CRH SSD
NOVEMBER 1987

CENTRAL REGION TECHNICAL ATTACHMENT 87-26

AN AID TO FORECASTING HEAVY SNOWFALL EPISODES[1]

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ABSTRACT. A conceptual model has been devised and tested to demonstrate the importance of assigning critical thermal profiles to the warm conveyor belt when diagnosing and forecasting the possibility of heavy snowfall (>6 in) events. Values of θ_w between +9°C to +12°C characterizing the ascending saturated air are highlighted as being critical to the precipitation physics accounting for the heavy snowfall. The corresponding mean temperatures for 700 mb, 600 mb, and 500 mb are -7°C, -15°C, and -23°C, respectively.

1. INTRODUCTION

Too often, the placement and timing of major snowfall episodes are not properly handled by current diagnostic and prognostic schemes. These deficiencies, coupled with poorly understood precipitation physics by synoptic meteorologists, preclude successful heavy snowfall forecasting. However, satellite imagery and conventional ground-based data have provided an opportunity for describing many of the smaller-scale features, especially the cloud and precipitation patterns. It is possible, for example, to make useful inferences about the fields of airflow (and to a limited extent the location of temperature gradients) from the form and movement of these same cloud and precipitation patterns, although this calls for some subjective interpretation of the patterns. The primary impediment to using conventional data effectively is now the forecaster's limited ability to make sense of the cloud and precipitation patterns in terms of the dynamical and thermodynamical factors that are producing them. Forecasters need conceptual models of precipitation systems. The purpose of this paper is to present an amalgamation of two previously published conceptual models that are thought to be helpful in the prediction of heavy snowfall episodes.

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2. PROCEDURES

Many researchers in the 1960's and 1970's used isentropic analysis to determine the three-dimensional trajectories of air motion through wave cyclones. The analysis and conceptual model of airflow through wave cyclones and comma cloud patterns put forth by Carlson (1980) was chosen for application in this work since it represents a logical extension of previous work, and yet retains a clarity and simplicity which favors immediate understanding and application.

The principal notion of the Carlson model incorporated into this study is that of the warm conveyor belt. Carlson defined the warm conveyor belt as that movement of moist air along surfaces of relatively higher values of equivalent wet-bulb potential temperature (θ_w) which originates in easterly flow in the warm sector south of the surface low pressure, ascends while turning northward approximately parallel with the surface cold front, achieves saturation near or north of the warm front, where it rises more rapidly, and then joins the upper-level westerly flow northeast of the surface low center. The warm conveyor belt is derived from air originating within the convective mixing layer and is typically 200-300 mb deep.[2] The clouds associated with the southwesterly flow along the cold front and north of the warm front from the comma tail and body, and usually can be easily identified on satellite imagery. The warm conveyor belt, then, is the primary delivery source of water vapor and resulting condensate into the wave system ascending through 700 mb, 600 mb (level of nondivergence) and 500 mb. See Fig. 9 from Carlson (1980), for example, reproduced here in Fig. 1.

Auer and White (1982) created a conceptual model of heavy snowfall which incorporated contributions from the kinematics, thermodynamics, and cloud physical aspects. They concluded that regions of ascending air developing the maximum rate of condensate near the level of nondivergence (600 mb) when temperatures are -15°C must be suspect for producing heavy snowfall (>6 in/12-hr). In their case study analysis, Auer and White envisioned rising air in physically conservative θ_w channels, observing the changes in saturation specific humidity and determining the rate of condensate. These θ_w channels are physically identical to the θ_w surfaces that make up Carlson's warm conveyor belt. Since it is well known that the ice crystal growth rate is a maximum in the dendritic crystal temperature envelope of -13°C to -17°C, Auer and White rationalized that if temperatures at 600 mb (where the maximum condensate is being delivered) are in this range, then the consumption of the condensate will be maximized by dendritic ice crystal growth resulting in a heavy snowfall episode. They collaborated their claim with a mini-climatological study of 75 heavy snowfall episodes which depicted saturated ascent through the level of nondivergence at $\theta_w = 9^{\circ}C$-$12^{\circ}C$.

The concepts of Carlson (1980) and Auer and White (1982) can now be amalgamated into a forecasting guide for heavy snowfalls by recognizing that a

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[2] This inflow is certainly recognized in one form or another by all forecasters; however, we will retain Carlson's nomenclature as a basis for discussion.

critical thermal structure of the warm conveyor belt from 700 mb through 500 mb must exist. To test this hypothesis, representative upper air soundings from a sample of 213 heavy snowfall episodes were used to characterize the thermal structure of 700 mb, 600 mb, and 500 mb of the warm conveyor belt, identified from satellite imagery and/or kinematic analysis. Of these 213 cases sampled across the United States (excluding mountain areas and snowfall episodes) between 1980 and 1986 in which warm conveyor belts were tentatively identified, 118 were falls between 6-9 in, 59 for depths between 9-12 in, and 36 for accumulations in the range of 12-24 in; the synoptic classification showed 114 episodes of closed circulation at 500 mb and 99 cases associated with migrating short waves at 500 mb.

3. RESULTS

The results of the total data set analysis are shown in Fig. 2. Approximately 77% of the cases occurred with warm conveyor belt temperatures at 500 mb between -22 to -25°C, 700 mb temperatures between -5 to -8°C, and 600 mb temperatures of -14 to -16°C. It should be noted that no heavy snowfall events occurred when the 500 mb temperature in the warm conveyor belt was colder than -27°C; and the number of episodes is strongly curtailed for temperatures colder than -25°C. At 500 mb, the mean, median, and mode temperatures for the distribution are -23.3°C, -23°C, and -25°C, respectively. At 700 mb, no major snowfall events occurred with warm conveyor belt temperatures colder than -11°C, while 30% of the episodes occurred with a temperature of -7°C. At 700 mb the mean, median, and mode temperatures for the distribution are -7.3°C, -7°C, and -7°C, respectively.

The temperature distribution at the assumed level of maximum vertical velocity (i.e., the level of nondivergence, or 600 mb) on the warm conveyor belt substantiates the premise that dendritic ice crystal growth at this level consumes the maximum rate of condensate during heavy snowfall events. With nearly 80% of the events characterized by temperatures between -14°C and -16°C, it appears that, climatologically, heavy snowfall episodes are described by the occurrence of a level of maximum vertical velocity on the warm conveyor belt at the habitat of dendritic crystals (-13°C to -17°C) which allows for the maximum delivery of condensate to be consumed by maximum crystal growth rates. Note that 95% of the events occurred within the envelope for dendritic growth; the small minority of events at -12°C and -18°C are probably a reflection of the variability of the level of nondivergence from its assumed pressure of 600 mb. The mean, median, and mode temperatures for the distribution are -14.8°C, -15°C, and -15°C, respectively ... right in the center of the dendritic crystal habitat. The temperature envelopes characterizing the ascending warm conveyor belt at 500 mb, 700 mb, and 600 mb that most frequently occur during heavy snowfall episodes are conveniently confined between θ_w = 9-12°C for saturated ascent. Ascent within the warm conveyor belt characterized by warmer or colder values of θ_w (i.e., warmer than -13°C or colder than -17°C at 600 mb) does not appear to be associated with heavy snowfall production. Figs. 3-5 show the temperature distributions for twelve hour accumulations of 6-9 in, 9-12 in, and greater than 12 in, respectively. There is obvious similarity between the corresponding distributions of each Figure. The heaviest snowfall events depict a slight cooling (0.5 to 1.0°C) at all levels for the mean, median, mode values; however, this probability is not significant. The Figures still emphasize the critical envelope of temperatures within the warm conveyor belt necessary for heavy snowfall production.

Finally, for the sake of general interest, Fig. 6 depicts the frequency for snowfall amounts partitioned by synoptic type. It can be noted that 82% of the events were confined to snowfalls of 12 in or less. For migrating tropospheric short waves with the appropriate thermal patterns within the warm conveyor belts, the snow depths typically ranged between 6-8 in for a 12-hr interval. Closed circulations, more apt to be quasi-stationary, were found to be more conducive to produce amounts in the 10-12 in range with the proper thermal fields.

4. SUMMARY

Carlson's (1980) conceptual model of flow through wave cyclones has been combined with the thermal guidelines for ascending air proposed by Auer and White (1982) to yield a convincing argument for the kinematic and thermodynamic structure of heavy snowfall events. An analysis of the temperatures occurring within the ascending air of the warm conveyor belt reveals that ascent within the θ_w envelope of +9°C to +12°C is significantly associated with heavy snowfall regimes. This ascent can also be identified by its coincidence with temperatures at 700 mb, 600 mb, and 500 mb of -7°C, -15°C, and -23°C, respectively.

Through the use of satellite imagery and conventional upper air analysis, simple diagnostic and prognostic techniques are available, as outlined here, for assessing the location and duration of heavy snowfall episodes.

5. NOTES

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6. REFERENCES

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Carlson, T. N., 1980: Airflow through midlatitude cyclones and the comma cloud pattern. Mon. Wea. Rev., 108, 1498-1509.

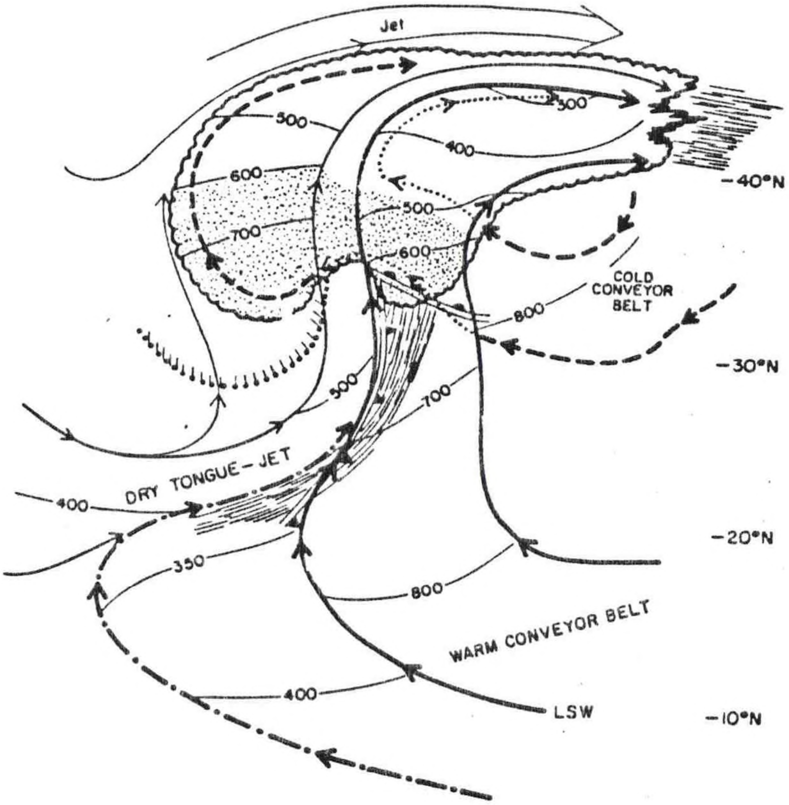

Fig. 1. A reproduction of Carlson's (1980) Figure 9 depicting schematic composite of airflow through middle-latitude cyclone. Details pertinent to this note include: heavy solid streamlines depicting airflow at top the warm conveyor belt; thin solid lines denoting the heights of the air streams (mb) approximately normal to the direction of the respective air motion; the region of dense upper- and middle-level layer cloud represented by scalloping and sustained precipitation by stippling; and the limiting streamline for the warm conveyor belt labeled LSW.

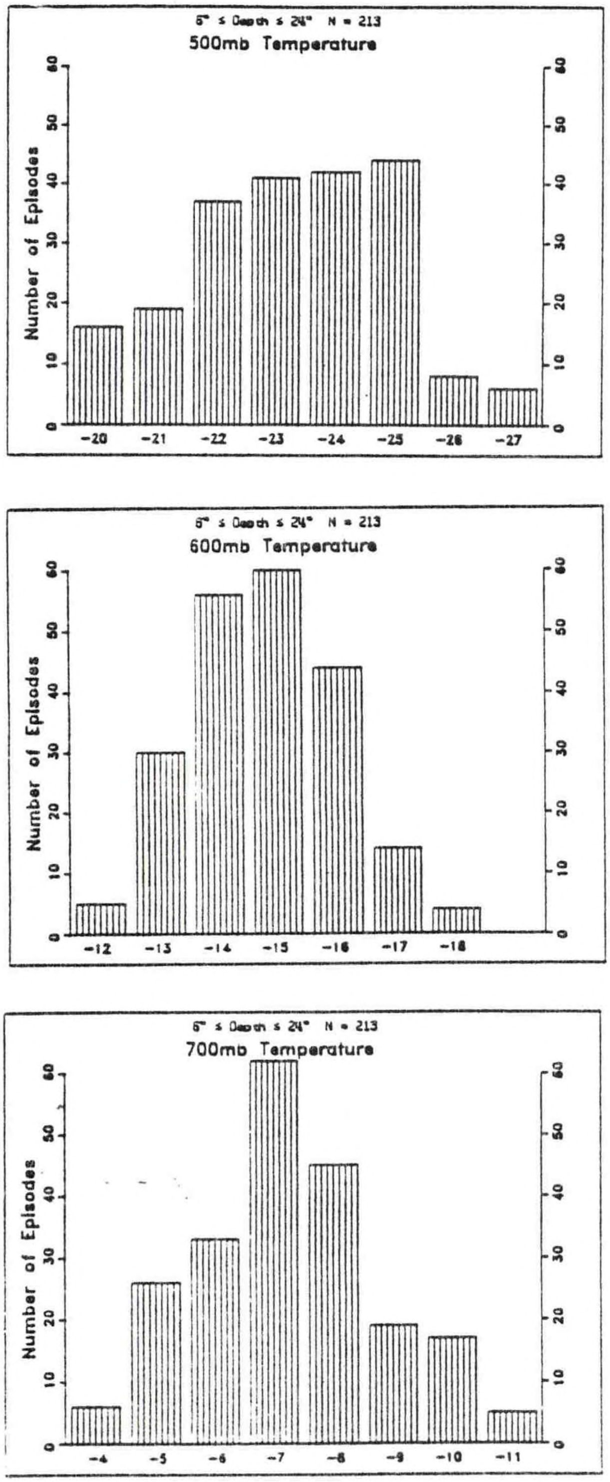

Fig. 2. Frequency histograms of the temperature (°C) occurring within the warm conveyor belt associated with closed circulations and short waves for 500, 600, and 700 mb during 213 heavy snowfall episodes ranging from 6 to 24 in during 12-hr.

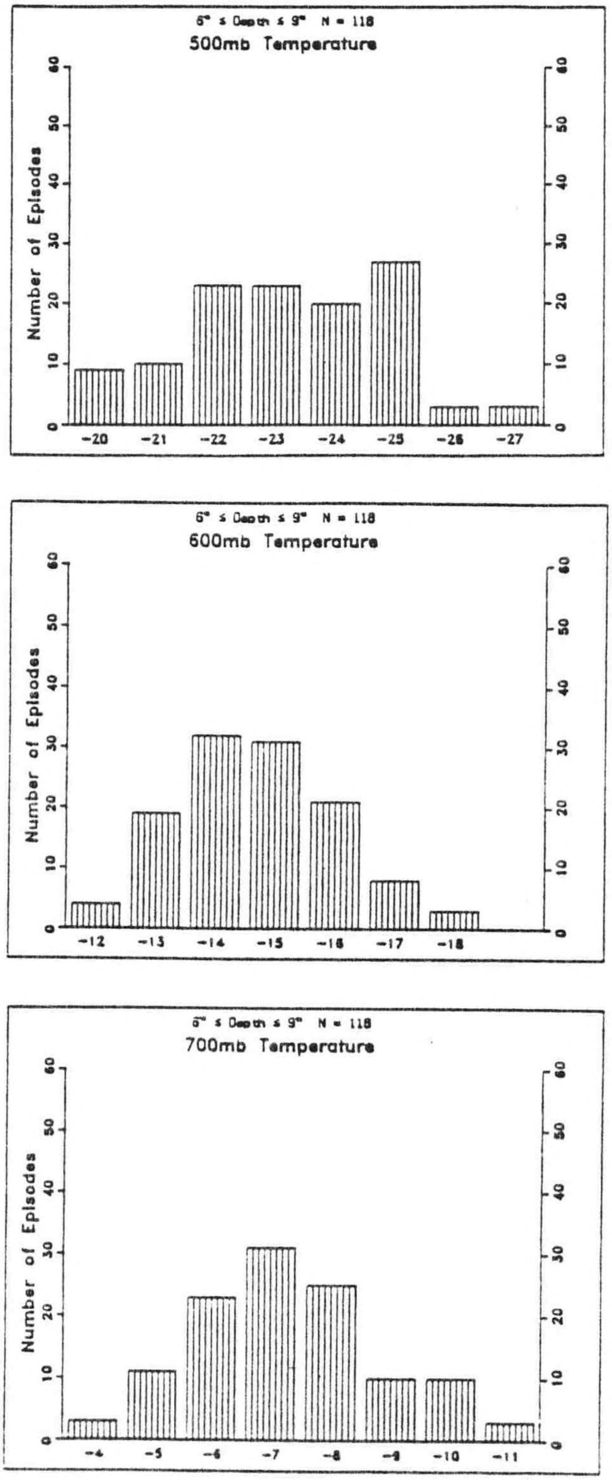

Fig. 3. Frequency histograms of the temperature (°C) within the warm conveyor belt for 500, 600, and 700 mb during 118 cases of heavy snowfall amounts between 6-9 in during 12-hr.

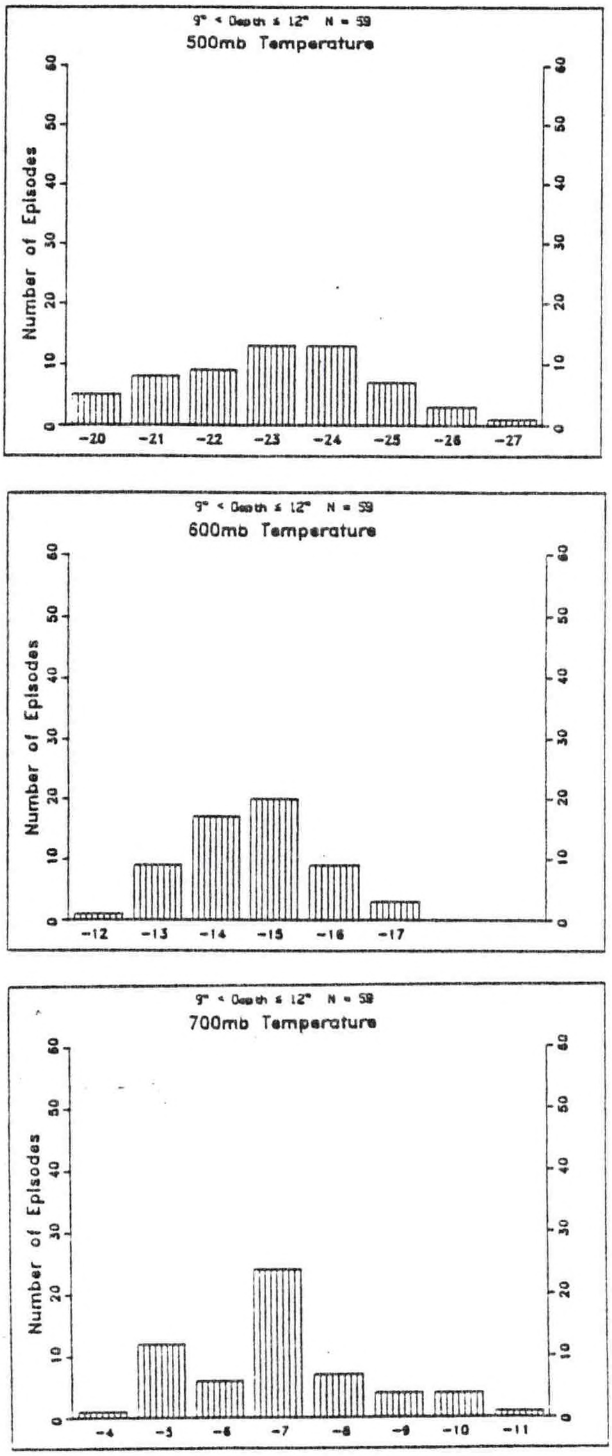

Fig. 4. Same as Fig. 3, except for 59 cases between 9-12 in.

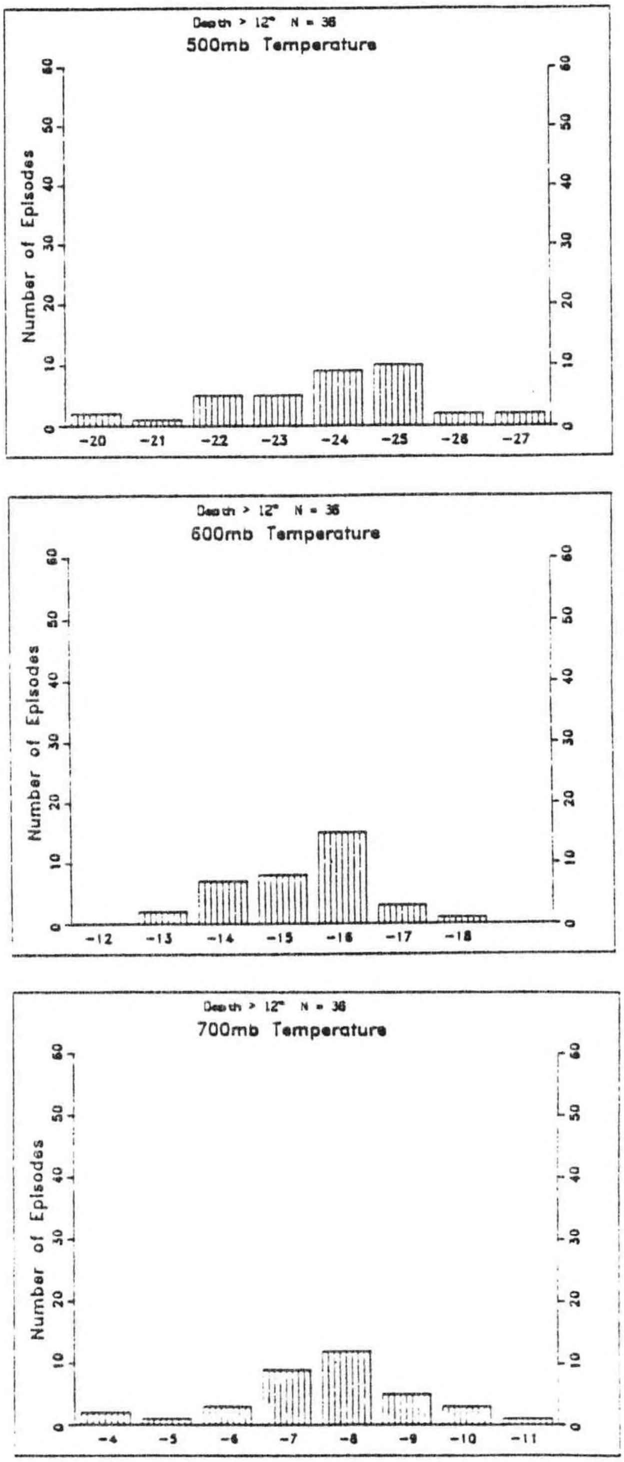

Fig. 5. Same as Fig. 3, except for 36

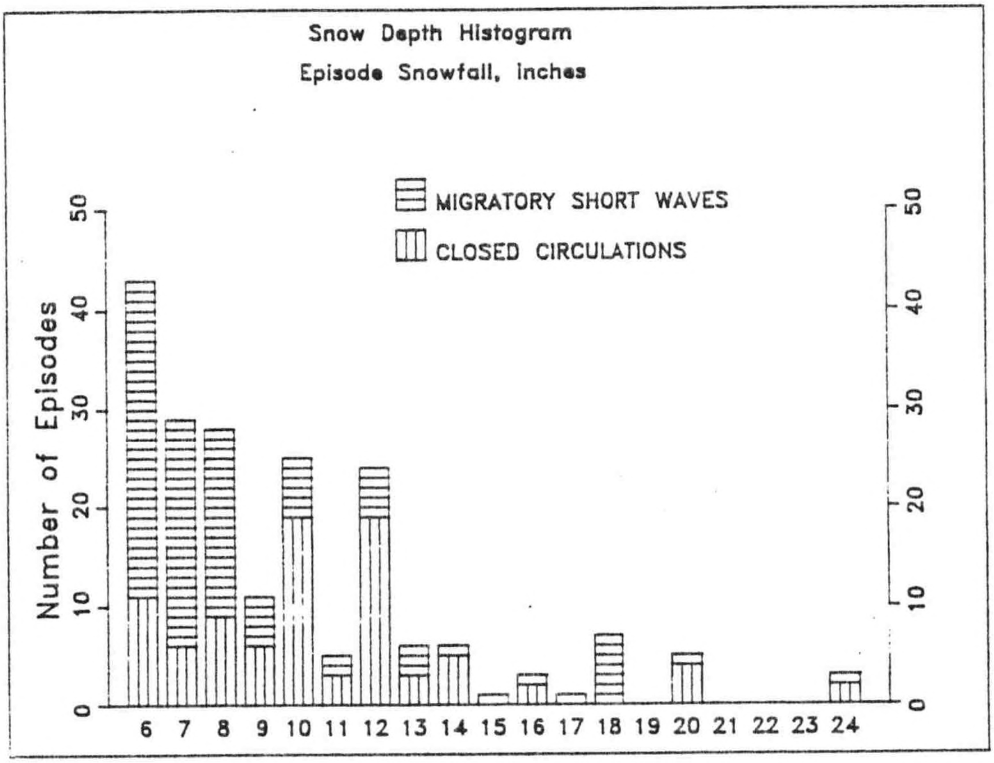

Fig. 6. Frequency histogram of 12-hr snowfall amount associated with frequent synoptic patterns.