SYNOPTIC CLIMATOLOGY OF HEAVY SNOWFALL OVER THE CENTRAL AND EASTERN UNITED STATES

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ABSTRACT

Verification shows that recent guidance and official heavy snowfall forecasts have achieved only a modest degree of success. Therefore, the synoptic-climatological relationship of heavy snowfall to those surface and upper-air features which are routinely forecast is studied in an attempt to improve operational forecasting of heavy snowfall east of the Rockies. The relationship is modeled in a way suitable for direct use on available circulation prognoses. The models relate percentage frequency of occurrence of heavy snowfall in 12-hr. periods to the initial 500-mb. absolute vorticity maximum, the 500-mb. height contours, the 1000–500-mb. thickness contours, and the surface low pressure center.

1. INTRODUCTION

The prediction of heavy snow is one of the Weather Bureau's most important functions, yet on the average, only a modest degree of success can be claimed. During the winter seasons of 1962–63, 1963–64, and 1964–65 heavy snow guidance forecasts for the entire United States were issued by the Quantitative Precipitation Forecast (QPF) Section of the National Meteorological Center (NMC). These forecasts were verified along with those issued by Forecast Centers with designated responsibility for areal heavy snow forecasting. The usual definition of heavy snow as 4 in. or more in 12-hr. time intervals was used. Verification intervals were only for the specific time periods of 0000 to 1200 GMT and 1200 to 0000 GMT. All forecasts verified were completed at an average time of approximately three hours before the beginning time of the forecast periods. The sizes of areas forecast and observed were measured in square degrees of latitude by planimeter and compared by "threat score." "Threat score" is defined as

$$\frac{A_c}{A_f+A_o-A_c}$$

where A_c=area correct, A_f=area forecast, and A_o=area observed.

Table 1 shows that over the three-season period only 12 percent of the total area of heavy snow forecast and observed was correctly forecast. The total of the area alerted in advance for heavy snow that did not occur and of the area observing heavy snow that was not forecast was a little more than seven times the area correctly forecast. These statistics indicate the need for further refinement of heavy-snow forecasting techniques. In view of the increasing accuracy of the products of numerical weather prediction, new models relating upper-air circulation features to occurrence of heavy snow are needed.

TABLE 1.—*NMC's guidance and Field Centers' official heavy snowfall areas (in square degrees of latitude) forecast (A_f), observed (A_o), and correct (A_c), and the corresponding "threat score" for the winters of 1962 through 1965. Note that numerical value of A_o is doubled since two sets of forecasts are verified as an entity*

Season	A_f	$2(A_o)$	A_c	Threat score
1962–63	2642.1	908.8	352.7	0.110
1963–64	1858.5	980.8	313.8	.124
1964–65	1617.3	1127.4	341.6	.142
Total	6117.9	3017.0	1008.1	.124

Fawcett and Saylor's [1] recent synoptic-climatological models of weather accompanying Colorado-type storms are proving extremely valuable in heavy-snow forecasting for the northern Rockies and Plains. A similar approach is followed in this study in developing relationships for use in forecasting the more important snow storms for that area of the United States east of the Rocky Mountains. The models developed present the synoptic climatology of heavy snow situations in terms of features of surface and upper-air circulation prognoses prepared on a regular basis at NMC.

2. PROCEDURE

The original set of data consisted of all heavy snow situations during the 1963–64 and 1964–65 seasons for that area of the United States east of 100° W., including that portion of Canada south of 49° N. and west of the northern tip of Maine. Heavy snow, as defined for this study, is snowfall of 4 in. or more over a minimum area of 4 square degrees of latitude (14,384 n. mi.^{2}) in the specific 12-hr. periods from 0000 to 1200 GMT or 1200 to 0000 GMT. There were 81 cases in the two seasons that met these qualifications. Fifty of these were associated with deepening and occluding surface low-pressure systems. This characteristic is common to all snowstorms

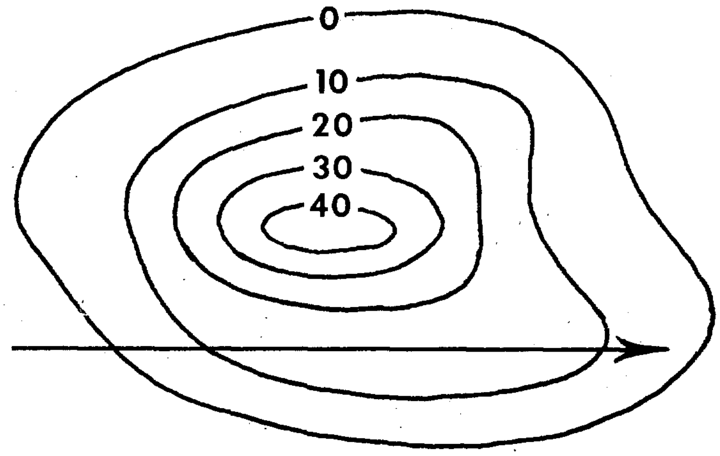

FIGURE 1.—Percentage frequency of occurrence of heavy snow with respect to the initial vorticity maximum and the direction of movement of the vorticity maximum during the following 12 hr. Origin is at initial position of vorticity maximum. Average direction and speed of movement of vorticity center, 61° at 35 kt. Scale 1:20,000,000.

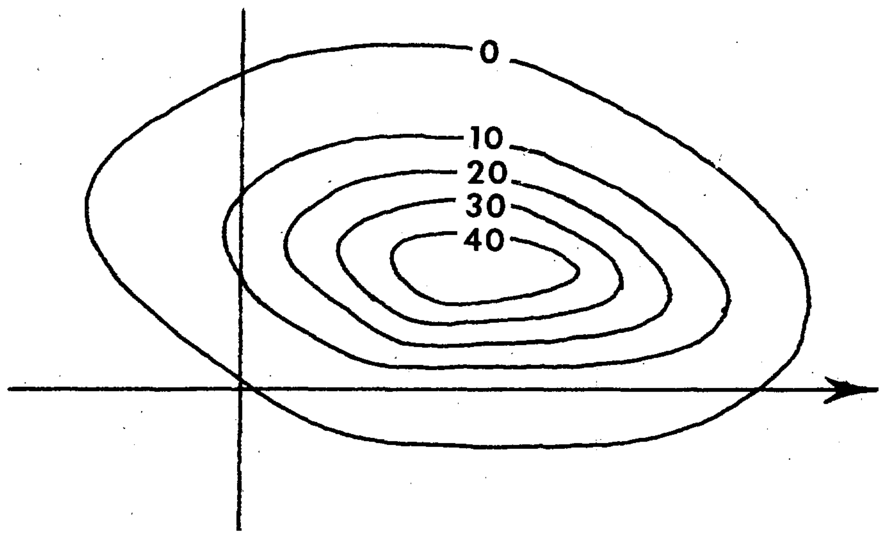

FIGURE 2.—Percentage frequency of occurrence of heavy snow with respect to the initial surface low center and the direction of movement of the center during the following 12 hr. Origin is at initial position of surface Low. Average direction and speed of movement of low center, 50° at 31 kt. Scale 1:20,000,000.

that reach severe intensity in the central and eastern United States. This study deals mainly with these more important weather situations (50 cases) unless it is specifically stated otherwise.

The relationship of 12-hr. heavy snowfall to selected circulation parameters at the beginning of the snowfall period was obtained in the following manner. First, a grid overlay with grid-interval of ¼ degree of latitude was placed over the observed heavy snow area in such a way that the origin was at the position of the initially observed 500-mb. vorticity maximum [1] with x-axis oriented in the direction of its observed position at the end of the 12-hr. snowfall period. Second, the occurrences of heavy snow in each grid square were tallied for all 50 cases and a smoothed analysis (fig. 1) made of percentage frequency.

Figure 2 was derived in the same manner, except the grid origin was placed at the initial observed surface low-pressure center with x-axis oriented in the direction of its observed position at the end of the 12-hr. snowfall period.

Figures 3 and 4, showing composite 500-mb. height and 1000–500-mb. thickness features, were derived similarly, except height and thickness values were tallied on a coarser grid (each square equal to 2 square degrees of latitude) before mean values were analyzed. Figures 3 and 4 were used to derive the composite 1000-mb. chart shown in figure 5. Superimposed on the composite charts (figs. 3, 4, and 5) is the percentage frequency of heavy snow as related to the vorticity maximum from figure 1.

[1] The 500-mb. vorticity analyses were obtained from the NWP barotropic prognoses with data cutoff at 1 hr. and 30 min. after regular upper-air observation time.

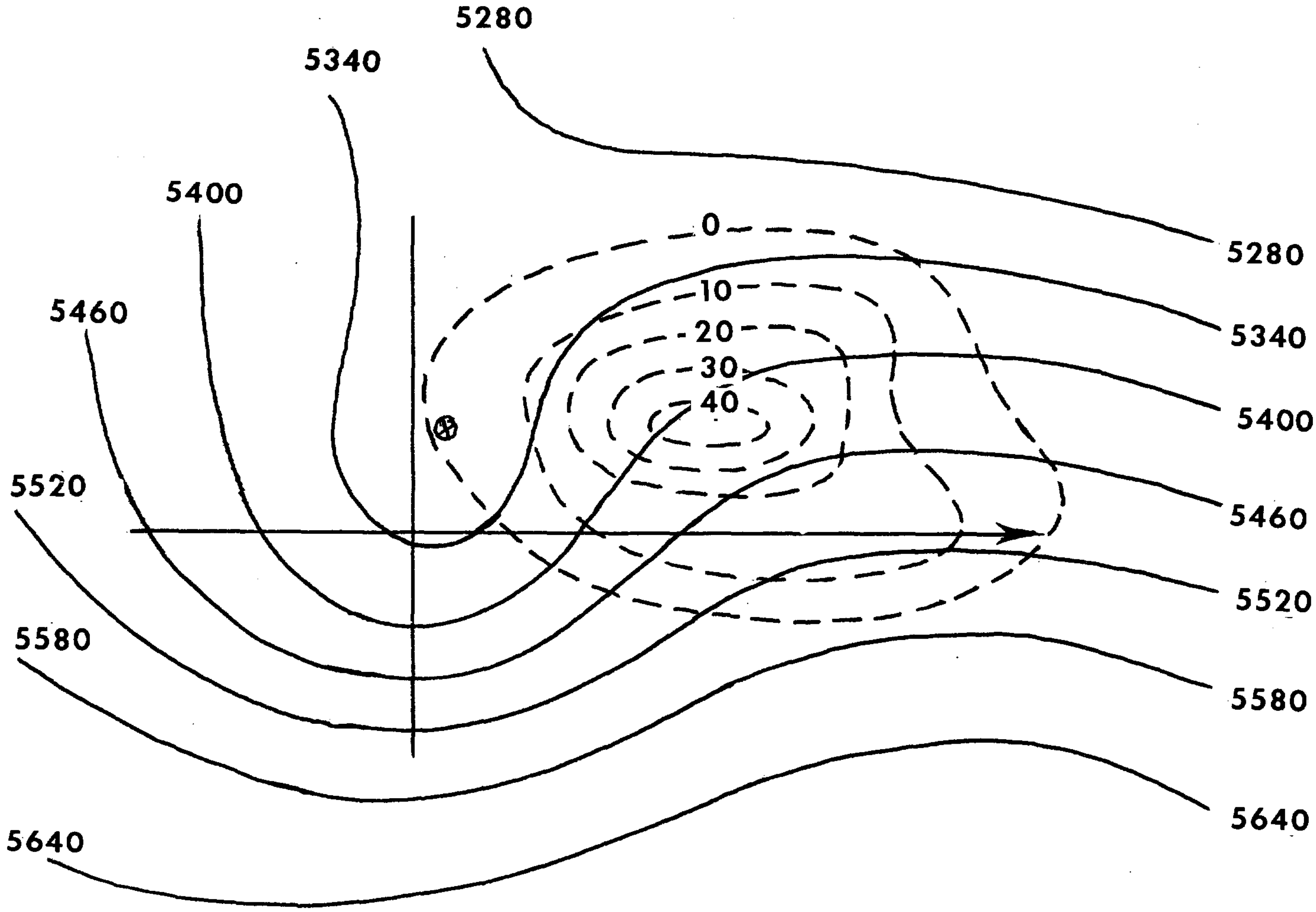

FIGURE 3.—Percentage of occurrence of heavy snow and composite initial 500-mb. chart (gpm.). Orientation is the same as figure 1 Scale 1:20,000,000.

3. DISCUSSION OF RELATIONSHIPS

Figures 1 through 5 indicate certain favored locations for the occurrence of heavy snow. The most favorable location with respect to the 500-mb. vorticity maximum is about 6.5 to 7 latitude degrees downstream and 2.5 latitude degrees to the left of the track of the maximum during the following 12 hr. The favored location with respect to the surface low-pressure center is about 5 latitude degrees along and 2.5 latitude degrees to the left of its path. This is in good agreement with Fawcett and Saylor's [1] findings about heavy snow associated with the Colorado-type cyclone. From the composite 500-mb. chart in figure 3, the best location for heavy snow is along the path of the 500-mb. Low and slightly downstream from the point where contour curvature changes from cyclonic to anticyclonic. Figure 4 shows heavy snow is most likely near the thickness ridge within the contour interval 5310 to 5370 gpm. The heavy snowfall distribution with the derived composite 1000-mb. chart in figure 5 is very similar to that shown in relation to the surface low center (fig. 2).

It is well known that the polar jet is often intimately associated with the occurrence of heavy snow. The model relationship for 40 cases (27 of these qualified as deepening and occluding low-pressure systems) during the 1963–64 season is shown in figure 6. The individual jet for each of these cases was delineated through careful consideration of observed 200- and 300-mb. data and 25,000- to 40,000-ft. winds. Further attempts to model the jet relationship to heavy snow were discontinued during the 1964–65 season. It was found that the available forecasting tools were incapable of predicting the location of the jet to a suitable degree of accuracy. Therefore, the model was found to be of limited forecast value.

4. ADDITIONAL DATA

Table 2 lists in order of areal rank the snowstorms with areal extent of 20 square degrees of latitude or greater. All nine of these were of the deepening and occluding type. The average areal extent for the original data set of 81 cases was 10.0 square degrees of latitude, while that for the 50 deepening and occluding cases was 11.9. Table 2

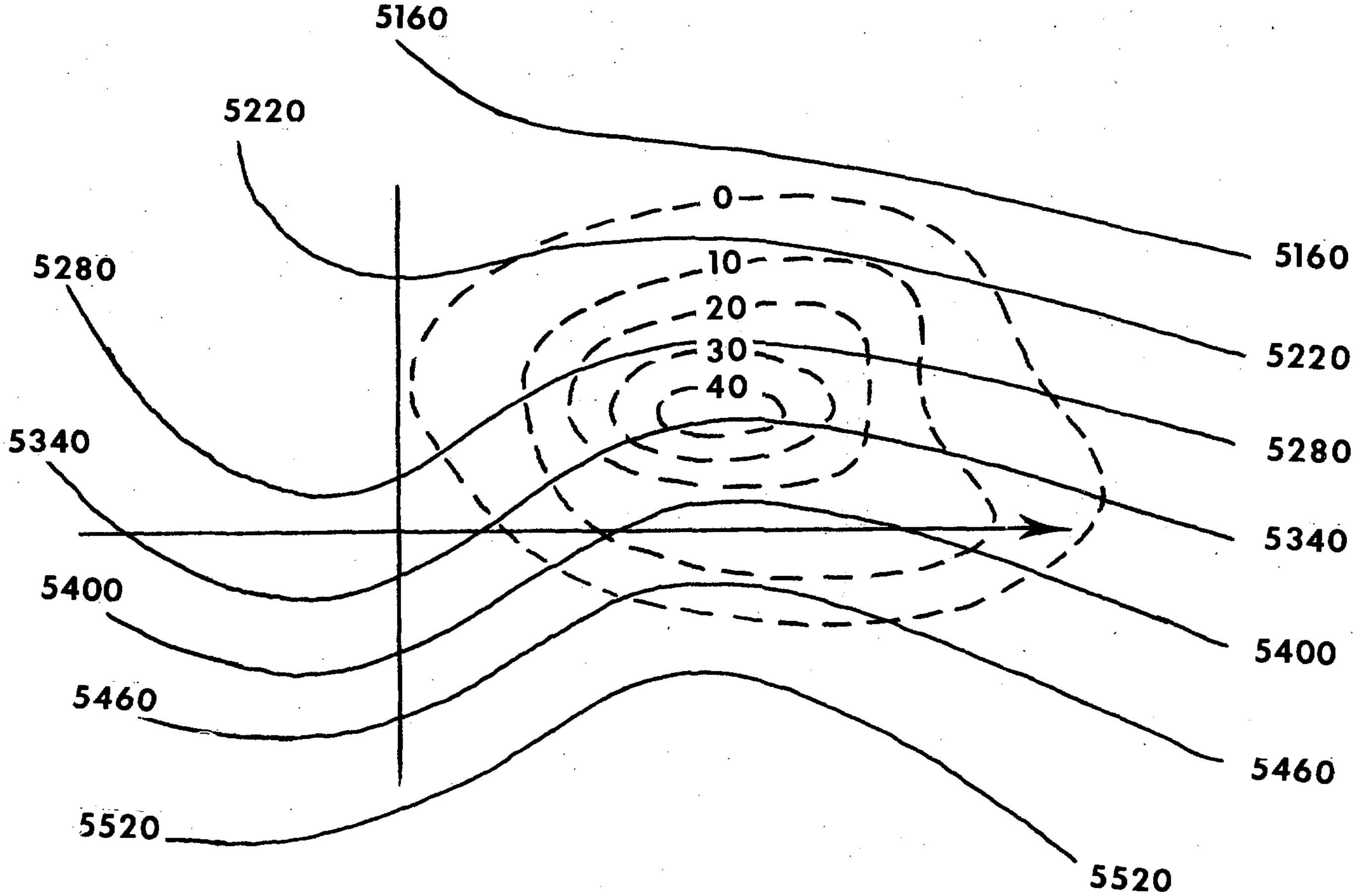

FIGURE 4.—Percentage frequency of occurrence of heavy snow and composite initial 1000–500-mb. thickness chart (gpm.). Orientation is the same as figure 1. Scale 1:20,000,000.

also lists the values of the vorticity maxima at 500 mb. associated with these top-ranking storms. It is clearly evident that a strong vorticity maximum is a prime requisite for the occurrence of heavy snowfall of major proportions.

Table 3 gives frequency distributions of a number of meteorological measurements for the 50 deepening and occluding cases. The average value of the vorticity maximum was 19.8×10^{-5} sec.$^{-1}$ (range 13.8 to 24.8), while that for the top-ranking cases was 21.7×10^{-5} sec.$^{-1}$. The average speed of movement of the vorticity maximum was 35 kt., while the average direction of movement was toward 61°. Only six cases occurred with movement of the maximum toward due east, or south of east; in the other 44 cases, this movement was in a direction north of east. The mean lowest observed 500-mb. temperature within a distance of 3° latitude from the vorticity maximum was −30° C. The lowest temperature was −36° C. and the highest was −21° C. The average speed of movement of the surface low-pressure center was 30 kt., while the average direction of movement was toward 50°. All except three surface Lows moved in a direction north of east.

Table 4 provides information on areal extent of heavy snowfall and strength of vorticity maxima for the entire set of 81 heavy snow situations.

TABLE 2.—*Top-ranking snowstorms and values of associated 500-mb. vorticity maxima. Date and time are for the beginning of the 12-hr. snowfall period. Area is in square degrees of latitude*

Rank	Date	Time (GMT)	Area	Vorticity ($\times10^{-5}$ sec.$^{-1}$)
1	2-25-65	1200	26.0	23.8
2	3-17-65	1200	25.8	18.1
3	1-13-64	0000	24.0	21.4
4	1-13-64	1200	23.5	24.0
5	1- 1-64	0000	23.5	20.0
6	2-26-65	0000	23.3	21.5
7	2-25-65	0000	21.8	20.9
8	2-12-65	0000	20.3	21.0
9	1- 1-64	1200	20.0	24.8

5. ADDITIONAL COMMENTS ON FORECASTING SNOWFALL

Although precipitation is the net result of many and complex interacting atmospheric processes, it is convenient to classify snowfall situations as to the main causal sources of upward motion. Storm precipitation may be thought of as the net yield of the producing capacity of the storm itself and the contribution which results from orographic effects. For that area of the United States under consideration and for the scale of the systems under study, we are primarily interested in the first of these components which is a direct function of the atmospheric dynamics

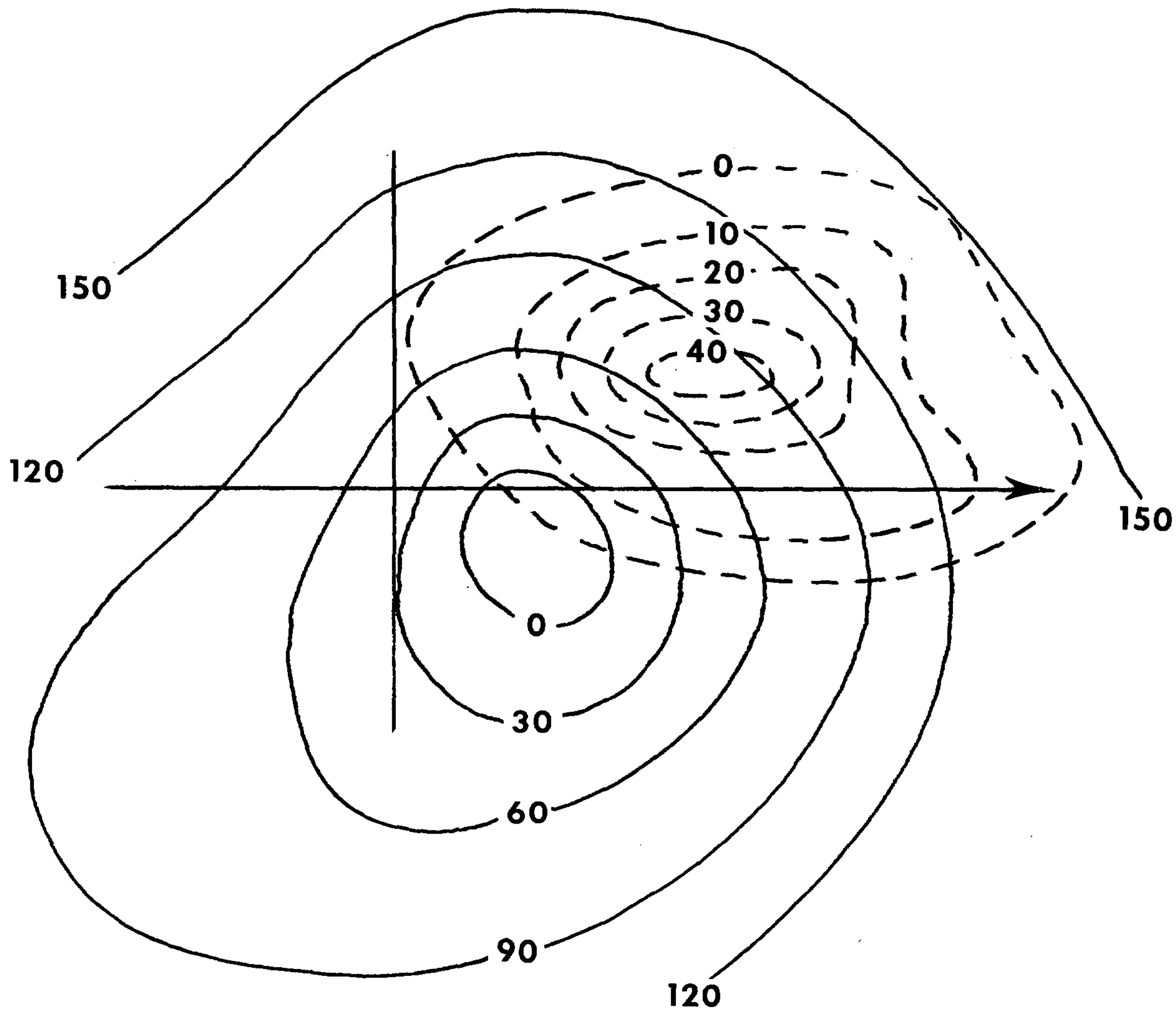

FIGURE 5.—Percentage frequency of occurrence of heavy snow and the initial 1000-mb. chart (gpm.), derived from the composite 500-mb. and 1000–500-mb. thickness charts. Orientation is the same as in figures 1, 3, and 4. Scale 1:20,000,000.

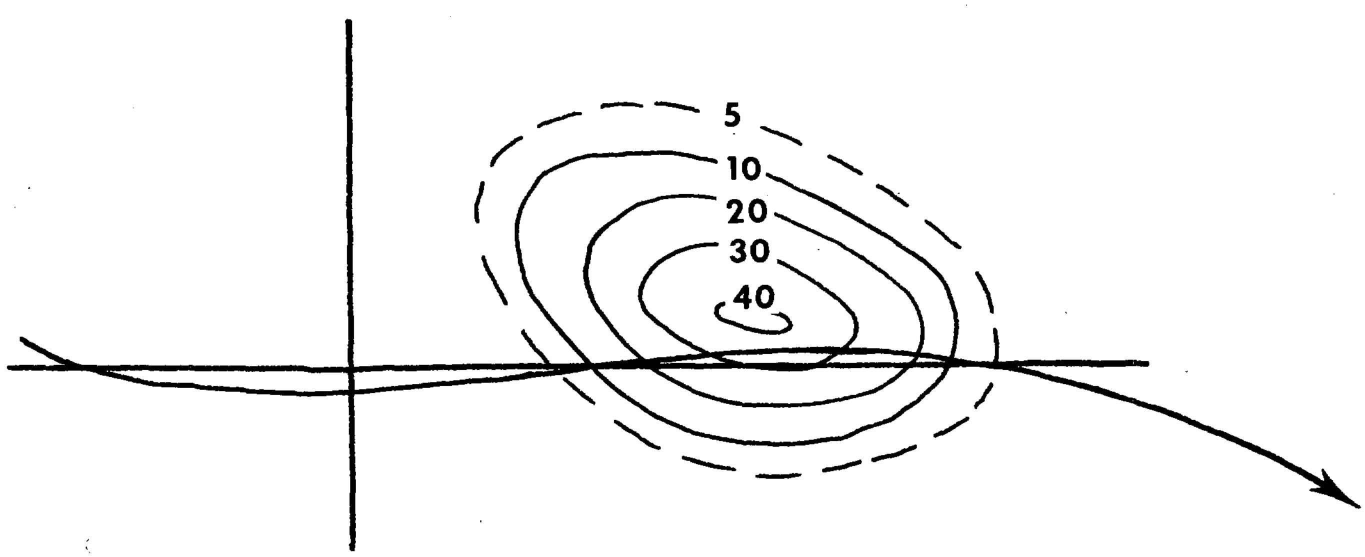

FIGURE 6.—Percentage frequency of occurrence of heavy snow with respect to the initial position of the jet stream. The x-axis is oriented along the jet and the y-axis passes through the position of the 500-mb. vorticity maximum. 40 cases 1963–64 season. Scale 1:20,000,000.

producing upward air motion. In identifying the dynamic processes creating vertical motion systems in the atmosphere, a conventional simplification is to assume geostrophic conditions. Then the vertical motions are dependent upon temperature advection (Laplacian of the temperature advection) and vorticity advection (vertical gradient of absolute vorticity advection). Warm advection (WA) and positive vorticity advection (PVA) generate upward motion, while cold advection (CA) and negative vorticity advection (NVA) generate downward motion.

TABLE 3.—*Frequency distributions—number of cases each season and two-season percentage frequency of occurrence. (Deepening and occluding type systems only).*

a. Value of absolute vorticity maximum at 500 mb. ($\times 10^{-5}$ sec.$^{-1}$)

Period	12.5–14.9	15.0–17.4	17.5–19.9	20.0–22.4	22.5–24.9
1963–64	0	3	7	11	6
1964–65	3	3	8	7	2
Two Seasons (%)	6	12	30	36	16

b. Speed of vorticity maximum at 500 mb. (kt.)

	10–19	20–29	30–39	40–49	50–59
1963–64	-----	5	14	8	-----
1964–65	3	4	9	4	3
Two Seasons (%)	6	18	46	24	6

c. Direction of movement of 500-mb. vorticity maximum (to nearest 10° of arc from N.)

	20	30	40	50	60	70	80	90	120	150
1963–64	-----	-----	3	7	6	7	2	1	1	-----
1964–65	1	3	4	5	3	2	1	2	1	1
Two Seasons (%)	2	6	14	24	18	18	6	6	4	2

d. Lowest 500-mb. temperature within 3° latitude distance of vorticity maximum (Below 0°C.)

	20–24	25–29	30–34	35–39
1963–64	2	12	7	6
1964–65	4	7	10	2
Two Seasons (%)	12	38	34	16

e. Speed of surface low-pressure center (kt.)

	10–19	20–29	30–39	40–49	50–59
1963–64	3	5	13	4	2
1964–65	3	9	10	1	-----
Two Seasons (%)	12	28	46	10	4

f. Direction of movement of surface low-pressure center (to nearest 10° of arc from N.)

	0	10	20	30	40	50	60	70	80	90	100	120
1963–64	-----	2	1	3	5	6	4	2	3	1	-----	-----
1964–65	1	1	1	4	1	5	4	4	-----	-----	1	1
Two Seasons (%)	2	6	4	14	12	22	16	12	6	2	2	2

g. Areal extent of heavy snowfall (Sq. degrees of lat.)

	4.0–7.9	8.0–11.9	12.0–15.9	16.0–19.9	20.0–23.9	24.0–27.9
1963–64	8	3	10	2	3	1
1964–65	11	4	2	1	3	2
Two Seasons (%)	38	14	24	6	12	6

TABLE 4.—*Frequency distributions—number of cases each season and two-season percentage frequency of occurrence. (All 81 cases)*

a. Value of absolute vorticity maximum at 500 mb. 10^{-5} sec.$^{-1}$

Period	10.0–12.4	12.5–14.9	15.0–17.4	17.5–19.9	20.0–22.4	22.5–24.9
1963–64	-----	-----	8	12	13	7
1964–65	3	7	4	14	11	2
Two Seasons (%)	*4*	*8*	*15*	*32*	*30*	*11*

b. Areal extent of heavy snowfall (Sq. degrees of lat.)

	4.0–7.9	8.0–11.9	12.0–15.9	16.0–19.9	20.0–23.9	24.0–27.9
1963–64	17	5	11	3	3	1
1964–65	27	6	2	1	3	2
Two Seasons (%)	54	14	16	5	7	4

It is common procedure in the QPF Section to classify snowfall as to its main dynamic source of upward motion, that is, WA-type snowfall or PVA-type snowfall. There are individual cases when snowfall is related completely to concurrent WA, while at other times it is completely related to concurrent PVA. However, the common occurrence is for the presence of both WA and PVA through a broad spectrum of variance in intensity of each. The presence of both is required to a considerable degree of intensity (considering the entire tropospheric layer) for the production of upward motion sufficient for major snowstorms. The main operational value of these synoptic-climatological models in forecasting heavy snowfall stems from their providing a quick assessment of circulation prognoses in terms of location of the most suitable environment (WA, PVA, and moisture) for production of heavy snowfall.

6. SUMMARY

The models developed present percentage frequency of occurrence of heavy snowfall in relation to selected circulation features for 50 important snowfall situations in the central and eastern United States. All these cases were commonly characterized by deepening and occluding surface low-pressure systems. These models can be used to determine quickly and objectively the most favorable location for occurrence of heavy snowfall, given a set of prognoses. This quick assessment of the forecast situation allows more time for the forecaster to deal with details (such as direction and speed of movement of vorticity maximum and surface low-pressure center, deepening of the 500-mb. and surface systems, delineation of the rain versus snow line, etc.) in predicting a reasonable and consistent pattern of heavy snowfall.

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REFERENCE

1. E. B. Fawcett and H. K. Saylor, "A Study of the Distribution of Weather Accompanying Colorado Cyclogenesis," *Monthly Weather Review*, vol. 93, No. 6, June 1965, pp. 359–367.

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