FACTORS LEADING TO VARIATIONS IN MONTHLY AND SEASONAL SNOWFALL OVER EASTERN UNITED STATES

By

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I. Introduction. - The large variations in snowfall which occur among winters have posed a problem of utmost complexity to meteorologists. It is probably not an exaggeration to say that the meteorological profession looks upon abnormally snowy and relatively snowless winters in any area as <u>curiosa</u> in just about the same way as the layman. Yet these year to year variations must have a physical explanation, for they are manifestations of short-period climatic fluctuations just as periods of drought, flood and increased vulnerability to hurricanes. Inasmuch as some weather abnormalities of this nature have been shown to be related to the prevailing large-scale (or planetary) upper-air wind systems of the Northern Hemisphere*, a similar though preliminary attempt is made in this paper to investigate the snow characteristics of winters in northeastern United States. This type of study is a necessary prelude to any rational attempt to predict the character of winter.

II. Sources of material - There are two primary sources of data used in this investigation: (1) snowfall totals for many stations in northeastern United States and (2) seasonally averaged or mean maps at the 700 mb (about 10,000 foot) level. The latter charts have been worked up for the four seasons since 1932, considering winter as the three months December, January and February. Owing to the availability of these charts, winter snowfall statistics were also worked up for these periods.

The northeastern cities whose records were conveniently available for these purposes are shown in fig. 1, together with the normal annual snowfall.

The December, January and February snowfalls for individual years from 1929 through 1959 for these stations were then tabulated, summed and averaged for the area, and the resulting average snowfalls were ranked in descending order, as shown in Table 1. Thus the winter of greatest average snowfall for this period was 1955-56 when 58.3" was observed (17.7" above the 30-year areal average) while the winter of least snowfall was 1931-32 when an average of only 26.2" was recorded (14.4" below average). A rough idea of the economic importance of this difference may be obtained by estimating the difference in total weight of the snow over this area in the snowiest and

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* A detailed account of these problems will be found in "30-day Forecasting-A review of a Ten Year Experiment" by the author, published as Vol. II, No. 6, of Meteorological Monographs by The American Meterological Society, Boston, Mass.

in the least snowy year. These estimates are approximately 70,000 compared to 30,000 megatons.

A sample of the upper air maps used in this study is given in fig. 2, where the solid lines represent contours of the 700 mb pressure surface, and the broken lines departures from long-term normals. In interpreting these maps the reader should bear in mind that the resultant wind blows parallel to the contours so that lower heights lie to the left of an observer facing downwind. The isopleths of departures from normal (broken lines) represent the anomalous component of the resultant wind. The relationship of this component to the broken lines is the same as that expressed above for the total wind related to the solid lines.

We shall now examine some of the high and low ranking snow years of table 1 in the light of the corresponding charts.

III. Patterns associated with light and heavy snow years.

When the mean flow charts for years of heavy and light snows are examined, it becomes clear that there are appreciable differences. This does not mean that a unique pattern of prevailing upper-air flow is observed for each category of snowfall, for snow-storms come in strange varieties. However, the charts associated with the six highest and six lowest ranks of table 1 suggest fundamental types of anomalous flow which indicate the abnormality of the snow regime. At first this correlation may not appear too surprising until it is realized that snow-storms are capricious and occur only a small number of days of the 90 making up the seasonal mean maps. Obviously, it would not be feasible to reproduce all the seasonal mean upper-air maps studied in this report; therefore only a few winter circulation patterns favoring heavy or light snow years will be shown. Unfortunately (and perhaps surprisingly), in the heaviest snow year, 1955-56, most of the snow occurred during the month of March, and therefore we cannot relate this to our seasonal charts for winter (December, January and February). This peculiarity is indicated by noting the respective ranking of the winter months of 1955-56 in table I (Rank 14 in December and February and Rank 13 in January). This case in itself is adequate evidence that snows are not confined to the months popularly associated with winter.

The winters 1957-58 and 1944-45, which rank 2 and 3 respectively, are quite typical for patterns making possible heavy snow-storms. The outstanding features of these charts (figs. 2 and 3) are (1) strong positive anomalies in the 700 mb contour patterns over much of Canada and adjacent portions of the Atlantic, (2) a stronger than normal trough over eastern United States and strong ridge over the Far West. These conditions represent weaker than normal westerly winds over much of the continent (low zonal index), the deployment of colder than normal air masses over eastern U.S., and the generation and steering of southern storms northeastward along the eastern seaboard. The accompanying departures of temperature are shown below the mean contour charts, and the prevailing (principal) storm tracks for the season are indicated by arrows superimposed on the contour charts. The accompanying departures of precipitation, to the right of the temperature anomalies, show that precipitation was not extremely heavy over most of the area, so that much of it was in the form of snow rather than rain. This was due in large part to the cold air masses prevailingly deployed in the anomalous patterns of upper-air flow.

The impression one obtains through study of many charts such as these and related material, is that an anomalous upper-level wind pattern becomes established for the winter and persistently recurs in similar form with only brief and transitory deviations. These anomalous wind patterns to a large extent set the stage for certain types of storm development in particular areas, and moreover, because of their ability to deploy warm or cold (and wet or dry) air masses into the storm areas determine the growth rate of the storm once formed. The course of the storms is also frequently determined by these quasi-stable wind patterns, which in effect steer them. Thus the central problem involved in winter snow characteristics, and indeed in all other types of climatic fluctuations, must involve the prevailing wind patterns of the general circulation of the atmosphere. We shall not attempt to discuss this basic phase of the problem in this brief report, but only mention that it still remains unsolved.

If now we look into the relatively snowless years, the lowest ranks of table 1, we find strikingly different patterns than for the heavy snow years.

One of the typical examples is afforded by the winter 1936-37, depicted by the charts reproduced in fig. 4. The most noteworthy feature is the anomalously strong trough over the far west flanked by strong ridges over the adjacent Atlantic and Pacific. This prevailing wind pattern results in warm temperatures over eastern U.S. and cold weather in the west -- an ideal situation for strong storm development and northward movement through the east-central portion of the country. These storms deposit copious amounts of precipitation (see percentage of normal precipitation chart in fig. 4), but owing to the enhanced flow of warm air from the south (relative to normal), precipitation over the northeast occurs mostly in the form of rain rather than snow. In other words, although these cases include strong storm-generating and developing mechanisms, the air masses injected into the storms are generally too warm to produce heavy snows in the northeast.

Obviously, years with abnormally light snow may also occur when the total precipitation (both rain and snow) for the winter is low. A common case of this kind (winter 1941-42) is shown in fig. 5, where the negative anomaly off the east coast is not surmounted by large positive anomalies as was the case in figs. 2, and 3 (heavy snow years). Thus the large-scale anomalous component of flow from the Atlantic, important for northeastern precipitation, was largely absent and replaced by drier air from continental sources in Canada. On the other hand in the wet snow years, like those illustrated in figs. 2 and 3, east coast cyclones appear to be diverted northward rather than eastward or become stalled by great blocking anticyclones which are other manifestations of the positive anomalies in northeastern Canada.

IV. Seasonal snow amounts in relation to mean temperature and precipitation.

In the foregoing section the large-scale nature of wind-patterns and related air mass interactions which help determine the winter snow picture for the Northeast was described. It is also of interest to select one station and try to relate the winter snowfall to the two elements mean temperature and total precipitation. This has been done for Albany, N.Y., as shown in fig. 6, where snow amount has been plotted against mean winter temperature and total precipitation. Outside the boxed-in area are six years with subnormal snowfall. The three to the far right indicate that although there was ample total precipitation (about normal) the temperatures were too warm. Of course, the temperatures during individual storms differ from the seasonal mean, and were probably still warmer. The three values below the boxed-in area are cases when the total precipitation was so low that even if it were mostly in the form of snow the total depth recorded would not be high. In general, however, it is seen that there is rather poor relationship between mean seasonal temperature, total precipitation and snow amount. The one portion of the graph indicating such a relationship is the area bounded by horizontal 6" and 8" lines for total precipitation, where the total snow amounts appear to increase fairly regularly with decreasing mean seasonal temperature. Part of this increase may be due to the lesser density of snow at low temperatures, as well as, more obviously, the less frequent occurrence of rains under these circumstances. Then again, one must consider the "feedback" of increased snow on the temperature of the overlying air. That is, heavy and more persistent snow accumulations naturally help to reduce air temperatures, both because of the greater albedo of snow and the heat required to melt or sublimate it.

The overall lack of clear cut organization of points in the graph points up the need for considering the large-scale factors (wind patterns, storm tracks, and air mass interactions) for a more complete understanding of winter snows.

V. Longterm variations in annual snowfall.

It is well-recognized that climatic fluctuations take place on many time scales: not only from year to year, but from decade to decade, century to century and up to epochs of geological time. Although the data used for this study are necessarily restricted to the winters from 1929-30 to 1958-59, they provide interesting information about fluctuations for the past three decades. Average annual snowfalls for three consecutive ten year periods beginning with 1929-30 are plotted in fig. 7. In the shaded area, except for Rochester, there has been a gradual increase in recorded snowfall from the 1930's to the 1940's and 1950's. On the other hand over most stations to the east of the shaded area a decrease set in especially from the decade of the 1940's to the 1950's.

Appreciable light on the reasons for this decadal variation is shed by composite (average) charts for the winters of the latter two decades. These are shown in figs.

8 and 9, and the change between these is shown in fig. 10. It is clear that the large scale prevailing wind patterns of the upper air were appreciably different between the two decades, and we shall attempt to explain why these changes favor an increase in snow over the shaded area but a decrease in the area farther to the east. In the 1940's the negative anomaly off the east coast and the anomalous northerly components of flow over the entire Northeast favor diminished precipitation. In the winter of the 1950's on the other hand, the anomalous flow is from the southeast over much of the concerned area. The map of difference between decades (fig. 10) brings into sharp focus the greater southeast drift of the 1950's relative to the 1940's. This anomalous drift indicates a greater prevalence of warm maritime air and air flow from the south in the latter decade. This condition favors increased warmth, increased moisture, and conduciveness to vertical ascent favoring precipitation. The increased warmth of the 1950's relative to the 1940's over the northeast is indeed demonstrated in fig. 11.

Especially over areas east of the Appalachians, this greater maritimity was apparently enough to raise the temperature during storms so that a large portion of the precipitation fell as rain rather than snow. Farther west, however, in areas of greater continentality where normal temperatures are lower, and where there is a diminished effect of warming due to increased maritimity, the increase in precipitation would naturally be more apt to occur in the form of snow. Here we have an example of opposite effects on the snow picture introduced in adjacent large areas by a still larger-scale phenomenon of the general atmospheric circulation.

In fig. 9 one should also note the lesser intensity of the ridge over western U.S. in the latter decade (associated with the large falls in height in fig. 10), indicating greater prevalence of the "Alberta type" cyclones which usually influence the northeast. Thus this increased cyclonic activity would also favor the 1950's relative to the 1940's as a snowier decade in the shaded area, but not to the east where greater maritimity prevailed.

VI. Summary

1. Variations in annual snowfall over Northeastern United States are associated and probably dependent upon the average patterns of the general atmospheric circulation in the vicinity of North America and adjacent portions of the neighboring oceans. These patterns influence the life history of storms, including their regions of genesis and path, in part by injecting air masses of differing properties in differing locations from year to year. These factors largely determine the snow picture.

2. These large-scale variations in wind pattern, highly germane to an understanding of annual variations in snowfall, give greater meaning to simple analyses of averages of elements associated with varying seasonal snowfalls at one station.

3. Even when averaged over decades there are large variations in overage snowfall. These, as well as inter-annual variations, appear to be highly correlated with the average mid-tropospheric prevailing wind pictures.

4. A special analysis of conditions during the 1940's and 1950's reveals a large area of increased snowfall from the eastern Great Lakes to the Appalachians and a general decrease east of here. These differences are associated with large-scale difference in the mean upper wind circulation between decades favoring increased maritimity and warmth in the 1950's but operating in such a manner as to increase snowfall well inland yet decrease it along the Atlantic Seaboard.

ACKNOWLEDGMENT

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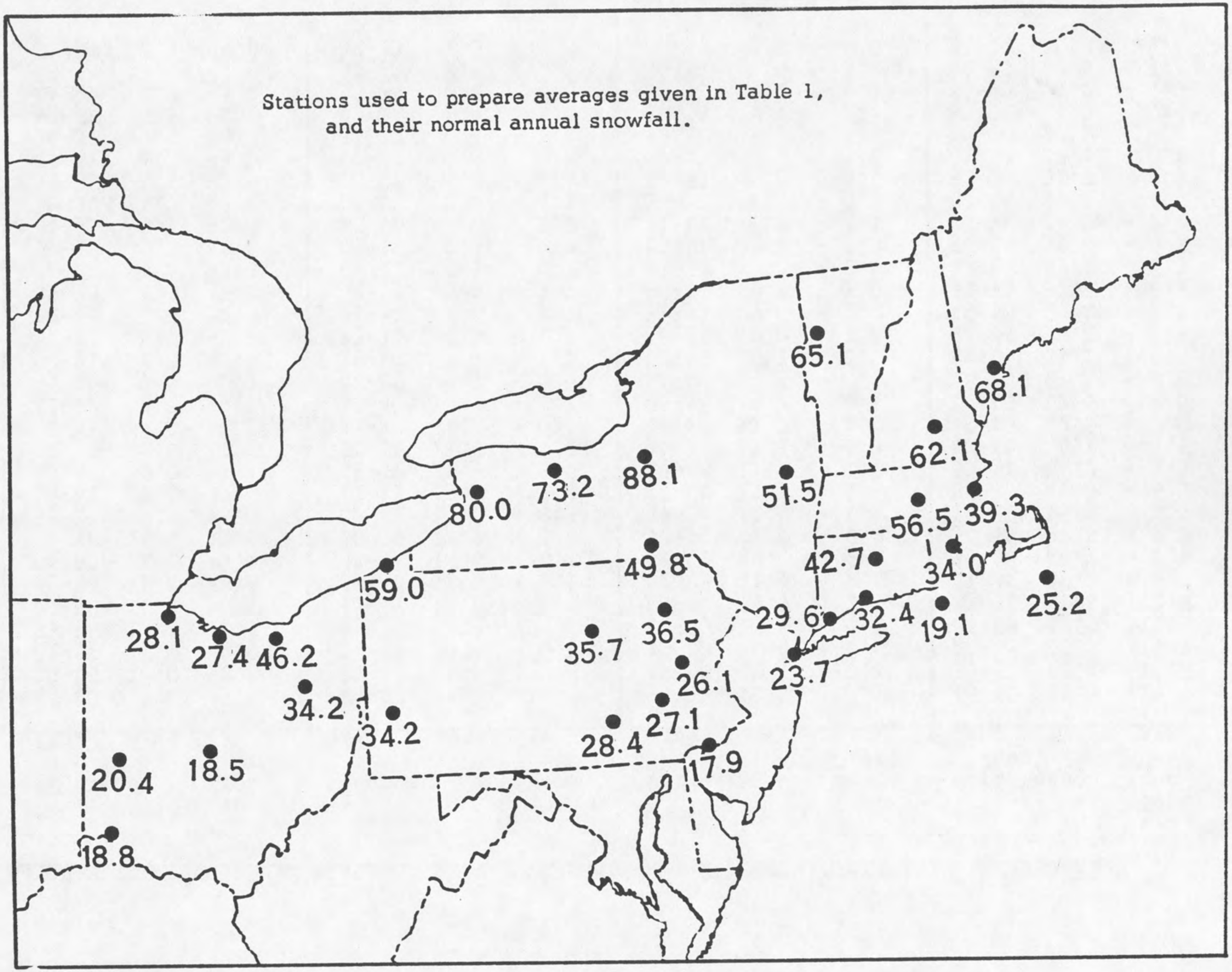
TABLE I

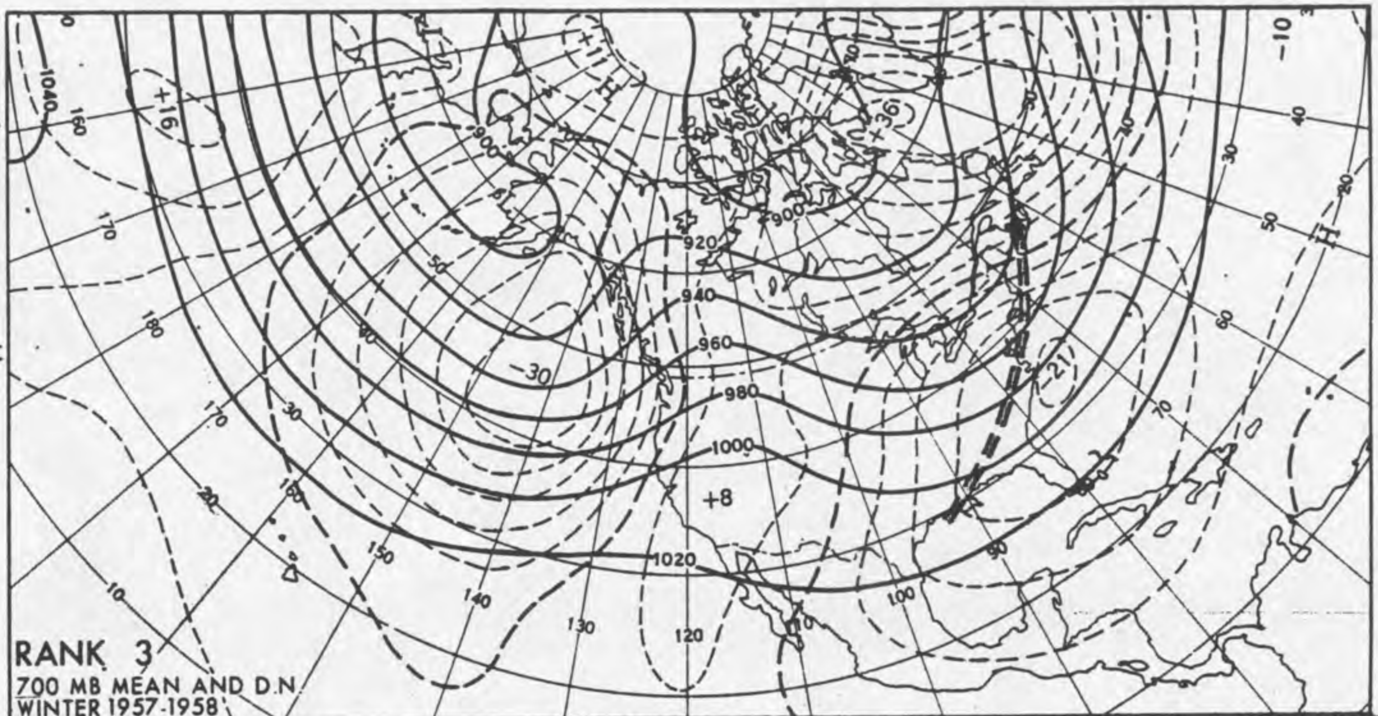
Average snow recorded at 32 stations over Northeastern U.S. for winters 1929 through 1959

Rank	December Year	December Avg.	Dep. from 30-yr. Avg.	January Year	January Avg.	Dep. from 30-yr. Avg.	February Year	February Avg.	Dep. from 30-yr. Avg.	Cold Season Total Year	Cold Season Total Avg.	Dep. from 30-yr. Avg.
1	45-46	17.4	+9.5	44-45	21.1	+10.8	33-34	20.1	+10.3	55-56	58.3	+17.7
2	44-45	16.0	+8.1	47-48	19.6	+ 9.3	57-58	20.1	+10.3	57-58	56.4	+15.8
3	51-52	15.8	+7.9	34-35	16.4	+ 6.1	39-40	16.6	+ 6.8	44-45	55.3	+14.7
4	33-34	12.4	+4.5	35-36	15.9	+ 5.6	46-47	15.9	+ 6.1	47-48	53.5	+12.9
5	47-48	12.3	+4.4	56-57	14.5	+ 4.2	49-50	13.7	+ 3.9	33-34	51.4	+10.8
6	29-30	11.4	+3.5	57-58	14.4	+ 4.1	44-45	12.3	+ 2.5	51-52	49.3	+ 8.7
7	56-57	11.1	+3.2	53-54	14.4	+ 4.1	51-52	12.0	+ 2.2	35-36	48.7	+ 8.1
8	50-51	11.0	+3.1	38-39	13.7	+ 3.4	32-33	12.0	+ 2.2	58-59	47.8	+ 7.2
9	35-36	10.9	+3.0	40-41	13.6	+ 3.3	35-36	11.7	+ 1.9	56-57	46.3	+ 5.7
10	42-43	10.4	+2.5	42-43	13.6	+ 3.3	43-44	11.3	+ 1.5	38-39	45.9	+ 5.3
11	48-49	9.0	+1.1	58-59	12.3	+ 2.0	47-48	11.2	+ 1.4	50-51	44.2	+ 3.6
12	58-59	8.6	+0.7	50-51	11.0	+ 0.7	34-35	11.1	+ 1.3	40-41	44.1	+ 3.5
13	54-55	8.0	+0.1	37-38	10.9	+ 0.6	45-46	11.0	+ 1.2	39-40	42.6	+ 2.0
14	46-47	8.0	+0.1	55-56	10.2	- 0.1	55-56	10.2	+ 0.4	42-43	42.6	+ 2.0
15	55-56	7.6	-0.3	48-49	9.7	- 0.6	41-42	9.5	- 0.3	46-47	41.4	+ 0.8
16	30-31	7.0	-0.9	39-40	9.2	- 1.1	54-55	9.1	- 0.7	45-46	41.1	+ 0.5
17	32-33	6.7	-1.2	30-31	9.0	- 1.3	38-39	8.0	- 1.8	34-35	39.1	- 1.5
18	52-53	5.9	-2.0	51-52	8.6	- 1.7	31-32	7.6	- 2.2	49-50	37.4	- 3.2
19	37-38	5.5	-2.4	52-53	8.6	- 1.7	48-49	6.8	- 3.0	53-54	36.4	- 4.2
20	39-40	5.4	-2.5	41-42	8.1	- 2.2	58-59	6.8	- 3.0	48-49	33.9	- 6.7
21	57-58	5.1	-2.8	29-30	7.5	- 2.8	50-51	6.8	- 3.0	54-55	33.9	- 6.7
22	34-35	5.1	-2.8	45-46	7.4	- 2.9	42-43	6.7	- 3.1	30-31	32.8	- 7.8
23	49-50	4.7	-3.2	46-47	7.2	- 3.1	30-31	6.4	- 3.4	43-44	32.5	- 8.1
24	38-39	4.4	-3.5	54-55	5.9	- 4.4	52-53	6.3	- 3.5	32-33	30.9	- 9.7
25	40-41	4.3	-3.6	49-50	5.3	- 5.0	40-41	6.2	- 3.6	41-42	30.4	-10.2
26	36-37	3.9	-4.0	36-37	5.1	- 5.2	53-54	5.9	- 3.9	29-30	30.1	-10.5
27	53-54	3.7	-4.2	43-44	4.7	- 5.6	37-38	5.2	- 4.6	37-38	29.7	-10.9
28	41-42	2.7	-5.2	33-34	3.8	- 6.5	29-30	5.1	- 4.7	36-37	27.7	-12.9
29	43-44	2.0	-5.9	31-32	3.6	- 6.7	56-57	4.6	- 5.2	52-53	27.5	-13.1
30	31-32	1.1	-6.8	32-33	2.5	- 7.8	36-37	3.8	- 6.0	31-32	26.2	-14.4

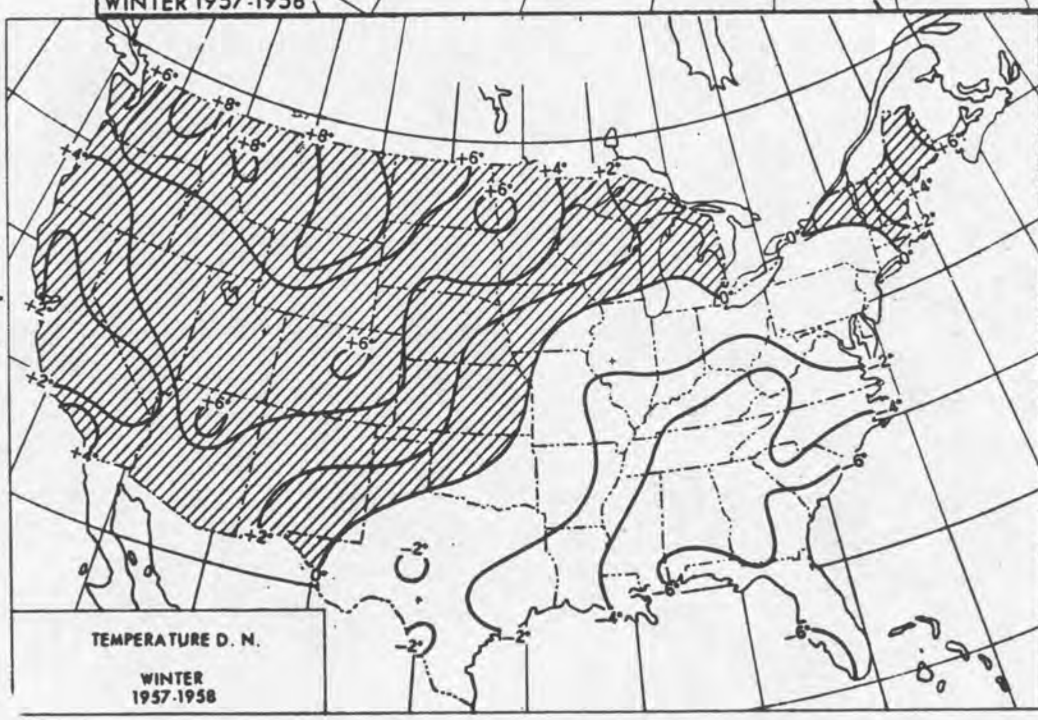


Stations used to prepare averages given in Table 1, and their normal annual snowfall.

Mean 700 mb contours (solid lines labelled in tens of feet) for winter 1957-58, and isopleths of departure from normal (broken) drawn for each 50 feet and with maximum values labelled in centers. Arrow denotes principal track of storms.

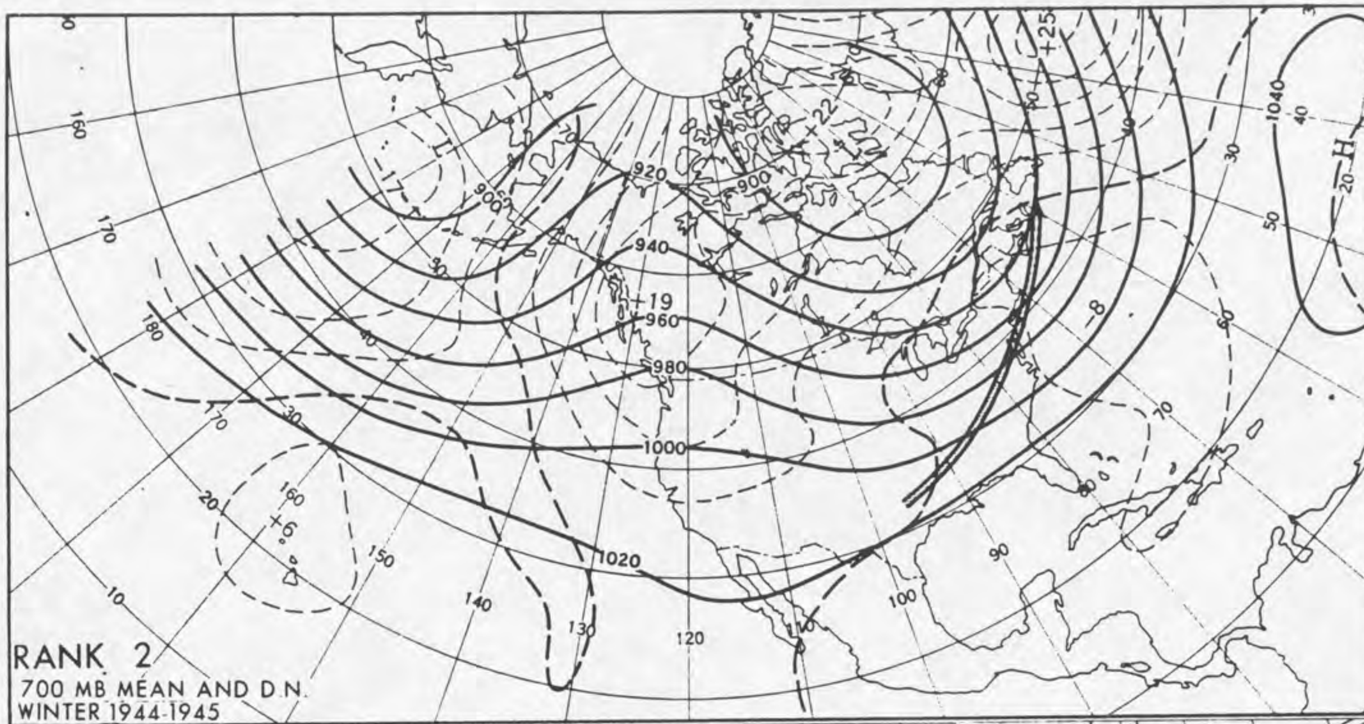


Associated Isopleths of departures from normal of temperature (°F).



Percentage of normal precipitation.

Mean 700 mb contours (solid lines labelled in tens of feet) for winter 1944-45, and isopleths of departure from normal (broken) drawn for each 50 feet and with maximum values labelled in centers, Arrow denotes principal track of storms.



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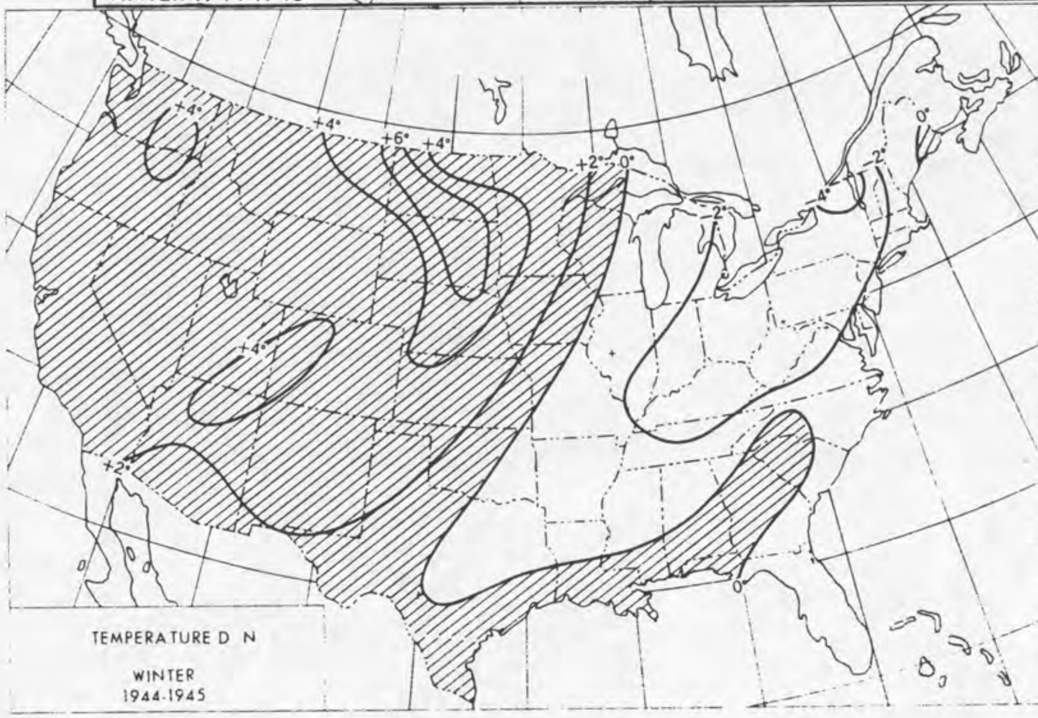
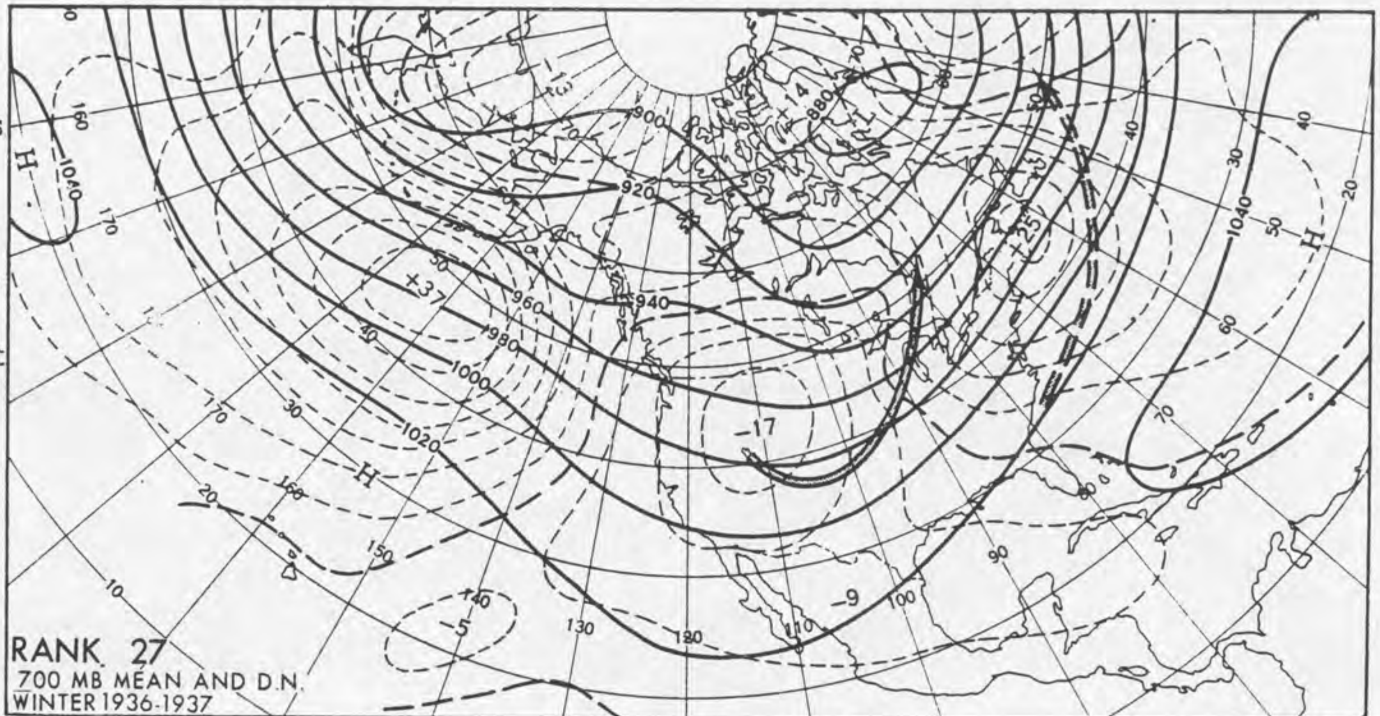
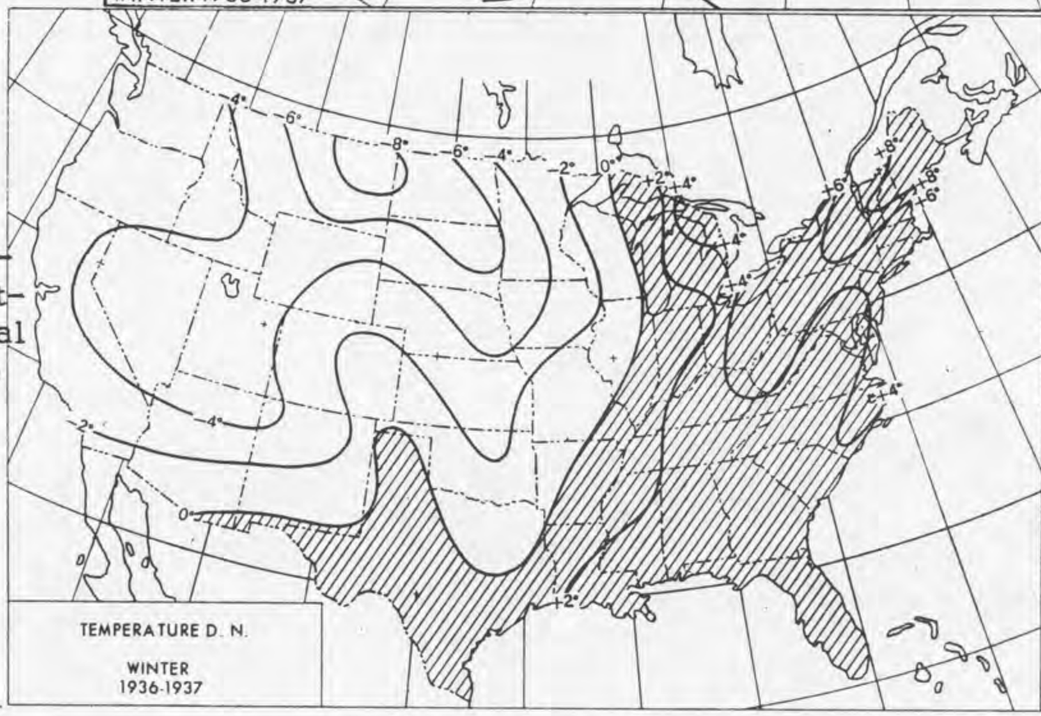


Percentage of normal precipitation.



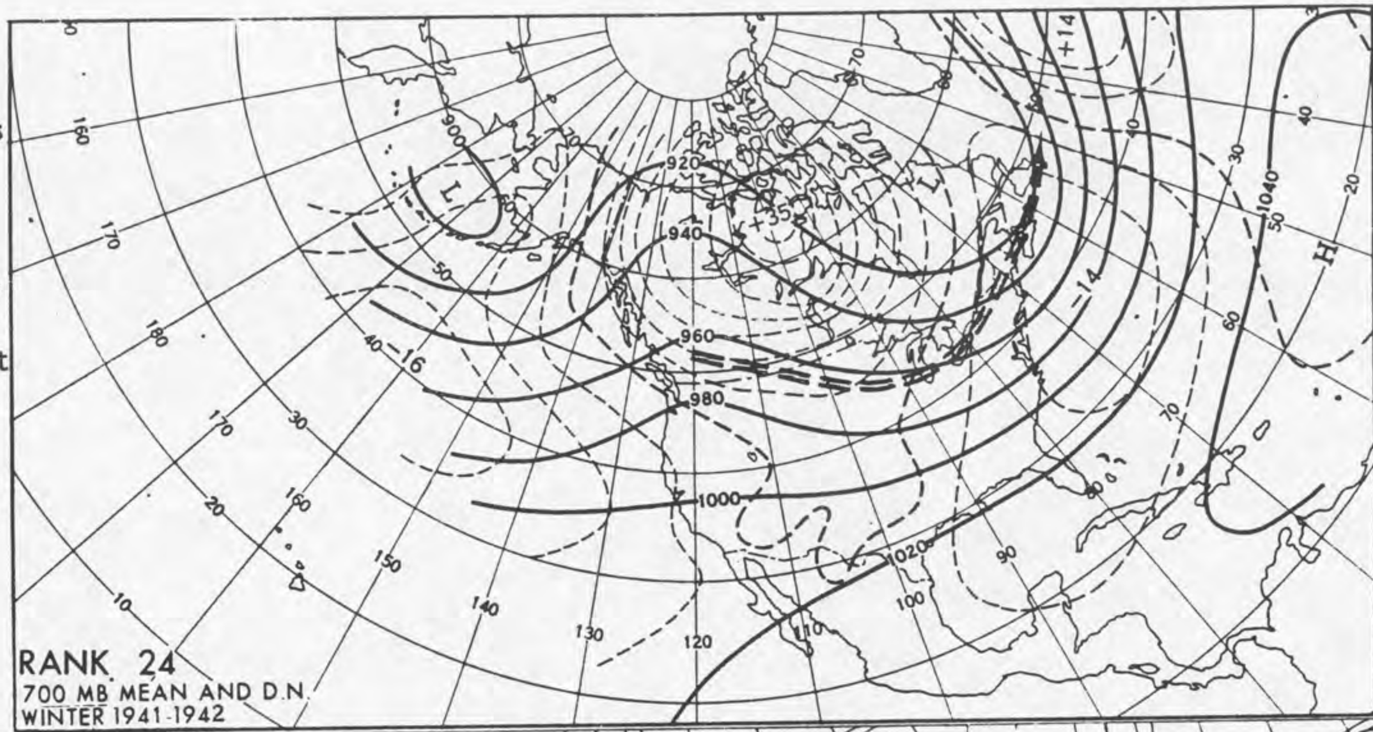
Mean 700 mb contours (solid lines labelled in tens of feet) for winter 1936-37, and isopleths of departure from normal (broken) drawn for each 50 feet and with maximum values labelled in centers. Arrow denotes principal track of storms.



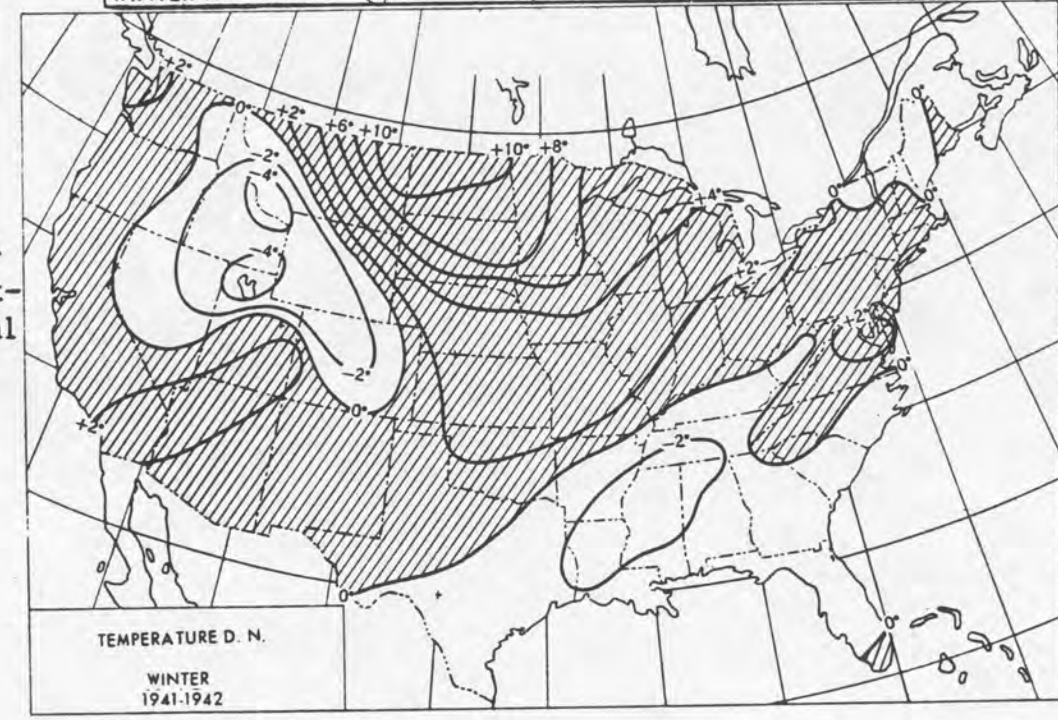
Associated Isopleths of departures from normal of temperature (°F).

Percentage of normal precipitation.

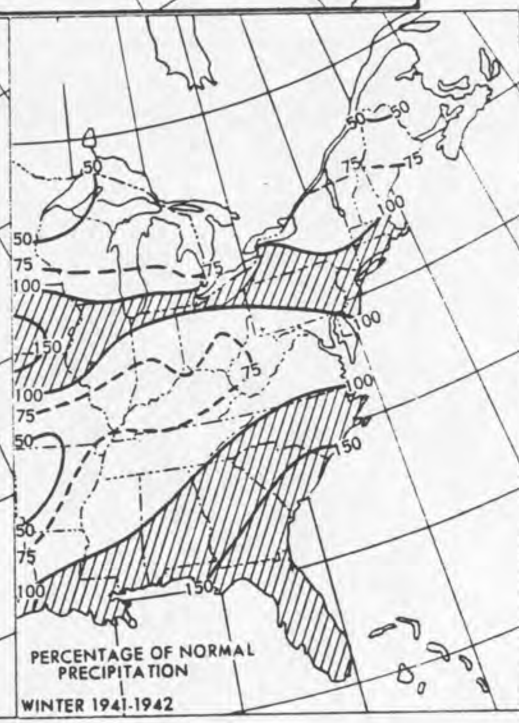
Mean 700 mb contours (solid lines labelled in tens of feet) for winter 1941-42, and isopleths of departure from normal (broken) drawn for each 50 feet and with maximum values labelled in centers. Arrow denotes principal track of storms.

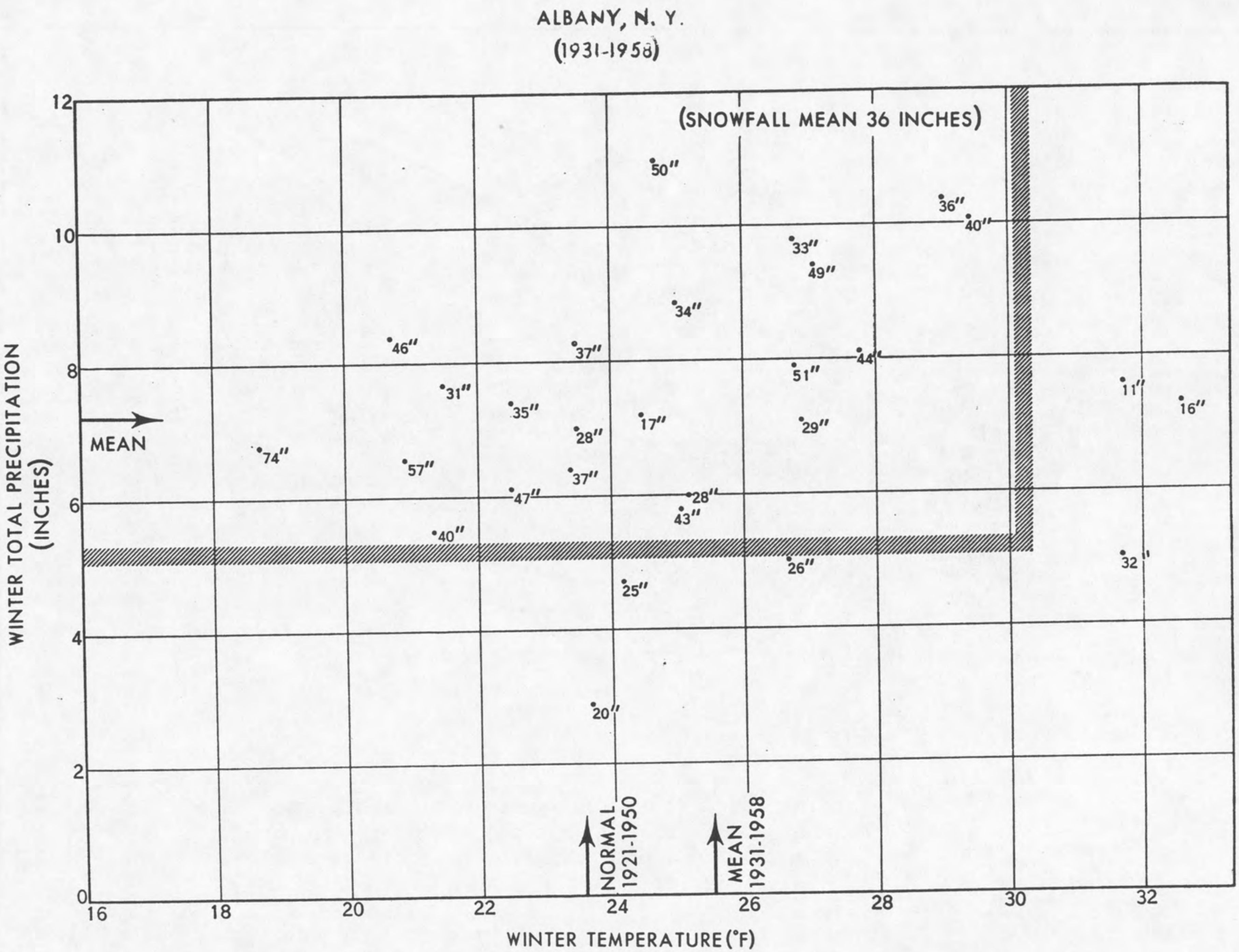


Associated Isopleths of departures from normal of temperature (°F).

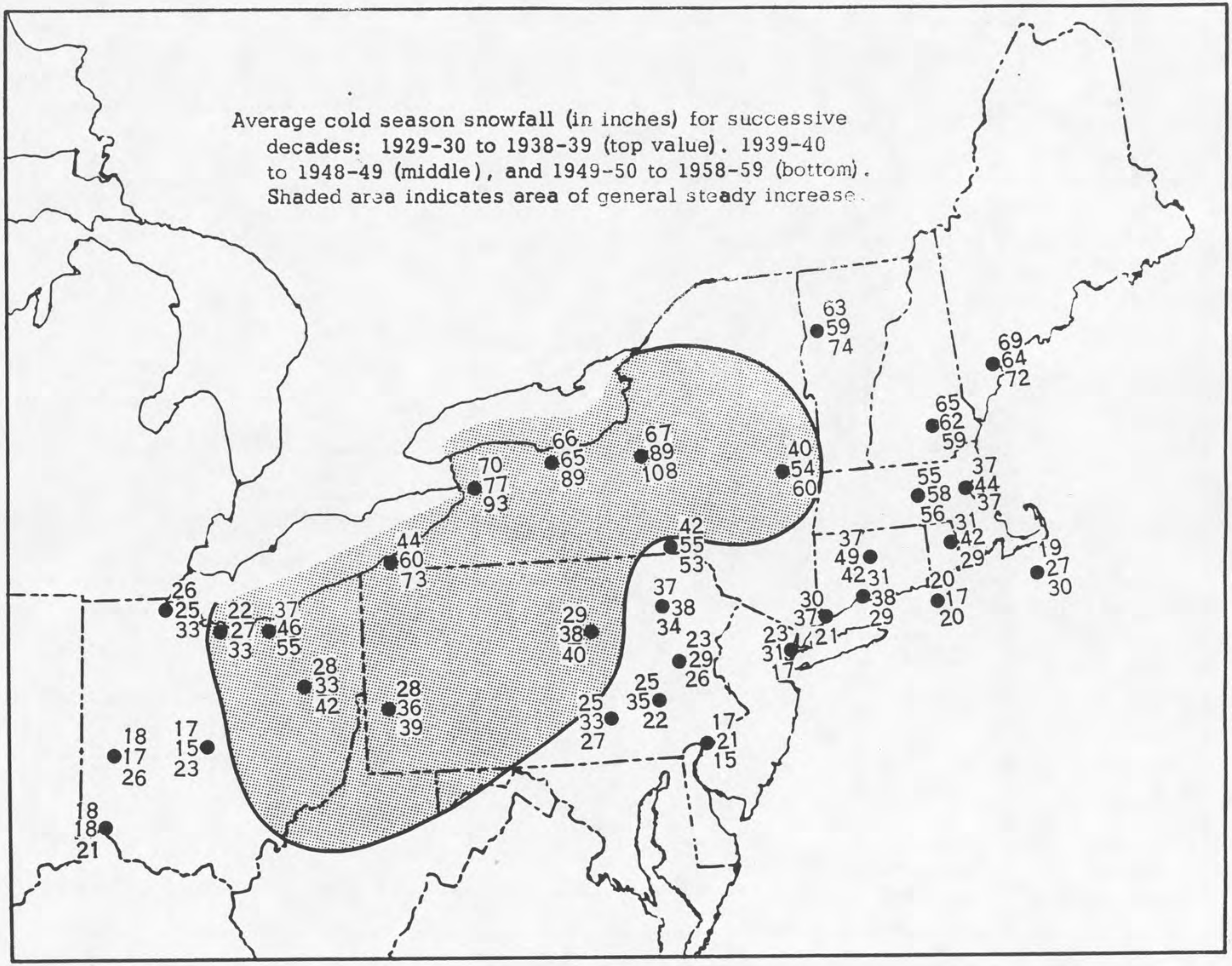


Percentage of normal precipitation.

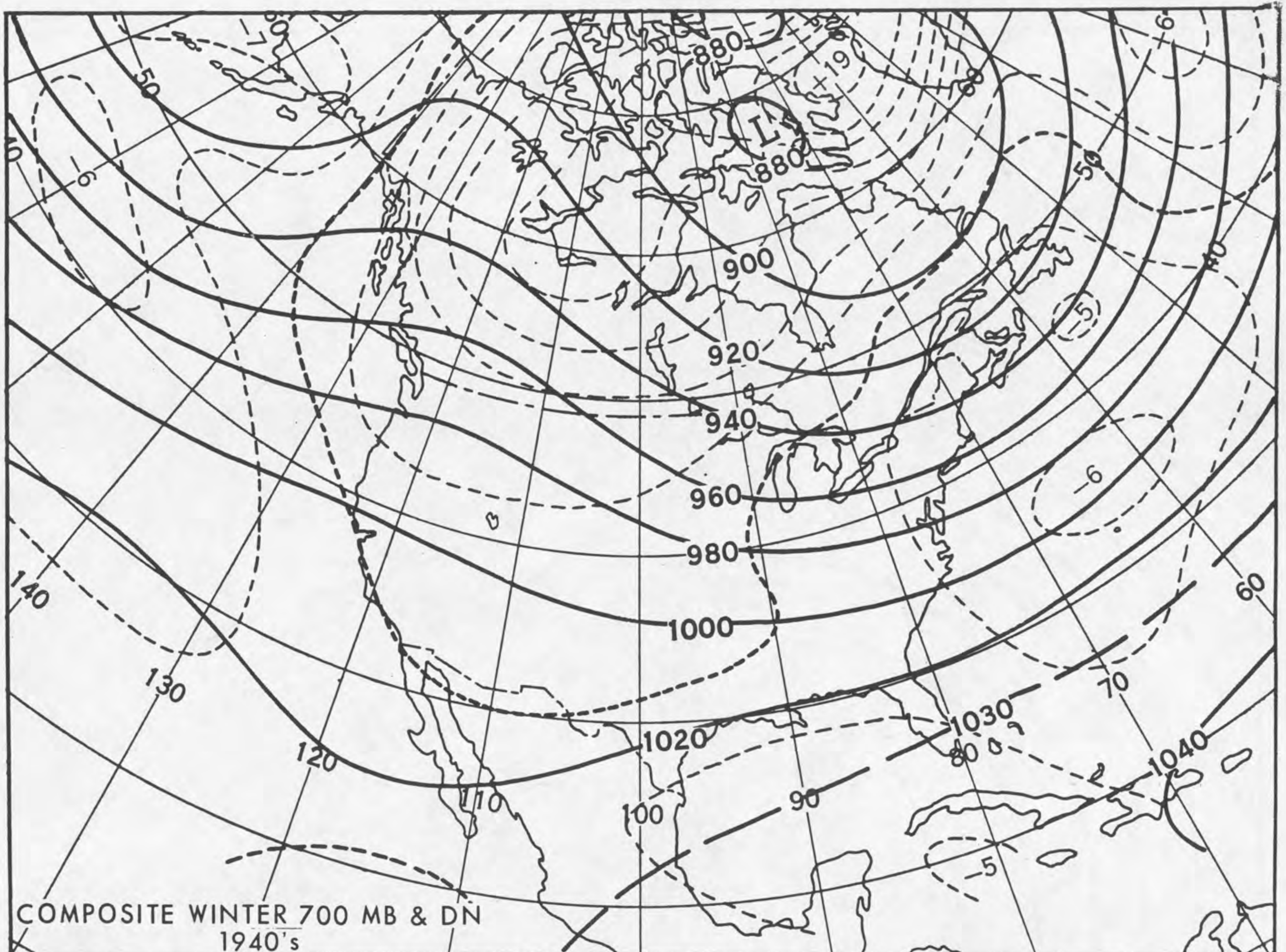




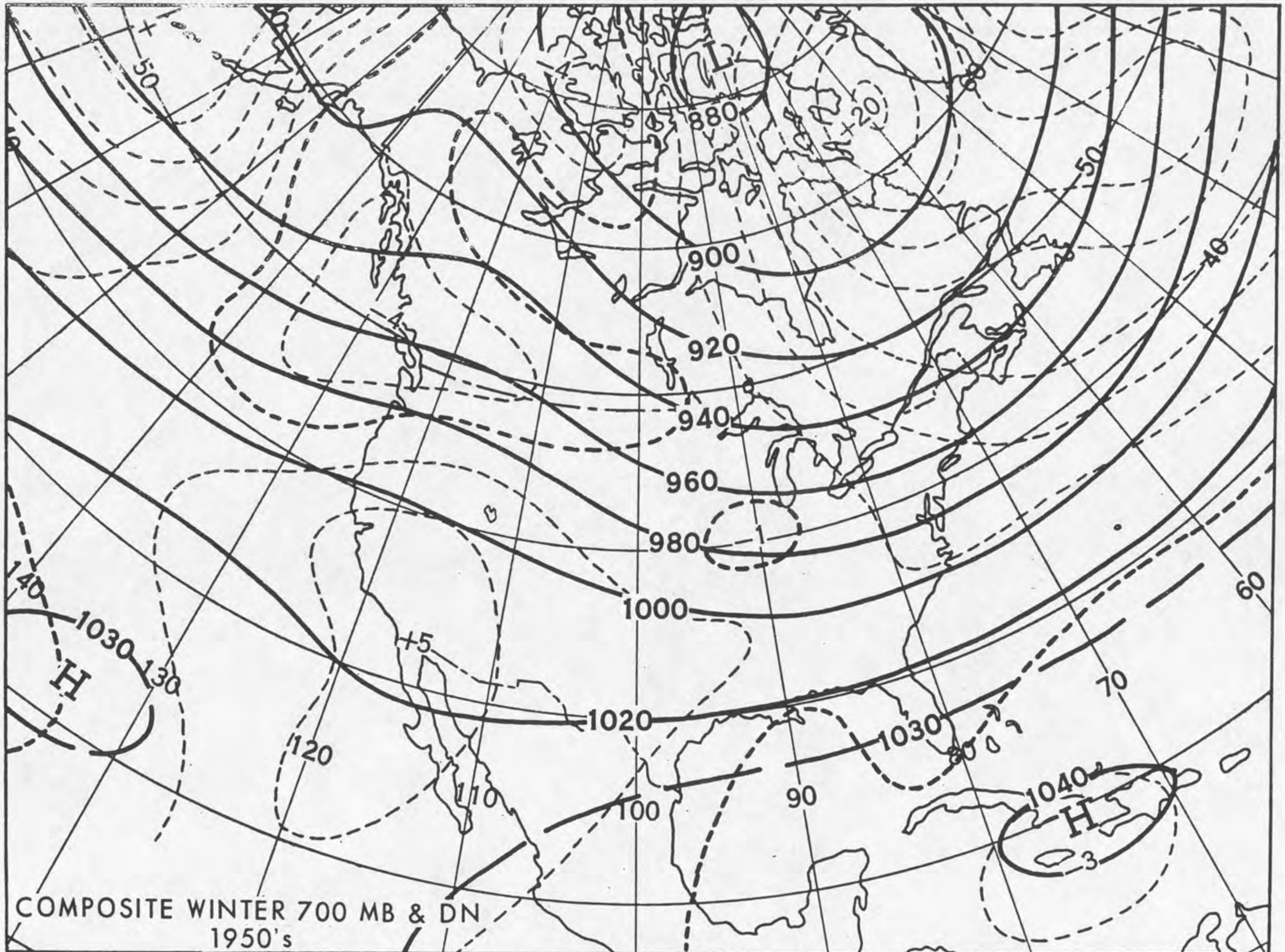
Winter snowfall (in inches) at Albany, N.Y. as a function of winter temperature and total precipitation.



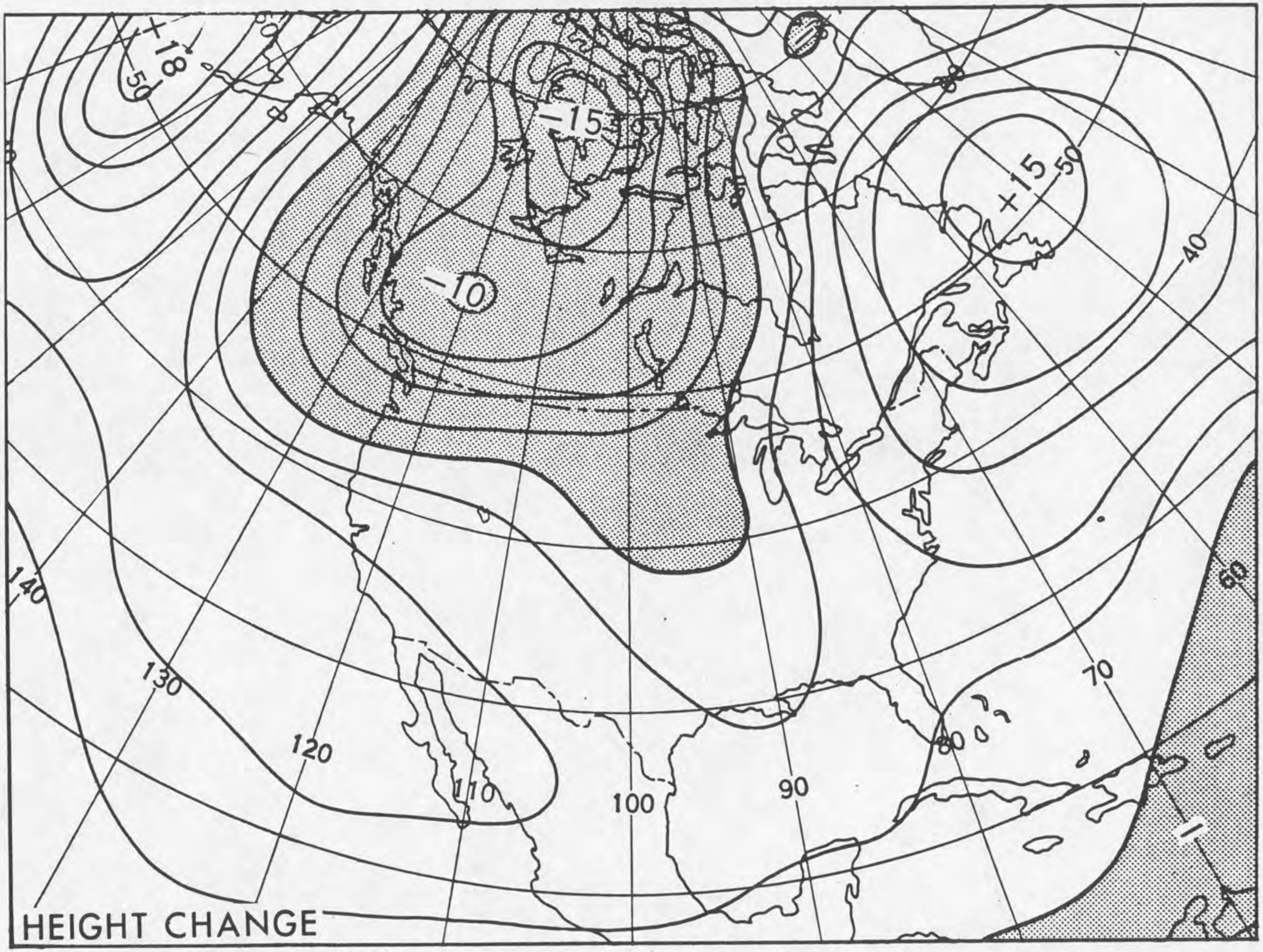
Average cold season snowfall (in inches) for successive decades: 1929-30 to 1938-39 (top value). 1939-40 to 1948-49 (middle), and 1949-50 to 1958-59 (bottom). Shaded area indicates area of general steady increase.



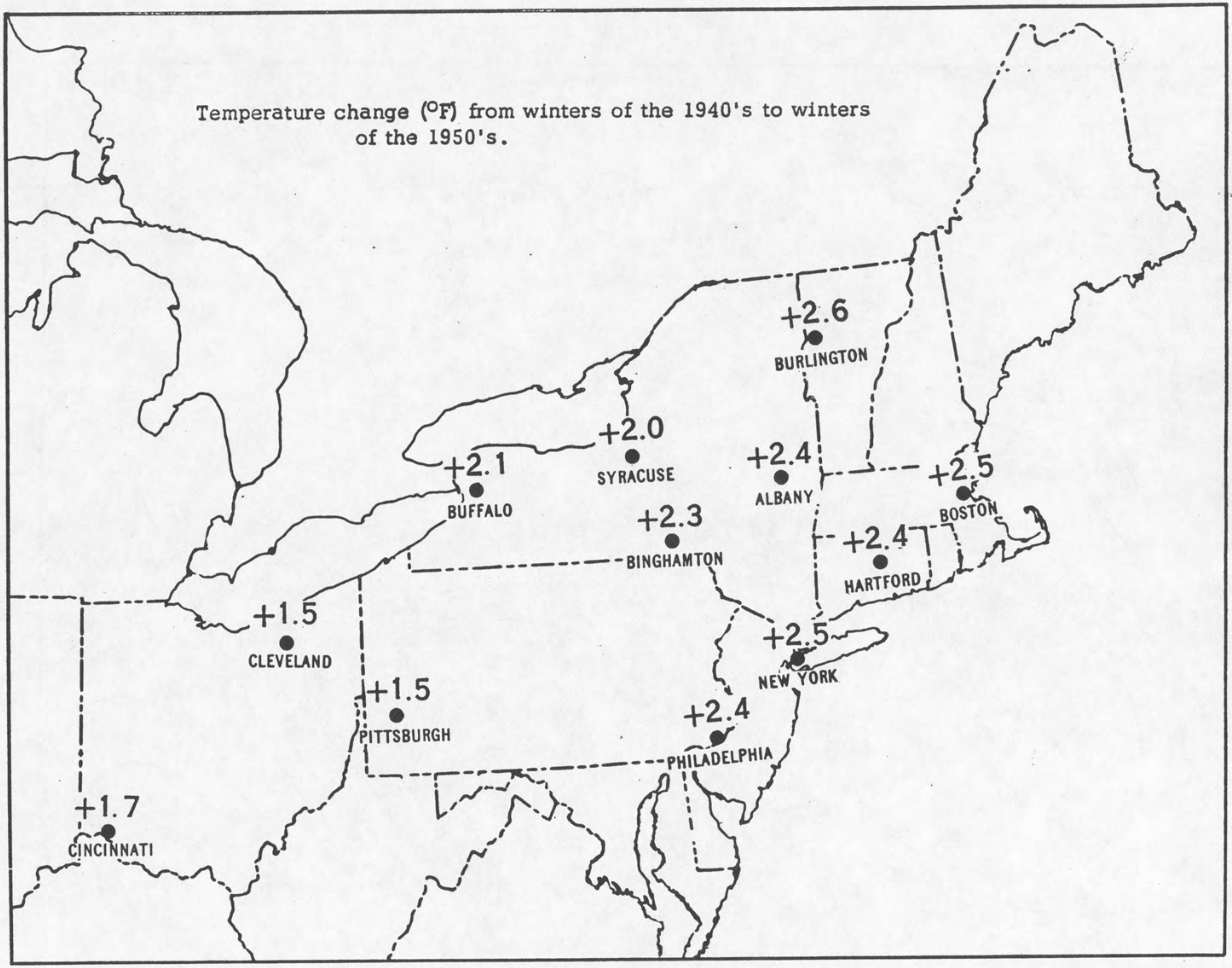
Composite (average) 700 mb contours (labelled in tens of feet) and isopleths of departure from normal (drawn for each 50 feet, with centers labelled) for winters of 1940-49.



Composite (average 700 mb contours (labelled in tens of feet) and isopleths of departure from normal (drawn) for each 50 feet, with centers labelled) for winters of 1950-59.



Change in contour height (chart 9 minus chart 8).



Temperature change (°F) from winters of the 1940's to winters of the 1950's.