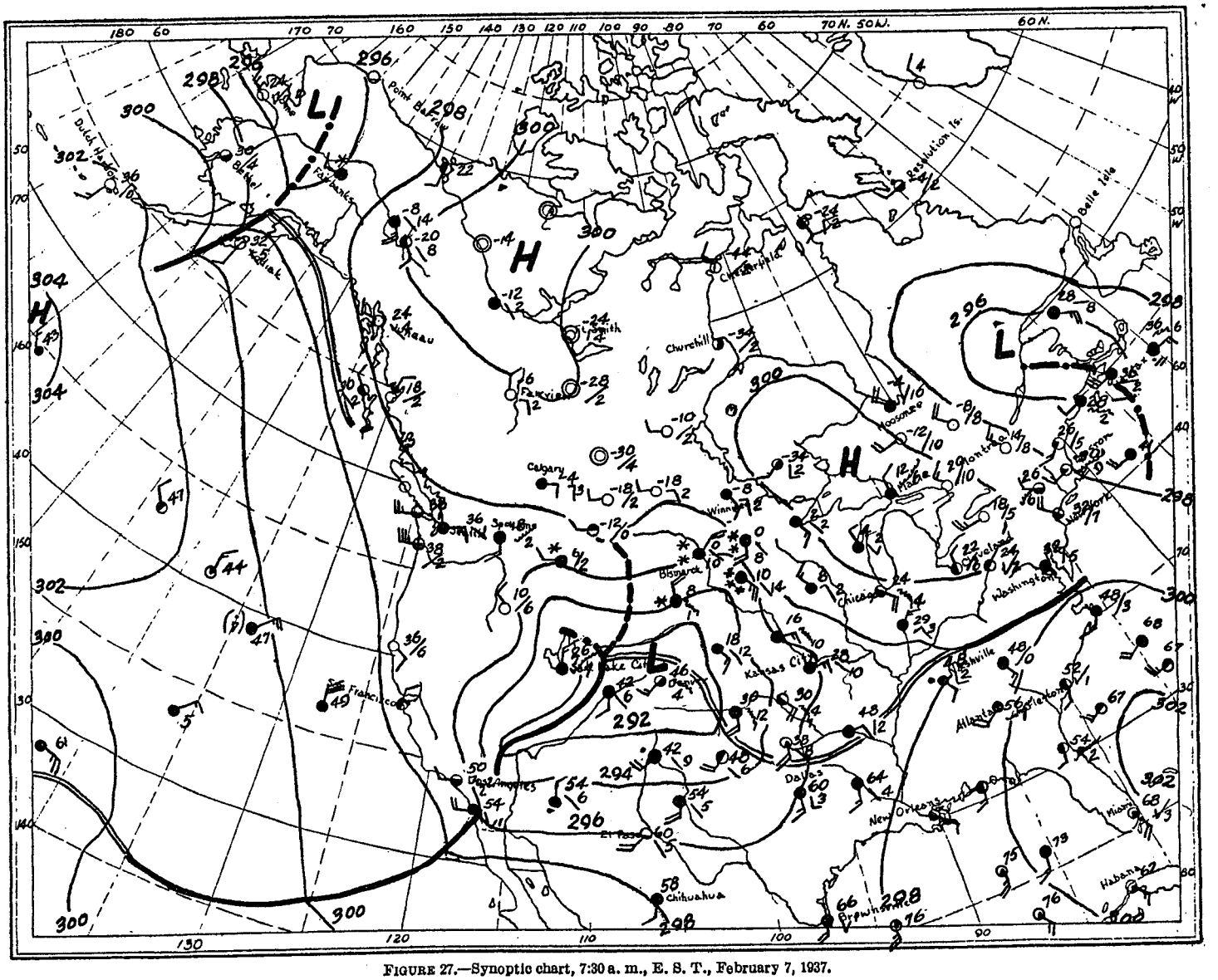

FIGURE 27.—Synoptic chart, 7:30 a. m., E. S. T., February 7, 1937.

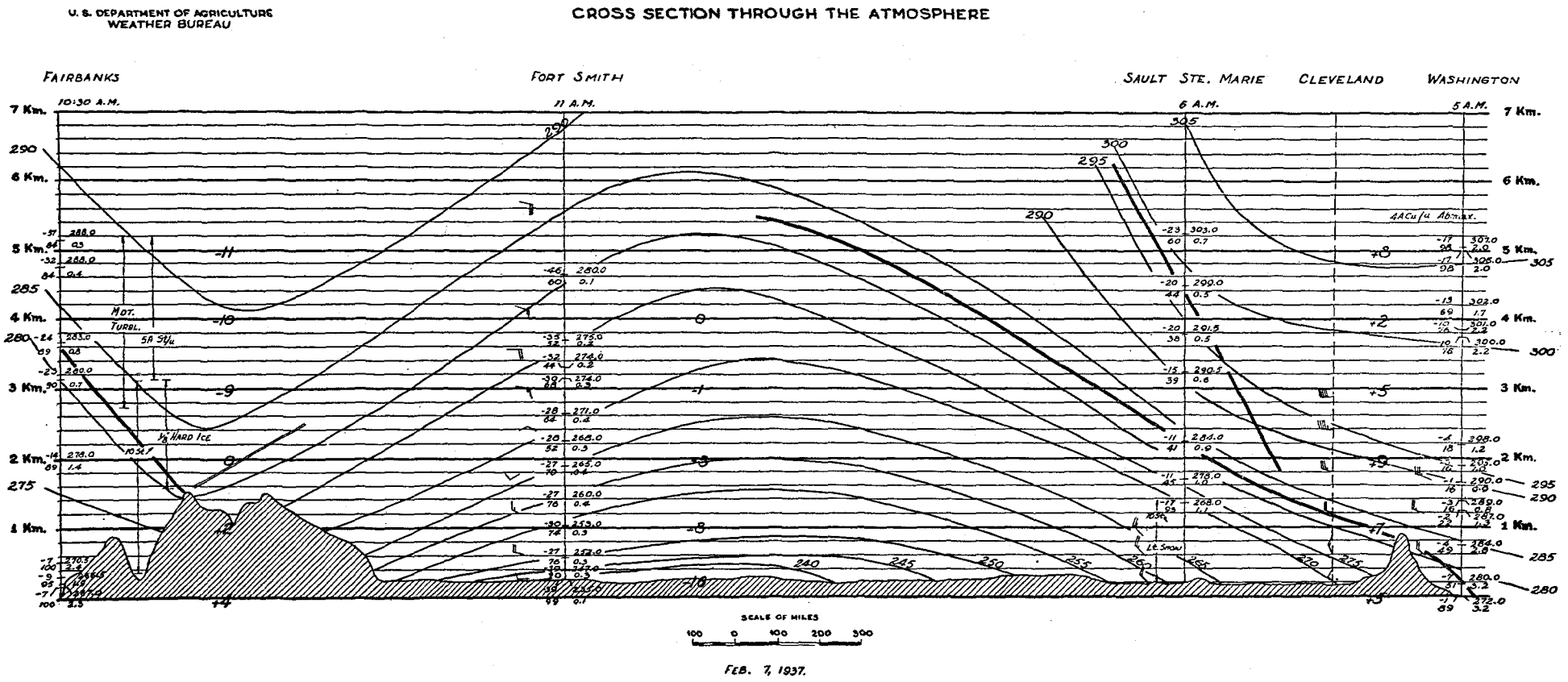

FIGURE 23.—Cross section, February 7, 1937.

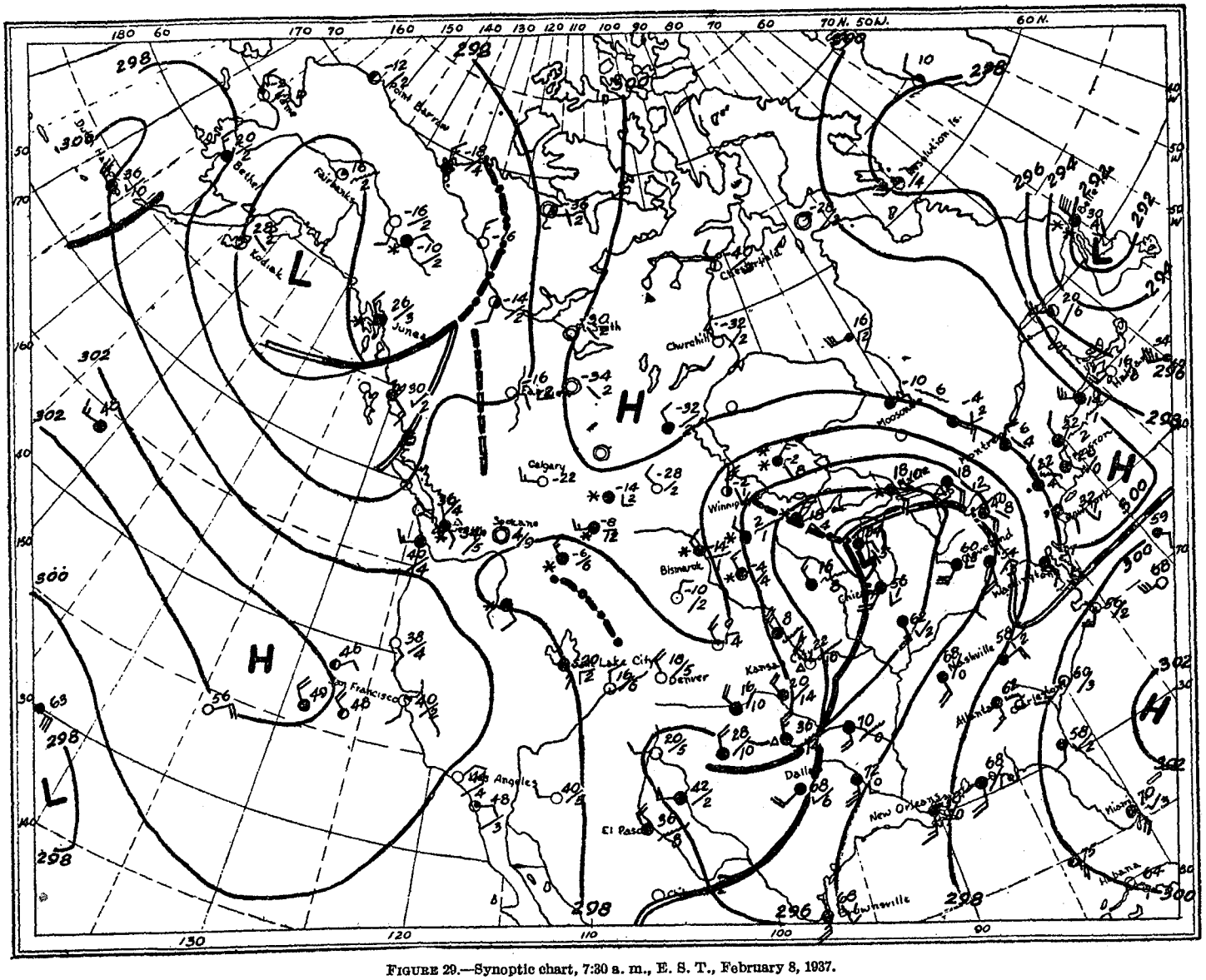

FIGURE 29.—Synoptic chart, 7:30 a. m., E. S. T., February 8, 1937.

CROSS SECTION THROUGH THE ATMOSPHERE

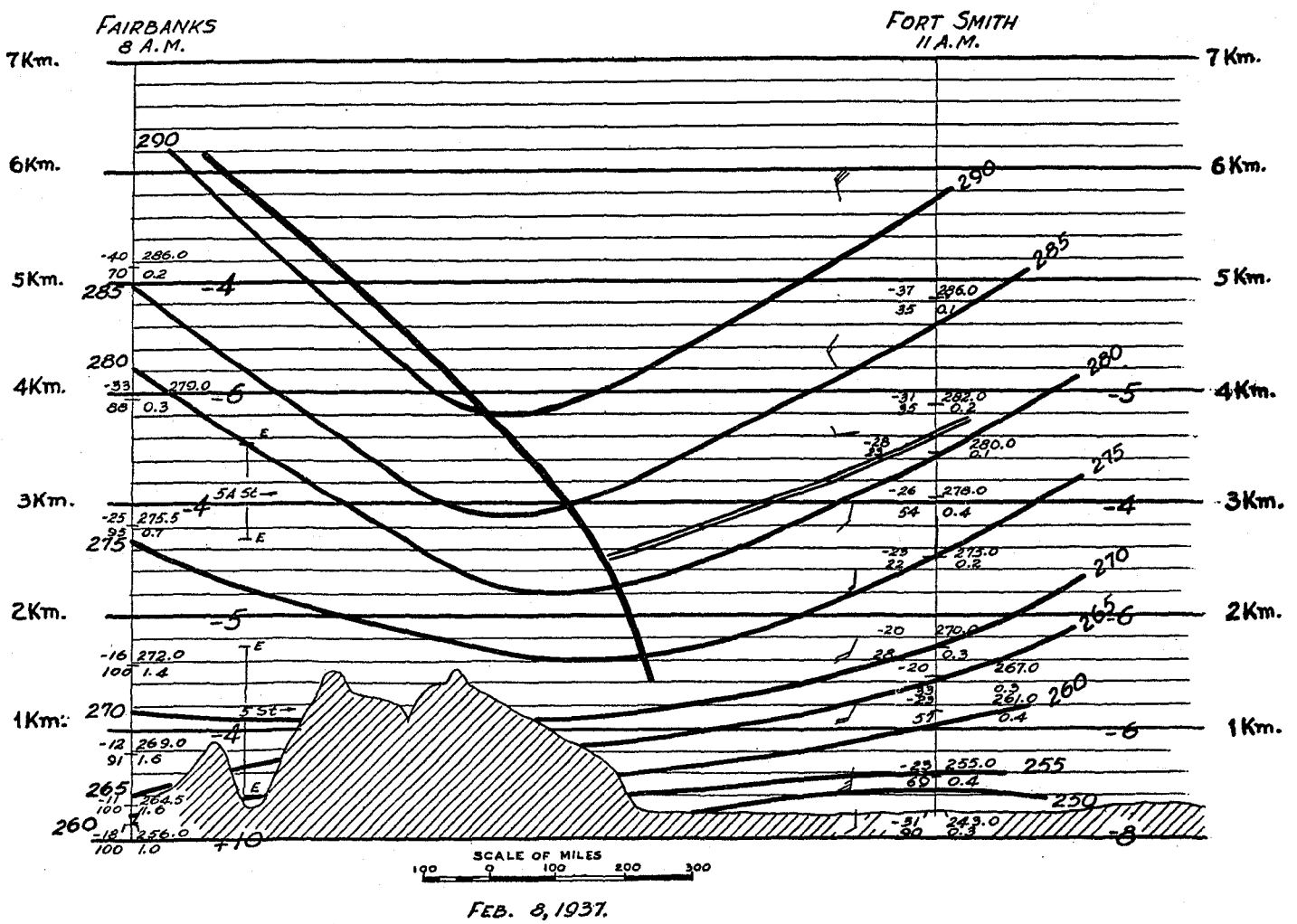

FIGURE 30.—Cross section, February 8, 1937.

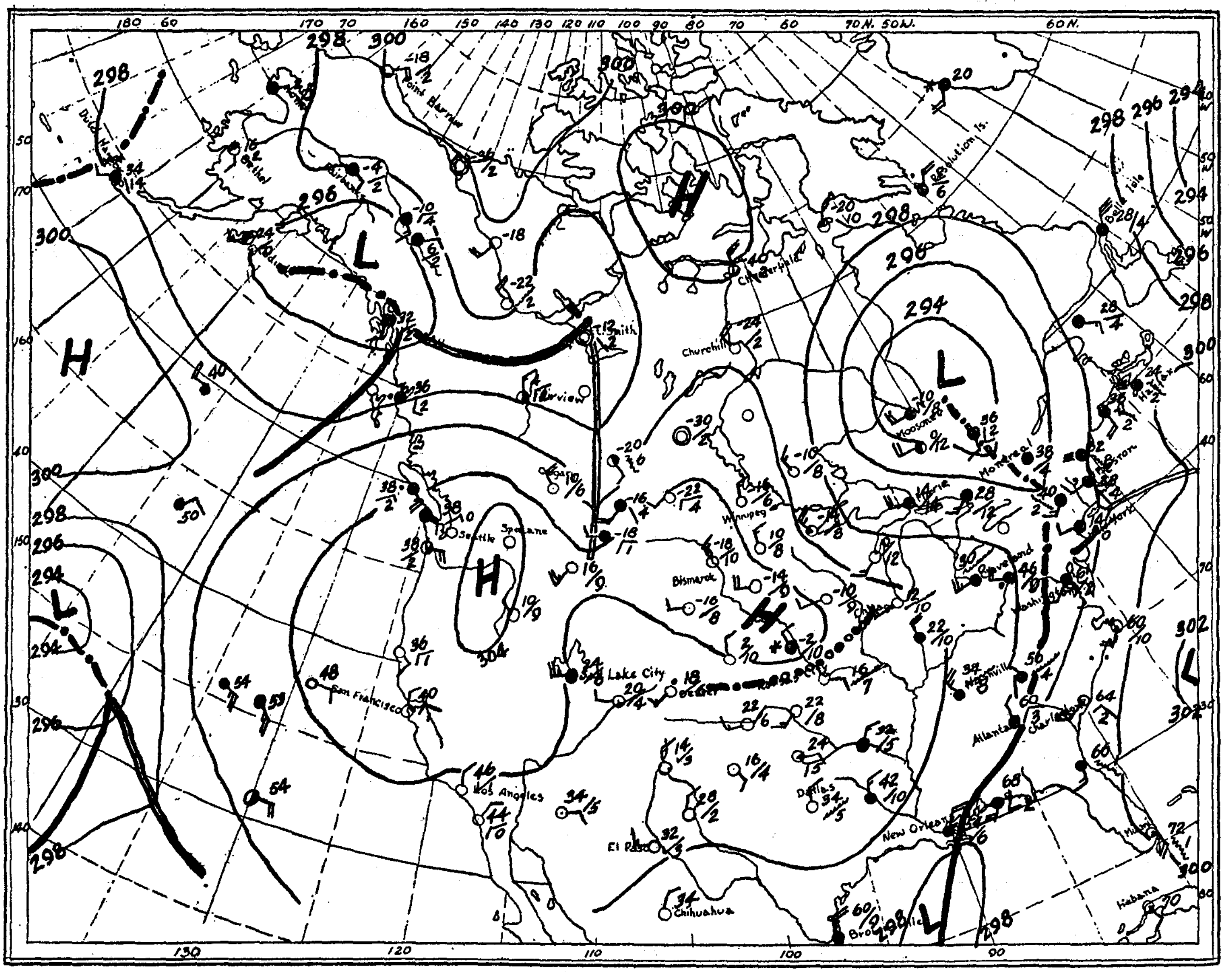

FIGURE 31.—Synoptic chart, 7:30 a. m., E. S. T., February 9, 1937.

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CROSS SECTION THROUGH THE ATMOSPHERE

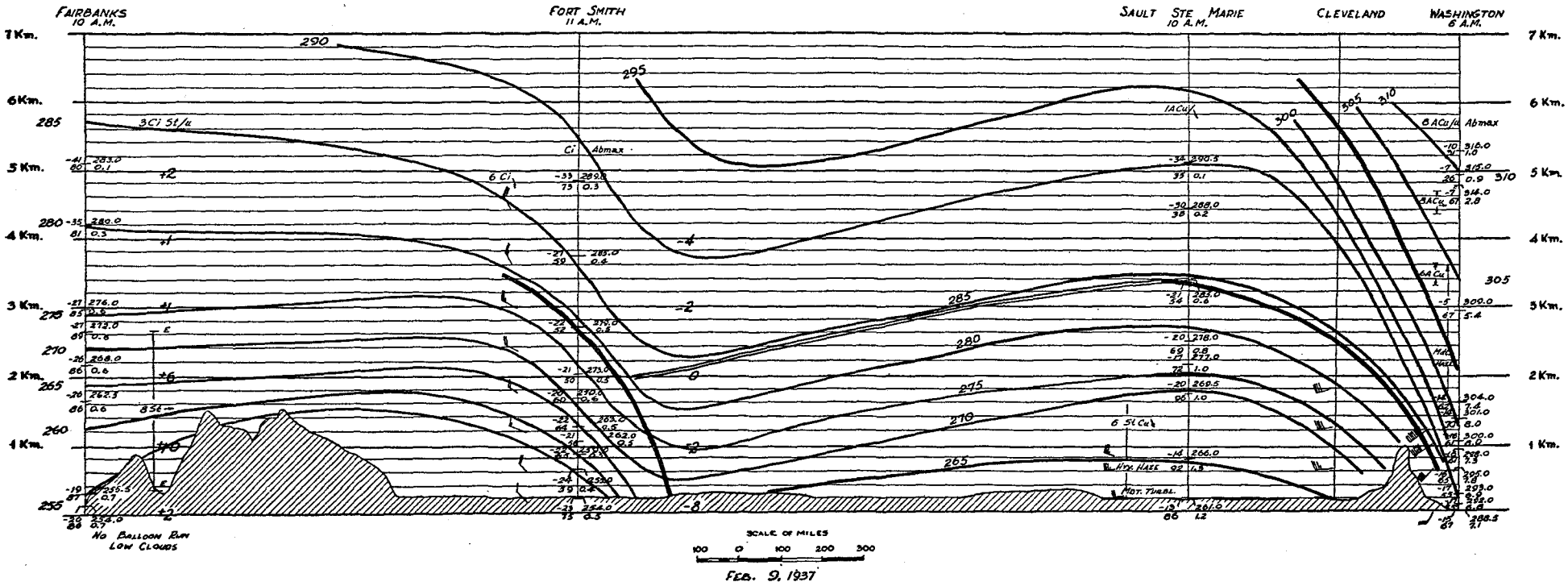

FIGURE 32.—Cross section, February 9, 1937.

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