CLIMATOLOGY OF SNOWFALL-EVENT CHARACTERISTICS AT DENVER

by

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INTRODUCTION

Distribution and timing of heavy snowfall along Colorado's Front Range are among the most challenging forecast problems faced by the National Weather Service forecasters at Denver (Dunn, 1987). Both the difficulty inherent in predicting orographic precipitation and the increasing demand for more precise forecasts contribute to these problems. Therefore, a snowfall-event climatology was developed to provide a background for forecasters regarding individual winter storms. The concept of an "event" is not new. This approach has been applied in hydrology and other related fields for many years (Brown et al., 1985). Since forecasters deal with individual events daily, the event-climatology approach was an appropriate way to proceed.

Two objectives are addressed in this study. The first is to describe the synoptic environment that is conducive to heavy snowfall events (8 inches or more of snow) at Denver, such as intensity of the baroclinic system at 850 mb, direction of geostrophic flow at 850 mb during periods of heavy snow, presence of a southward moving cold surge east of the Front Range, existence of surface low development, and location of surface low development. The second is to present two event characteristics specifically important to forecasters and supply physical reasons for their occurrence: 1) starting and stopping time of an event, and 2) predominate wind direction that is observed during light, moderate and heavy snowfall.

DATA

The methodology used in this study included two steps. First the large mass of snowfall amounts were separated into entities defined as snowfall events. Second synoptic features that led to heavy snow at Denver were identified, and the analysis of snowfall-event characteristics were analyzed for individual events.

Snowfall Data base

The historical data set used in this study consisted of 40 years of observation records from the National Weather Service Forecast Office in Denver. These observation records were analyzed for hourly reports of frozen precipitation. These reports were copied and categorized according to snowfall event. A snowfall event was defined to be a period of time during which any type or intensity of snow was observed at the station. A break between events was identified when a 12-h time period elapsed with no precipitation.

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Analysis Methods

From a subset of 50 snowfall events, analysis of orographic effects and strength of baroclinic systems led to the identification of five consistently observed features contributing to heavy snow at Denver. Three features related to orographic effects were: northeasterly flow at 850 mb, a cold surge at the surface, and the location of surface development. The development of the 850-mb baroclinic system and the existence or lack of existence of surface low development were identified based on the general analysis of baroclinic systems. The criteria used to identify the five features follow.

• The direction of geostrophic flow was determined by the direction of the contours at 850 mb near Denver.

• Existence of a cold surge was identified when a tight surface gradient running northwest-southeast along the edge of the mountains from Alberta to Colorado was evident, and the wind speed increased, changed direction, and the temperature dropped at several stations within the surge. These features are similar to those represented by a front. However, in these cases, no defined boundary exists.

• The location of the surface low development was identified as east of the mountains when a new surface low formed east along of the Rocky Mountains located within Colorado boundaries.

• Intense baroclinic development at 850 mb was defined by the existence of warm advection ahead of and cold advection to its rear.

• Existence of surface low development was noted when one consolidated low pressure system was formed.

From the 1402 snowfall-events included in the data base, ten characteristics of individual snowfall events were tabulated. However, the starting and stopping time and predominate wind direction are discussed here. The starting and stopping time of each event was determined using a frequency distribution constructed from the data base. This distribution included the number of times an event began and ended during each hour for a 24-h time period. The predominate wind direction for separate snowfall intensities (s-, s, s+) was determined from hourly surface observations from a subset of 8-inch or greater snowfall events. The hourly wind directions that occurred within eight 45° ranges were totaled and plotted on a wind rose, a convention used for plotting wind direction.

RESULTS

The following sections discuss the five synoptic features important to heavy snowfall events at Denver. One particular case, 23-25 December 1982, which produced 23.8 inches of snow at Denver, contained each of the five characteristics. This case is a likely choice to illustrate and discuss these features. Two additional characteristics common to individual snowfall events also will be investigated.

Synoptic Characteristics

Each of the five synoptic features that will be discussed are identifiable characteristics in winter storms. Not every event displays all five, but most of these features are present in each snowfall event. The predominate location for surface low development during heavy snowfall events at Denver was the southeast corner of Colorado. Figure 1 shows the beginning stages of surface low development that preceded heavy snow at Denver. Six hours later (Fig. 2), surface development exploded resulting in one confined and organized surface feature. Eleven of the 14 cases displayed this characteristic. The resulting geostrophic flow around the surface low increases the low-level upward motion due to the sloping terrain of the eastern plains. Generally, when the surface low developed over or west of the Rocky Mountains Denver did not receive heavy snow.

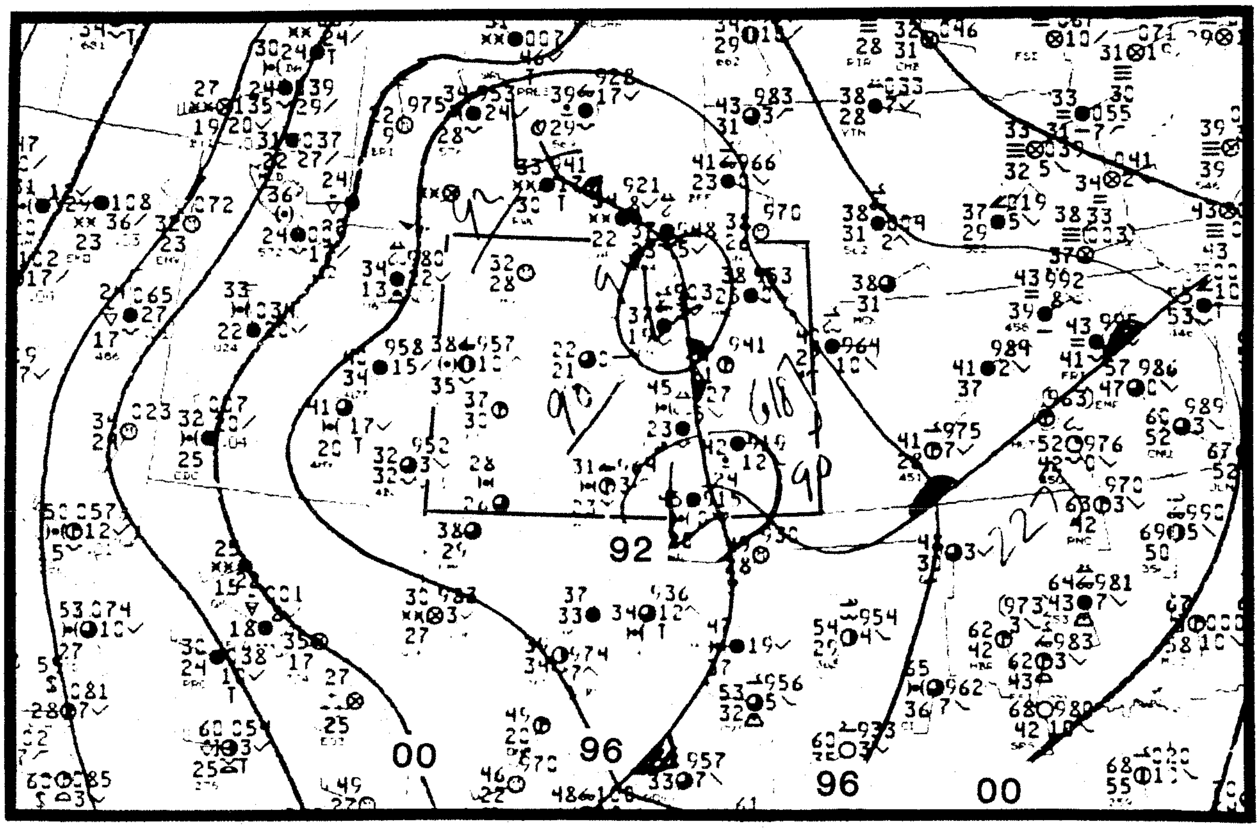


Fig. 1. Analysis of surface pressure for 00 UTC 24 December 1982. Isobars are labeled every 4 mb.

Also shown in Fig. 2 is the intense existence (opposed to lack of existence) of surface low development. Only two of the 14 events analyzed did not contain some evidence of surface low development. The third important feature was the presence of a cold surge that is usually located along the Front Range of Colorado. A surge can be identified at several stations in Wyoming (Fig. 2) by strong winds (15 to 20 kts), an increase in snowfall intensity, and a decrease in temperature. Six hours later (Fig. 3), the surge continued south through Denver (station 469) and Limon (LIC). Both stations experienced an increase in wind speed and snowfall intensity, and a decrease in temperature. Another six hours later (not shown here), the surge continued south reaching the surface low pressure and displacing it away from the plains of Colorado. In many of the cases analyzed, as the surge passed Denver an increase in the snowfall intensity occurred. This same phenomena was also observed by Schlatter et al. (1983) and Dunn (1987). Both authors noted an increase in snowfall intensity at the surface as a surge moved through. Several hours after passage, the surge reached the surface low and had the effect of displacing the low away from the plains, signaling the end of the snowfall event.

Intense baroclinic development at 850 mb is another important feature for heavy snow at Denver. Figure 4 shows the intense 850 mb development that occurred during the 1982 case. Strong warm and cold advections were present ahead of and behind the developing system. Twelve of the 14 events analyzed contained this characteristic. At 850 mb the most observed geostrophic flow was primarily from the northeast (Fig. 4). This northeasterly flow, supplied by the combination of orography and the wind flow pattern, contributes to the upward motion on a smaller scale. The addition of upslope combined with the large scale dynamics can increase the local snowfall considerably. Not all of events display these characteristics as distinctively as the December 1982 case, however, the general signal can be detected.

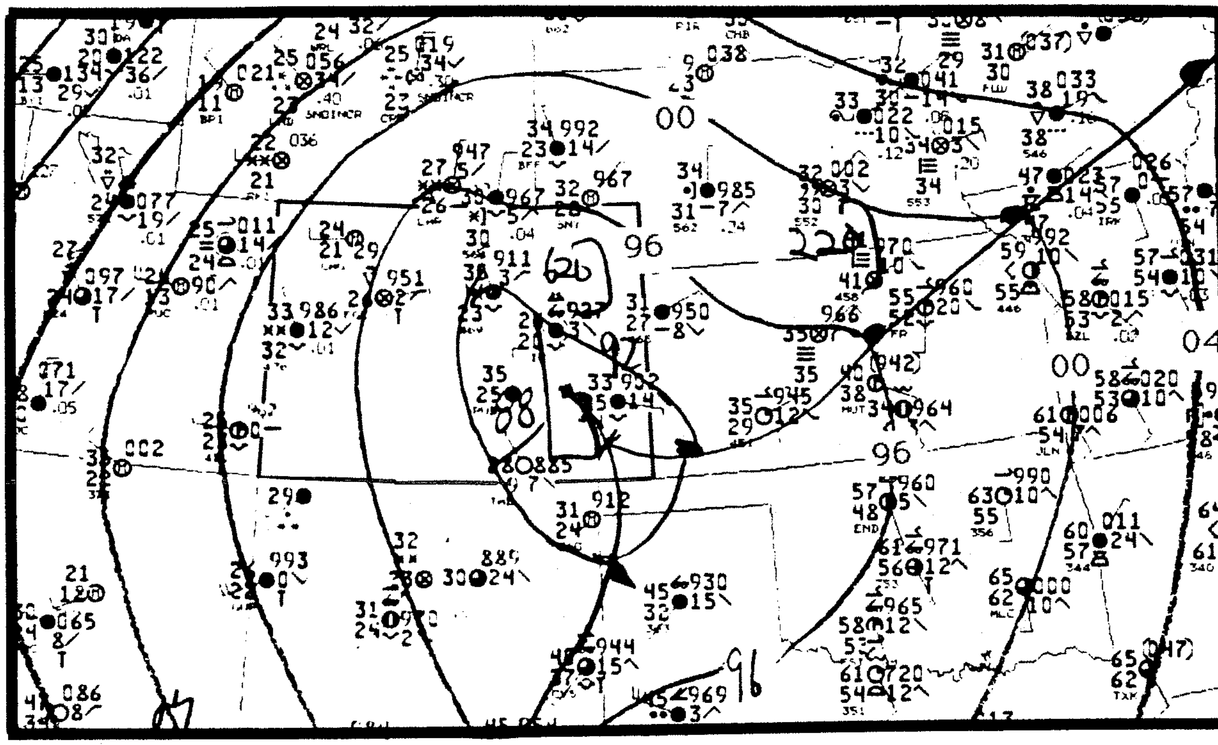


Fig. 2. Analysis of surface pressure for 06 UTC 24 December 1982. Isobars are labeled every 4 mb.

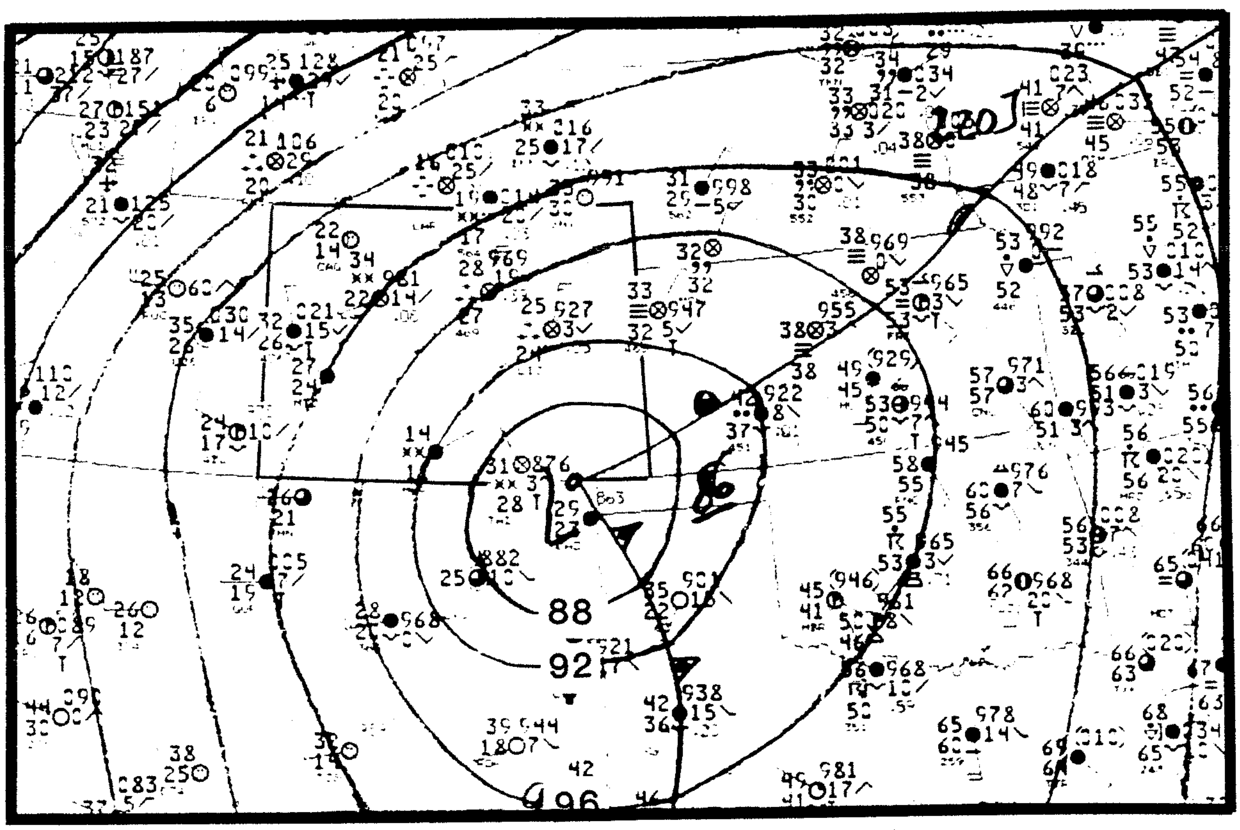


Fig. 3. Analysis of surface pressure for 12 UTC 24 December 1982. Isobars are labeled every 4 mb.

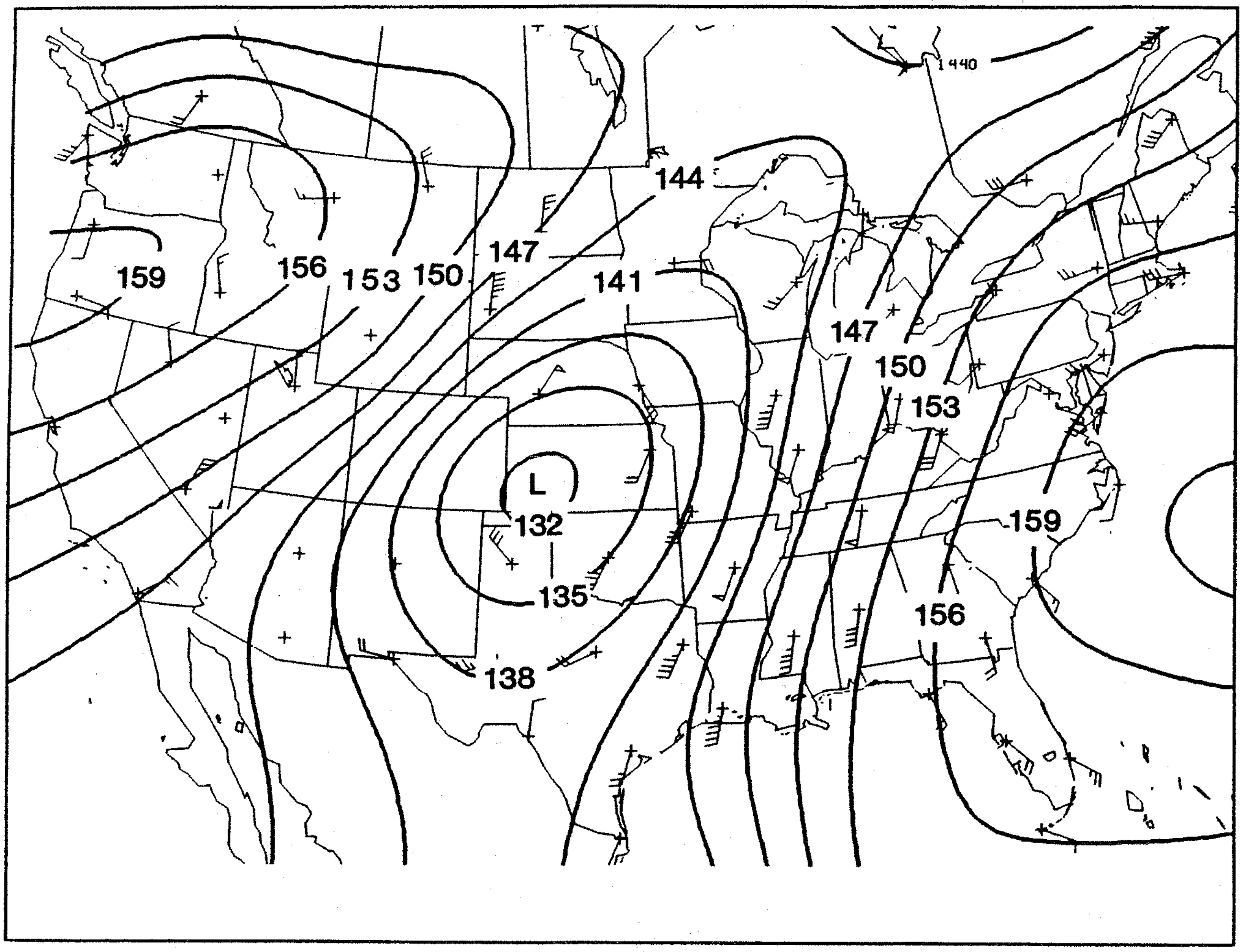


Fig. 4. Analysis of height for 850 mb at 0 UTC 25 December 1982. Contours are labeled every 30 m.

Snowfall-event characteristics

One of the most troubling forecast problems is being able to identify the starting and stopping time of precipitation for a given event. In the majority of cases of this study, the typical winter scenario is that a frontal passage moving from the north or northeast precedes precipitation. Therefore, accurate timing of the frontal passage is the key to estimating the starting time of precipitation. At the present time, however, output from numerical models is the main source of data used to predict the timing of frontal passages. Because of the orography of the Front Range, surface fronts become highly distorted as they enter northeast Colorado (Toth, 1987). The timing of the front determined by the model is not necessarily representative of the actual timing observed at the station. Therefore, in order to provide a background for forecasters, a histogram of starting and stopping times was developed to determine if a distinct time period exists when the majority of snowfall events begin or end. Distinct features immediately become evident: most frequent ending time for snowfall events is early to mid-morning, and most frequent start time is late afternoon and early evening, usually around rush hour. This can be clearly identified in Fig. 5, where between points A and B, a peak in ending times and a lull in starting times are apparent. Conversely, between points B and

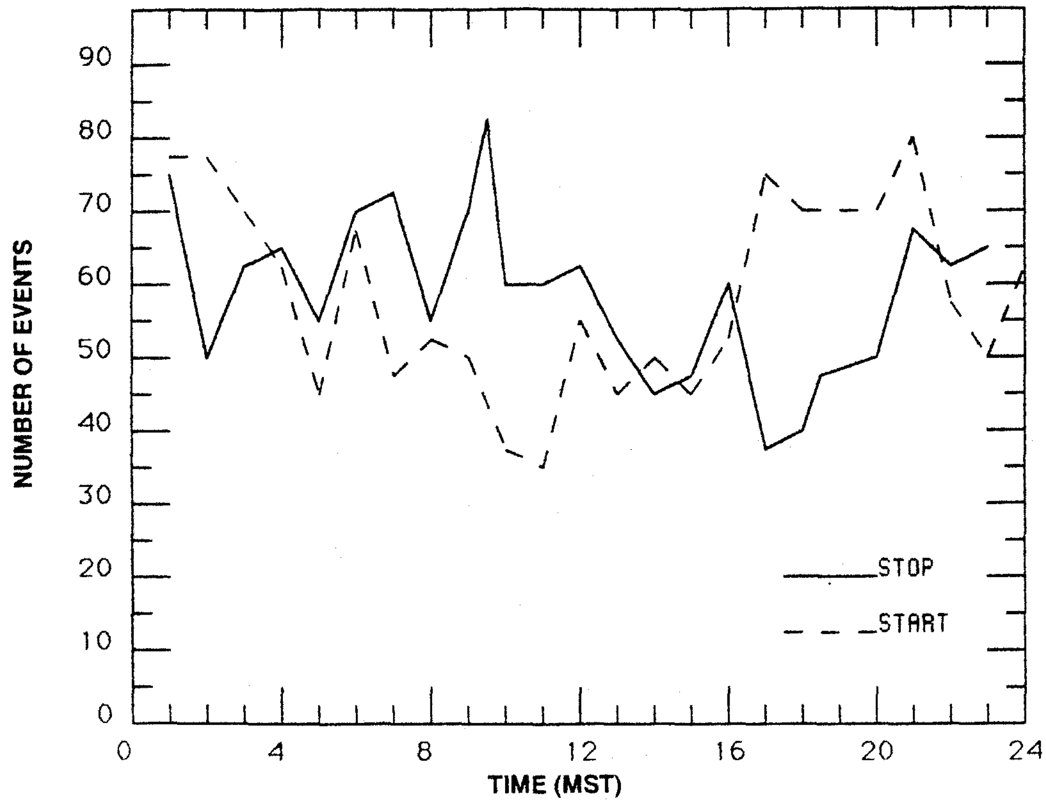


Fig. 5. Histogram of starting (----) and stopping (   ) times from the 1402 data base.

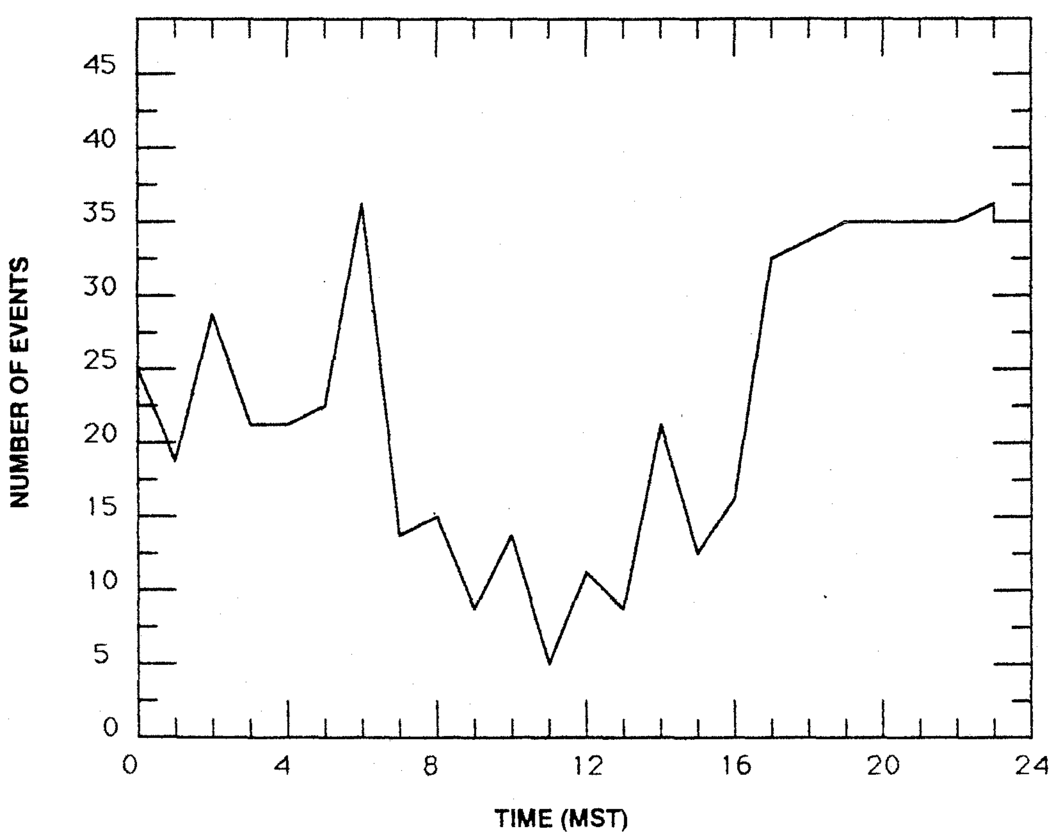


Fig. 6. Histogram of cold frontal passages at Denver (from Wiesmueller, 1982).

C, a lull in ending times and a peak in starting times are visible. Therefore, if precipitation is assumed to begin soon after frontal passage, one could hypothesize that frontal passages are more frequent in the early evening hours. These results agree with those discussed by Wiesmueller (1982), who showed that frontal passages are more frequent after 1600 MST (Fig. 6). He noted that the fluctuation was a function of the diurnal heating cycle. The diurnal variability in the timing of frontal passages is more pronounced in spring (when the majority of heavy snowfall events occur) and summer than in fall and winter.

The second characteristic is the predominate wind direction that is observed during heavy snowfall events. Due to the character of the Front Range, mountains to the west and sloping terrain to the east of Denver, a low-level wind flow perpendicular to the mountain barrier would produce upward motion, known as upslope flow. Where there is a surface flow in Denver with a north to northeast component, upslope occurs. This is due to the existence of a prominent, shallow east-west ridge south of Denver, which extends east of the Rocky Mountains. Because of the complexity of the terrain, snowfall events producing this type of flow display tremendous gradients in the observed snowfall pattern (Dunn, 1987), thus making wind flow patterns an important forecast problem. Figure 7 (a-c) shows the frequency of hourly wind observations with respect to wind direction separated according to snowfall intensity. All three intensity categories display a predominate wind direction between 315 and 360 degrees, but with an appreciable number of observations with wind in the range 00 to 45 degrees. These directions indicate an upslope component, but suggest also that there is normally a low-level wind component parallel to the contours of elevation. One theory that may explain the non-upslope component of the wind is a convergence zone that forms just east of Denver with the heaviest snow found to the west. The convergence zone is shown in Fig. 8 and can be identified by the northweast winds behind the zone and east-northeast winds ahead of the zone. Denver (Aur) is reporting northwest winds and moderate snow. The formation of the convergence zone is not easy to explain but has been linked to the presence of cold air damming, discussed by Dunn (1987). The complex flow around Denver is not fully understood and is a topic for future discussion.

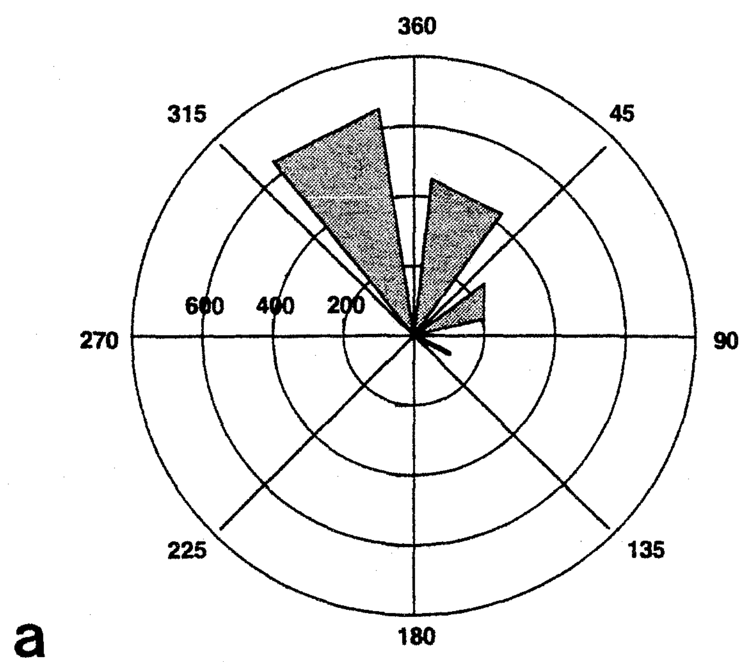
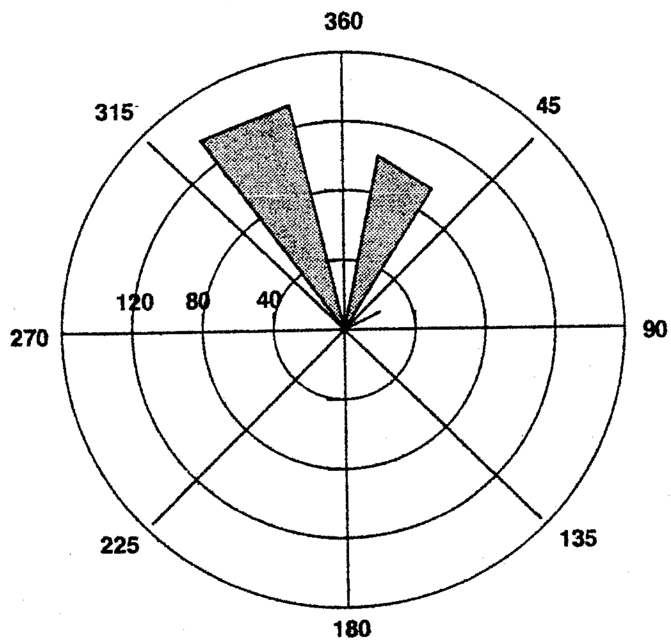


Fig. 7. Wind rose containing the frequency of wind observations with respect to wind direction for light snowfall intensity (a), moderate (b), and heavy intensity (c).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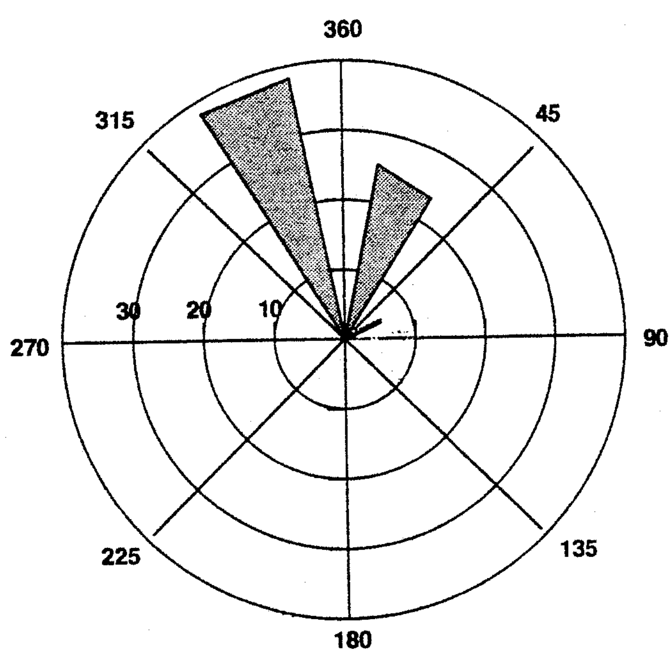
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c

Fig. 7. (Cont.)

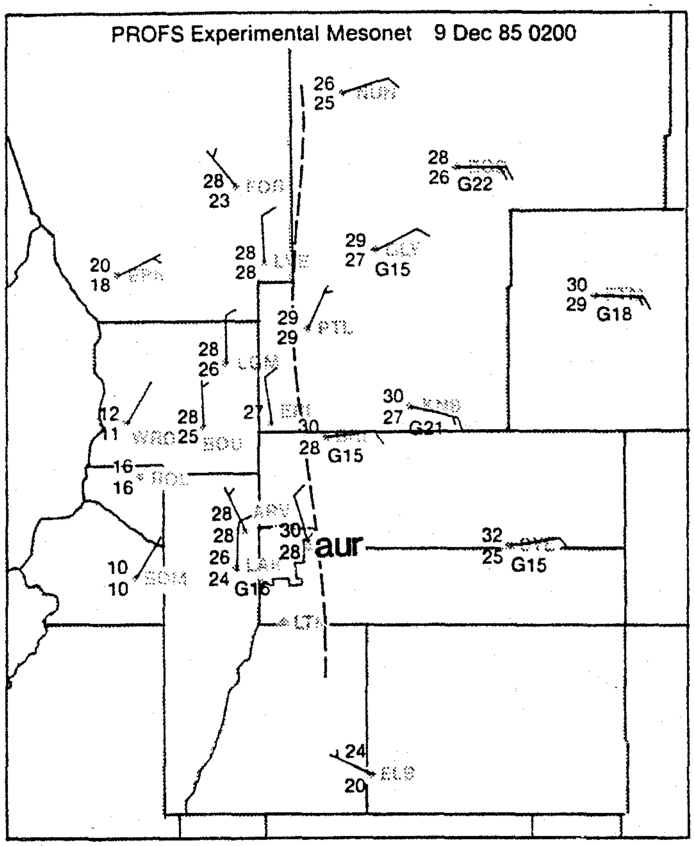

Fig. 8. Mesonetwork of stations east of the Front Range (from Dunn, 1987). Convergence line is just east of Denver (aur) where moderate snow was reported.

SUMMARY AND CONCLUSIONS

The results presented in the preceding sections provide a general description of snowfall events based on historical data at Denver, Colorado. Some conclusions that can be drawn regarding individual snowfall events include the following:

1) The identification of the synoptic structure is the primary source when determining if a heavy snowfall event is possible. The characteristics of this structure that are important for heavy snowfall at Denver are: the occurrence of surface development located in eastern Colorado, a cold surge which modulates the snowfall intensity at the surface, and an intense baroclinic system must be present at 850 mb producing strong northeasterly/easterly geostrophic flow.

2) When model guidance concerning timing of frontal passages is difficult to identify, one can assume that the preferred starting time for snowfall events is around rush hour (1600-1700 MST) and not during mid-day.

3) In addition to wind directions that indicate upslope, a component parallel to the terrain was discovered. This northwesterly component suggests the presence of a convergence zone within the vicinity of Denver which significantly effects the distribution of heavy snowfall.

This study considered the characteristics of individual snowfall events based on a historical data set. Snowfall events were created using only the information contained in the precipitation record. The analysis consisted of characteristics for Denver. The same investigation was done for snowfall events at Colorado Springs and revealed different characteristics. The "event" approach can be applied to many different meteorological variables, such as the investigation of "freezing" events or rainfall events. However, the motivation for this study was to supply a significant background for Denver forecasters regarding individual snowfall events. If the forecasters are aware of the characteristics concerning winter storms, then their interpretation and understanding of daily model output will improve.

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