A SYNOPTIC CLIMATOLOGY OF TEXAS WINTER STORMS

Ted Ryan
Stacie Hanes

NOAA/National Weather Service
Weather Forecast Office
Fort Worth, Texas

Abstract

Between the years of 1948 and 2005, 50 winter storms with snow and sleet accumulations of four inches or more affected the northern and central portions of the state of Texas. The upper level flow pattern of each storm case was examined and classified into one of six synoptic types. Additionally, geopotential height, moisture, and temperature anomalies associated with each case were studied in order to find quantitative similarities that may be used for operational forecasting. Results indicate that each synoptic regime possesses unique thermal and moisture profiles. Winter storms which exhibit characteristics similar to those presented here may be easier to forecast after one identifies the synoptic type. Characteristics of each synoptic pattern are discussed in detail to allow maximum application in the operational forecast setting.

Corresponding Author: Ted Ryan
NWS Weather Forecast Office
3401 Northern Cross Blvd
Fort Worth, Texas 76137
e-mail: ted.ryan@noaa.gov

1. Introduction

In general, winter storms usually have greater impacts on the population at lower latitudes than the same storm would at higher latitudes (Hart and Grumm 2001). People living in the southern half of the United States are less accustomed to winter precipitation and this can cause tremendous disruption to daily life. This is especially true across much of Texas, where any amount of snow and sleet can be detrimental to air and ground travel due to limited resources devoted to snow removal. A cursory examination of the National Climatic Data Center's (NCDC) publication *Storm Data* confirms this and also validates the fact that winter storms play a major role in automobile accidents with hundreds of winter weather-related accidents reported each year in Texas. The Fatality and Analysis Reporting System (FARS; online info at: www-fars.nhtsa.dot.gov/) recorded a total of 69 deaths in Texas automobile accidents between the years 1994-2006 when snow was falling.

Winter weather forecasting is challenging for any location, but in Texas, where snow storms are more infrequent than in other parts of the country, they can be even more difficult to predict. While mesoscale models and other numerical guidance are readily available to assist in forecasting, computer models can have great difficulty predicting winter weather accurately across Texas. This is in part due to very limited rawinsonde observation data across the higher terrain of Mexico to the southwest and also the moisture-rich Gulf of Mexico to the southeast. Because winter weather events are rare in Texas, forecasters are generally unable to gain sufficient experience with respect to a particular model's relative forecast strengths and weaknesses as is the case for more typical weather patterns. As a result, forecasters should have a climatological reference in which to compare to computer model guidance in order to acquire confidence (or doubt) in a particular prognosis. It is anticipated that forecasters across Texas, and perhaps other regions in the southern United States, will be able to apply some of the findings in this paper to better forecast winter weather events.

There have only been a few studies on winter weather synoptic climatology in the Southern Plains. In one such study, Branick (1985) examined 79 Oklahoma snow events spanning 16 years and identified six categories of snow-producing systems. The research presented here also identifies six types of systems (Fig. 1), many of which were identical to Branick's research with a few exceptions. Due to a better statistical sample size, Branick was also able to create sub-categories, yielding a total of two additional patterns based on the intensity of the upper level system. Additionally, our study revealed a regime not identified in Branick's work which appears to only produce snow over north Texas. Mixing ratios, temperatures, and their anomalies were not addressed in Branick's research to

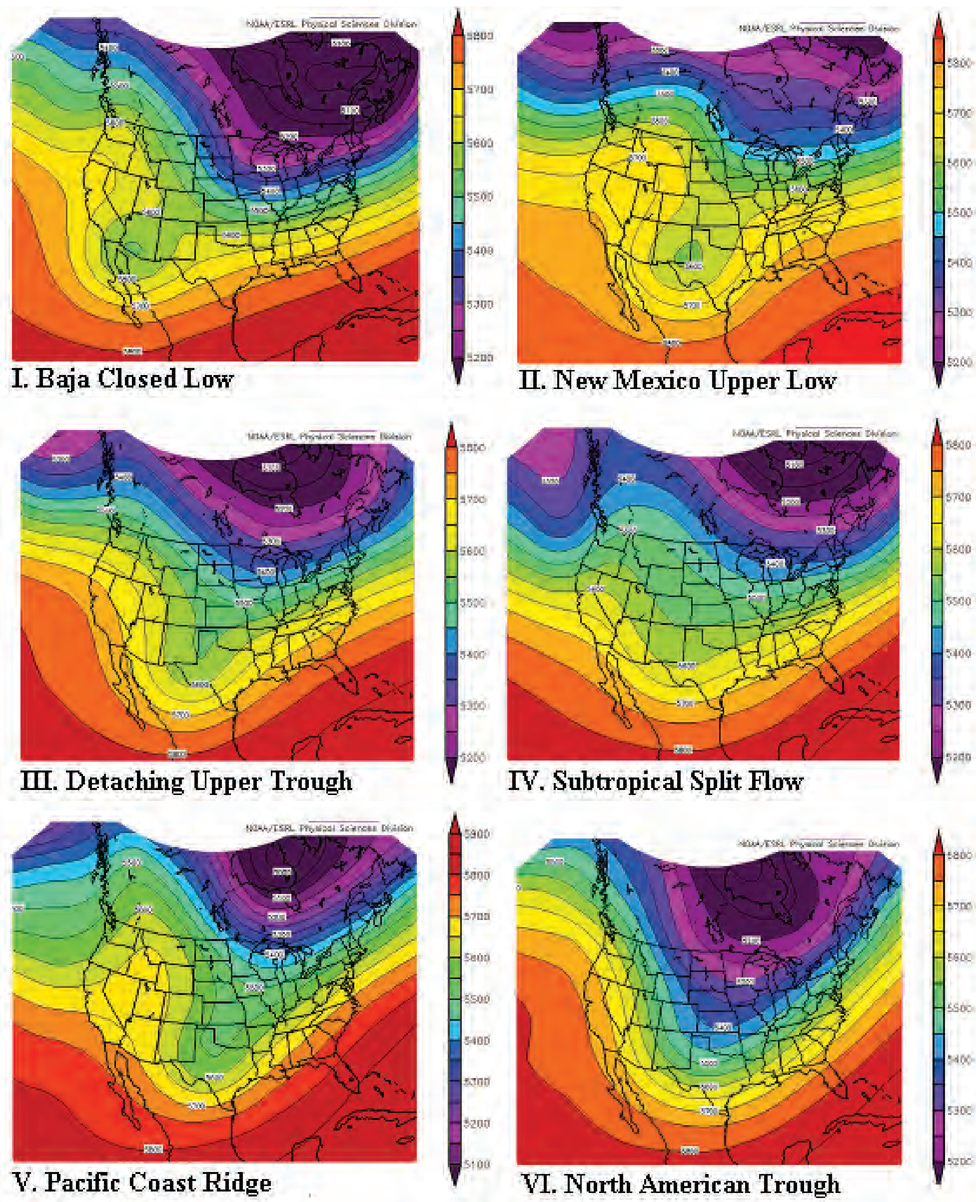


Fig. 1. Charts of 500-mb composite means are shown for the six synoptic types. Solid lines with interval shading are contours of geopotential height in decameters.

the extent that they are in this study. Despite Oklahoma's close proximity to our study region, slight variations in synoptic and mesoscale climatology resulted in five to six times fewer snowfall events. These discrepancies, along with differing methodologies, warranted a separate study for Texas.

2. Methodology

Manual analysis was used to create an isopleth map (Fig. 2) of mean seasonal snowfall for the study area from National Weather Service (NWS) Local Climatological Data for the years 1965 to 1995 (NCDC). Detailed snowfall records ceased after 1995 because the Automated Surface Observing System does not measure snowfall accumulations. The seasonal snowfall (defined as total snowfall from July of one year through June of the following year) effectively combines the precipitation for a given winter season. It should be noted that many locations across the southeastern half of the study area often go several years between accumulating snow events, and the seasonal average snowfall can be misleading.

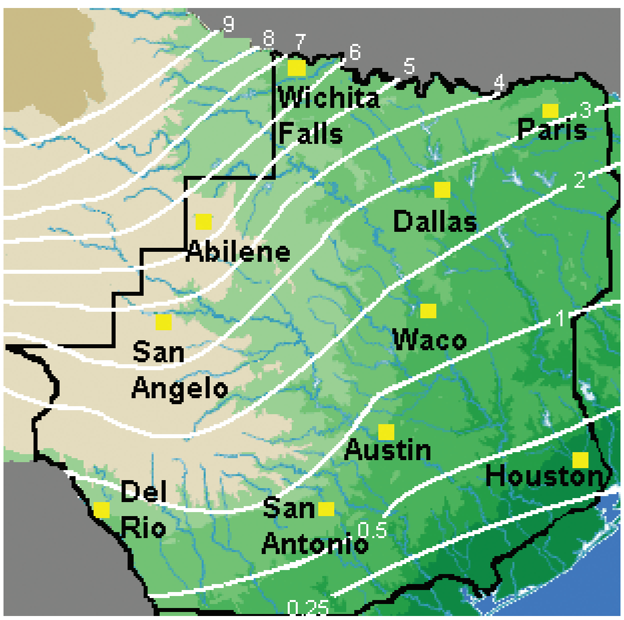


Fig. 2. Texas mean seasonal snowfall with study area outlined in black. Solid white lines are snowfall contours in inches.

The study area (Fig. 3a) includes portions of all eight geographical regions in Texas, including the Piney-Woods area of East Texas, the Gulf Coast region, the South Texas Plains, the Hill Country, the Big Bend region, and the Panhandle Plains (Fig. 3b). Our area of interest was limited to the sections of Texas that have rare to very rare (approximately less than once a year to less than once a decade) occurrences of four or more inches of frozen (i.e., snow and/or sleet) precipitation. Four inches was chosen as the minimum value because the issuance of a NWS winter storm warning in Texas is required when frozen precipitation is expected to total four or more inches within a 12-hour period.

Geographic delineations were made to help forecasters correlate synoptic pattern recognition to more precise areas. Figure 3c shows the sub-regions which comprise the study area. These regions were defined based on the annual average number of snow events a particular area experiences. For example, the Northwest region is more than four times more likely to receive snowfall than the South Central region, due to its higher terrain and closer proximity to storm tracks and colder air. Regional boundaries were also loosely based on present county warning areas of NWS Weather Forecast Offices (WFOs) across Texas.

Texas winter storm events often include several forms of precipitation. This study only includes those events with accumulation of four or more inches of frozen precipitation measured within the study area, regardless of whether rain and/or freezing rain also fell during the events. For brevity, it is assumed that for any event with four inches or more of frozen precipitation, the majority of it was snow. Cases were determined using NWS cooperative data and a local compilation of winter weather events for the years 1968 to 1985. The analysis begins in 1948 when upper air data was regularly obtained. A total of 50 winter storm events (Appendix 1) were identified between the years of 1948 and 2005 with snow or snow and sleet accumulations of at least four inches.

The synoptic pattern classifications presented here occur throughout the cool season, but sometimes do not produce heavy snow or perhaps any snow at all. Null events will be defined as those resulting from one of the synoptic patterns which did not produce four or more inches of frozen precipitation. The null cases may produce sleet and/or snow less than four inches, freezing rain, rain, or no significant precipitation at all. Limiting factors which keep these events from producing heavy snow may be: (1) an unfavorable vertical temperature profile, (2) an unfavorable vertical moisture distribution, and/or (3) inadequate duration of precipitation production with the system.

Even though null events are not included in this research, they can still have significant impacts upon the study region if any amount of winter precipitation is expected. Future research should investigate synoptic patterns that are similar to those presented here but did not produce heavy snowfall. By researching the synoptic events which produced heavy snowfall, favorable patterns have emerged in this research which should assist recognition of null cases in the operational forecast setting.

National Centers for Environmental Prediction/

Fig. 3-a

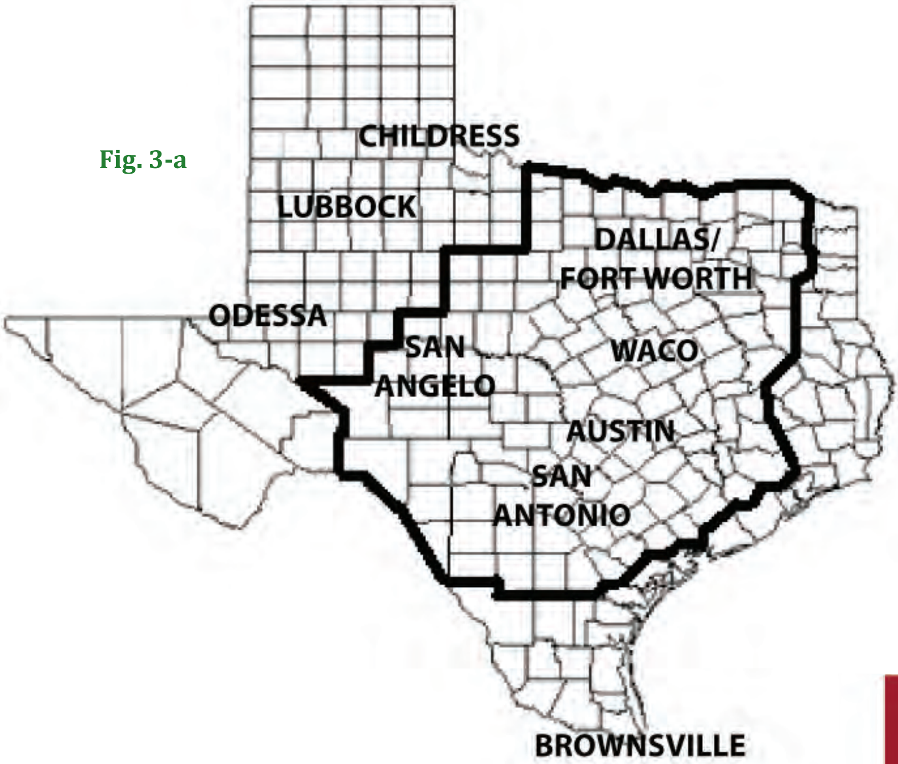


Fig. 3.

a) Map of the state of Texas with state and county borders and cities for reference. The study area is outlined.

b) Geographical regions in the state of Texas.

c) The study area is outlined in a thick black line with smaller snowfall regions outlined within it.

Fig. 3-b

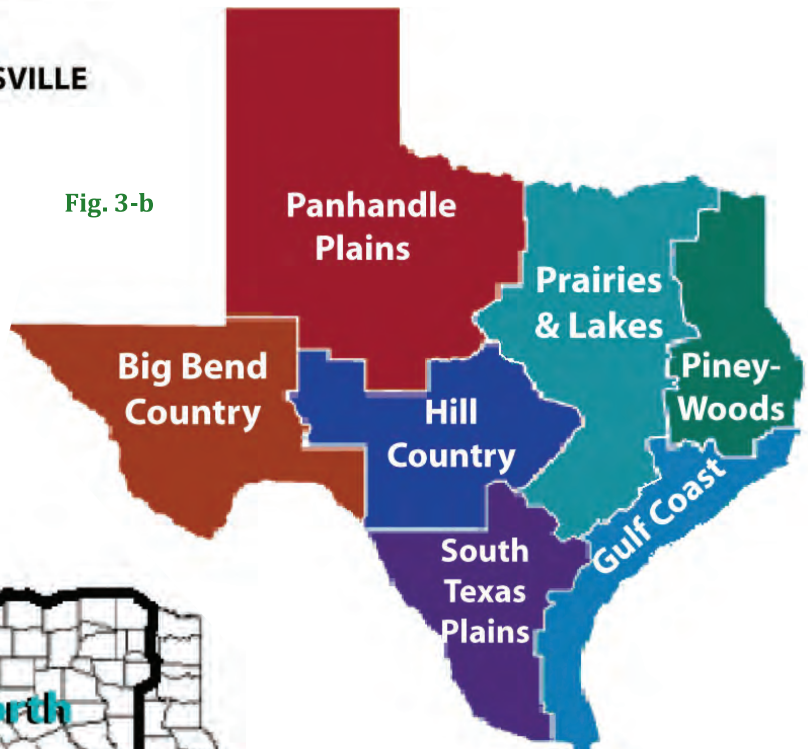
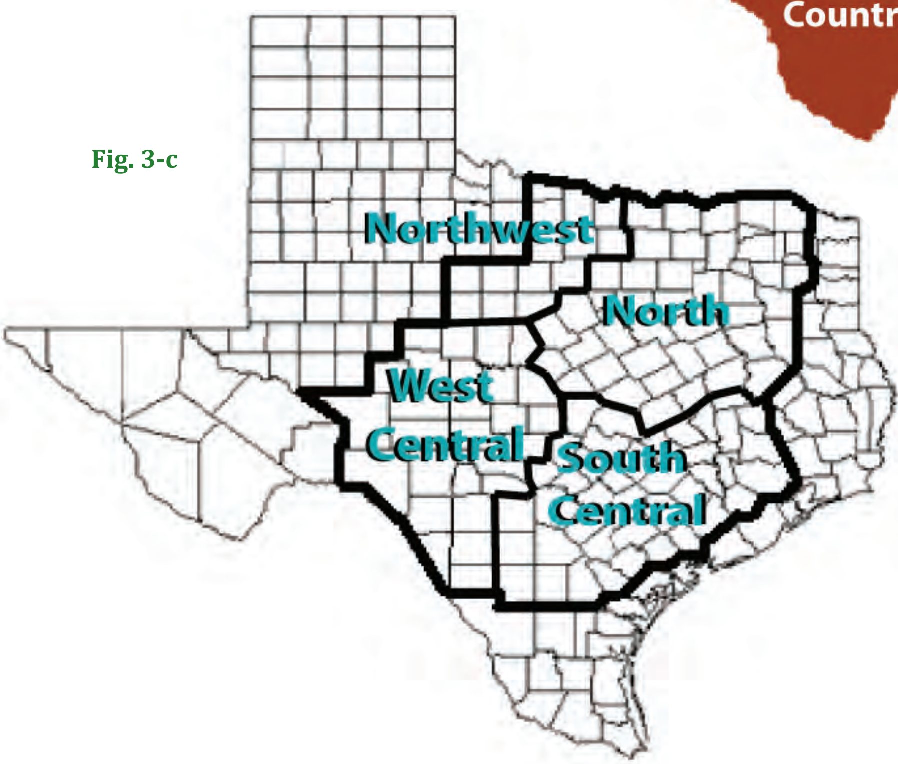


Fig. 3-c



National Center for Atmospheric Research (NCEP/NCAR) Reanalysis data (Kalnay et al. 1996) were used to study standard pressure heights, temperatures, and moisture associated with each snowfall event. Each case was subjectively analyzed and grouped based on the most prominent similarities of their 500-mb synoptic pattern. Composite means of each synoptic type's 500-mb pattern were also produced to provide an objective analysis of their individual evolutions. Six synoptic classifications emerged from the 50 cases, and were given names that best represented the features of that particular regime.

Table 1 shows the number of cases per synoptic type as well as the average maximum snow amount, average snow area, and preferred snow band orientation. The synoptic classifications identified were:

a. Baja Closed Low
b. New Mexico Upper Low
c. Detaching Upper Trough
d. Subtropical Split Flow
e. Pacific Coast Ridge
f. North American Trough

Several temperature, moisture, and anomaly parameters which could be helpful in identifying these patterns operationally were recorded at or just before the onset of snowfall as determined by surface reports. Temperatures and mixing ratios at 500 mb, 700 mb, and 850 mb for each case were recorded over the region where the heaviest snow fell. Since saturation of the 850-mb layer is required to produce significant snowfall, mixing ratios at 850 mb are not listed because they essentially mirrored the saturation values of the given 850-mb temperature. Temperatures at 500 mb were recorded for each case in the core of the upper level low or shortwave that produced the snowfall regardless of whether it was located within the study region. One exception was the North American Trough regime, which often had no identifiable shortwave or upper low. In these instances the 500-mb temperatures were documented over the region where the snow fell. These and other parameters were ordered by synoptic type in Table 2.

Anomalies were calculated for each case in order to provide quantitative characteristics for the synoptic patterns as a whole to aid in identification of the main features. In general, higher anomalies occur at higher

Synoptic Type	Average Max Snow Amount (in)	# of Cases	Preferred Snow Band Orientation	Average Snow Area (mi^2)
Baja Closed Low	9.0	4	SW to NE	20,415
New Mexico Upper Low	7.2	7	W to E	2,823
Detaching Upper Trough	6.8	18	W to E	13,267
Subtropical Split Flow	6.9	9	SW to NE	7,269
Pacific Coast Ridge	6.3	4	WSW to ENE	10,884
North American Trough	5.6	8	W to E	4,718

Table 1. Average maximum snow amounts within the study area and the number of events analyzed for each synoptic type, as well as snow band orientation and average snow area.

Synoptic Type	500 mb				700 mb				850 mb
	T	T anom	q	q anom	T	T anom	q	q anom	T
Baja Closed Low	-23.8	-2.3	2.0	1.8	-2.8	-0.3	4.5	1.5	-2.3
New Mexico Upper Low	-24.9	-1.4	1.4	1.2	-6.1	-1.1	4.3	1.8	-1.9
Detaching Upper Trough	-24.9	-2.1	1.3	1.2	-6.8	-1.6	4.1	1.8	-3.2
Subtropical Split Flow	-22.6	-1.2	1.3	1.3	-5.3	-1.0	3.8	1.2	-3.6
Pacific Coast Ridge	-27.3	-2.0	0.9	0.3	-9.0	-1.8	3.0	1.2	-4.3
North American Trough	-26.1	-2.0	1.1	0.8	-11.3	-1.9	2.7	0.5	-6.8

Table 2. Average temperatures (°C), T, standardized temperature anomalies, T anom, mixing ratios (g kg^{-1}), q, and standardized mixing ratio anomalies, q anom, at 500 mb and 700 mb; 850-mb temperatures for all six synoptic types.

latitudes, but in order to determine if an anomaly is truly significant, use of standardized anomalies is recommended (Grumm and Hart 2001). Standardized anomalies adjust for seasonal and latitudinal differences by dividing the anomaly by one standard deviation, as shown by

$$N = (X - \mu) / \sigma \qquad (1)$$

where N is the standardized anomaly, X is a variable, μ represents the centered-daily mean value, and σ represents the centered-daily standard deviation.

While sub-freezing 850-mb temperatures were critical for the occurrence of snowfall in every case, 850-mb temperature anomalies had little correlation to the type of snow producing synoptic pattern. Rather, 850-mb temperature anomalies more closely relate to the latitude where snow fell in the study area. For instance, the 850-mb temperature anomalies for snow events which occurred across the northern part of the research area usually were negligible, but snow events in the southern portions always yielded high anomalies.

3. Results

a. Baja Closed Low

In the Baja Closed Low pattern, an upper level low becomes cut-off from the mean flow and drifts over the northern Baja region of Mexico (Fig. 4). The upper low is either stationary or slow-moving and is located well to the west when snow is falling across the study region. These events are long-lived, which is likely a testament to the slow movement typically associated with cut-off lows. Although only four snowfall events were identified with this type of setup, Baja Closed Lows produced the highest average areal coverage of four-inch snowfall, and two of the events produced maximum totals up to 12 inches.

Average 500-mb, 700-mb, and 850-mb temperatures for the Baja Closed Low were among the warmest of all the synoptic categories. This pattern had the highest atmospheric moisture content of all six synoptic types identified, with 700-mb and 500-mb mixing ratios, averaging 4.5 g kg^{-1} and 2.0 g kg^{-1}, respectively. Pronounced anomalies in the temperature, height, and moisture

Fig. 4-a

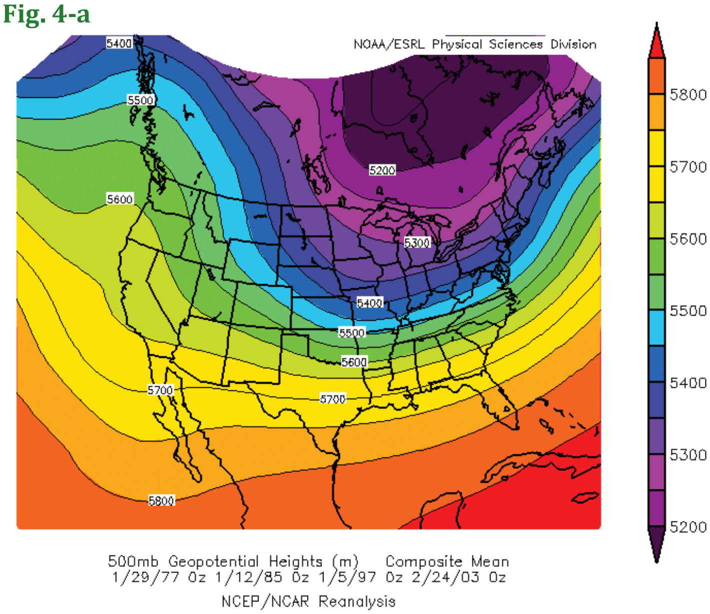


Fig. 4-b

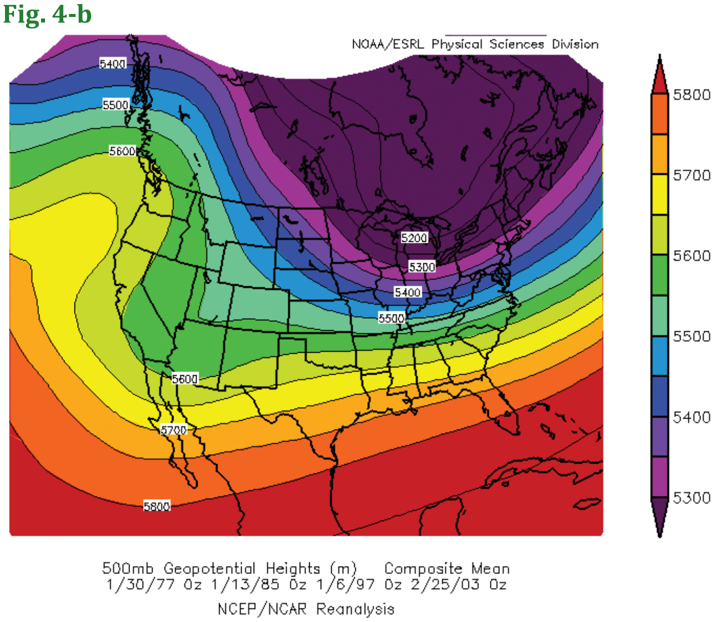


Fig. 4-c

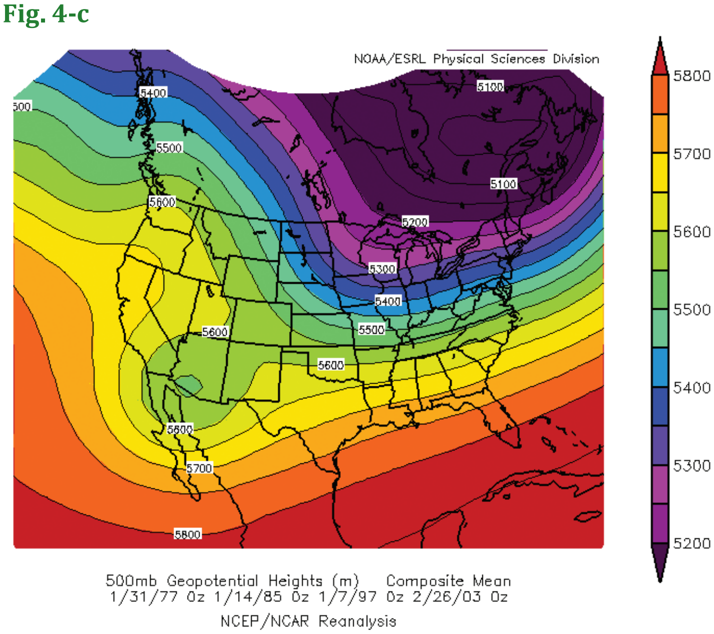


Fig. 4. Charts of 500-mb Composite Means for the Baja Closed Low cases based on NCEP/NCAR reanalysis.

a) 48 h before the event

b) 24 h before the event

c) at the height of the event. Solid lines with interval shading are contours of geopotential height in decameters.

Fig. 5-a

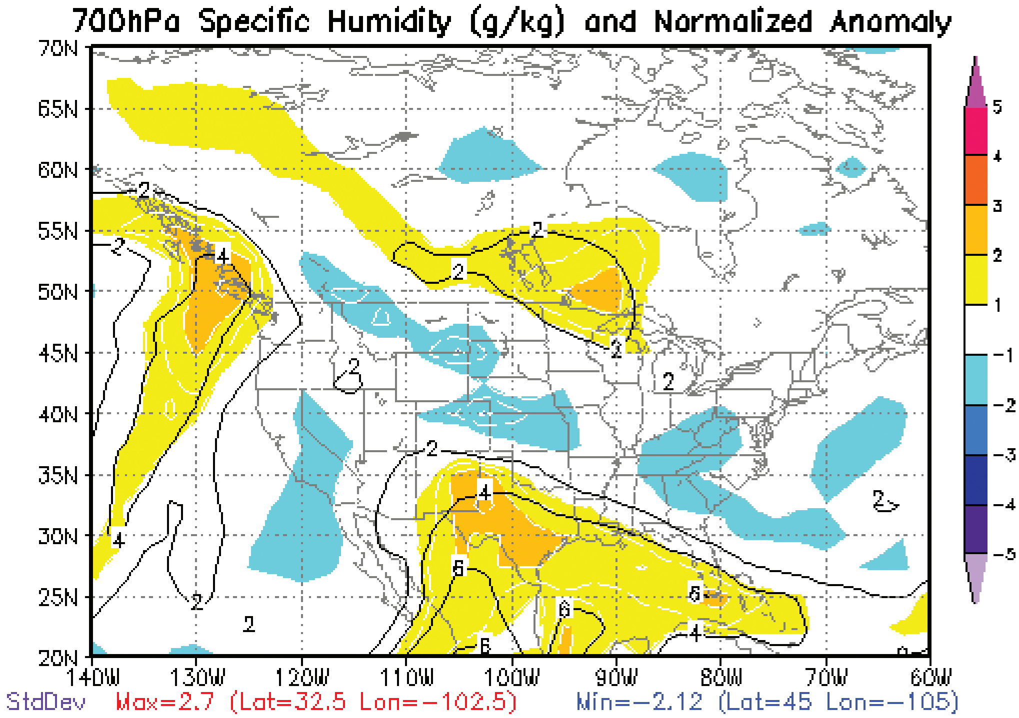


Fig. 5-b

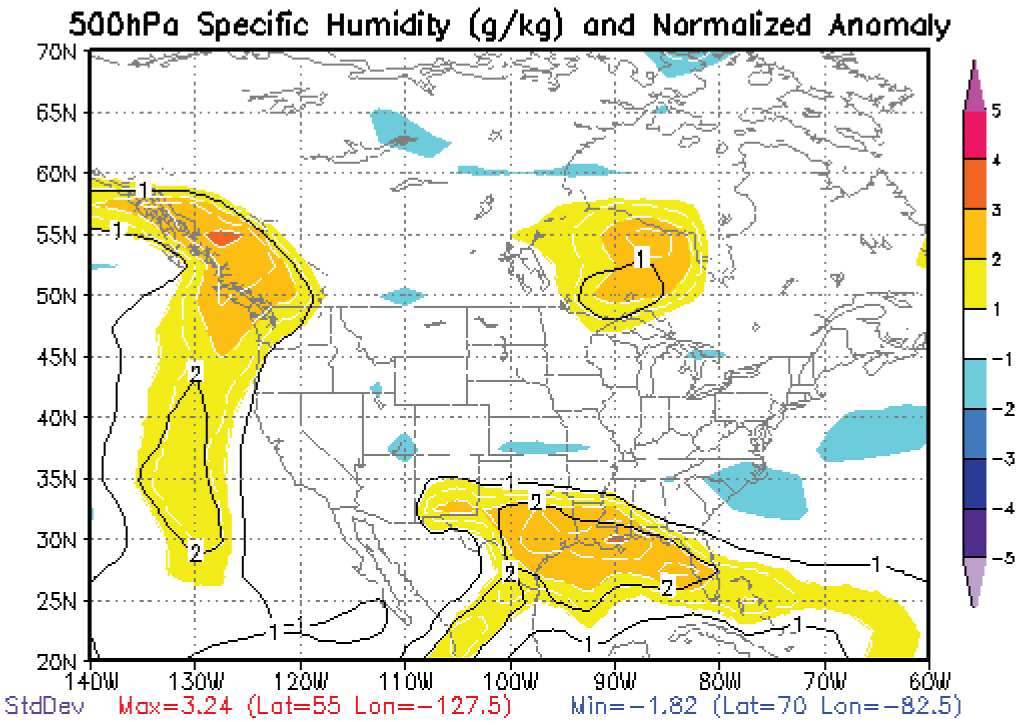


Fig. 5. Specific humidity (solid black lines in g kg-1) and associated normalized anomalies (shading) at

a) 500 mb

b) 700 mb from a Baja Closed Low case at 12 UTC on 13 January 1985.

fields existed with these kinds of cases. The 500-mb height and temperature anomalies averaged two standard deviations below normal. Moisture anomalies at 500 mb and 700 mb were 1.5 standard deviations above normal, indicative of the influx of subtropical moisture from the Pacific Ocean as seen in Figure 5.

The Baja Closed Low systems have no shortage of moisture give the favorable fetch from the subtropics. Rather, the main limiting factor is a subfreezing column of air which is difficult to attain given the inherent warm advection associated with southwesterly flow aloft. During the last 60 years, snowfall events with this pattern only occurred within the climatologically coldest time of the year, either in January or February. Forecasters should closely monitor model and observed temperature profile forecasts, and if temperature profiles support snow, the potential exists for snow amounts over four inches across a large area. Since cold air may be the limiting factor for these systems to produce heavy snowfall, null cases would mostly be comprised of events which produced rain and/or freezing rain.

b. New Mexico Upper Low

The evolution of the New Mexico Upper Low (Fig. 6) begins as an amplified upper level pattern with a ridge along the Pacific coast and a weak and broad trough across the Rocky Mountains. A northeastward expansion of the Pacific ridge into the northern Rocky Mountains develops as the ridge axis becomes oriented from southwest to northeast. Southeast of this upper level ridge, at the base of the positively tilted trough, an upper level low begins to close off over New Mexico. The positioning of these upper level features places Texas in a region where cold air is in place at the low levels as the upper level low develops and intensifies over the Four Corners region and tracks eastward into Texas.

Seven of the events studied were identified as New Mexico Upper Low events. This pattern exhibited only weak 500-mb standardized height and temperature anomalies associated with the upper level low. Temperature anomalies at 700 mb averaged one standard deviation below normal. Compared to the other regimes, average 500-mb and 700-mb temperatures were near the median, but 850-mb temperatures were the warmest of all the synoptic types. The key anomalies associated with this pattern were in the moisture fields, almost two standard deviations above normal, as 700-mb mixing ratios averaged 4.3 g kg^{-1} (Fig. 7). The moisture at 500 mb was less pronounced but still had a normalized anomaly near +1.5. This suggests that null cases would primarily result from an unfavorable vertical temperature profile, not a lack of moisture.

The New Mexico Upper Low system is a favorable setup for localized heavy snowfall and produced the second highest maximum snowfall amount of all the synoptic types. It also had the least areal coverage of four inches or more snowfall. This is likely due to the fact that the subfreezing air in these systems is limited to a small area just under the upper low. A case by case analysis shows that most of these events tend to occur in the West Central region of the study area. None of these cases produced four or more inches of snow over the South Central region.

This is an efficient snow-producing pattern, and as such has little correlation with respect to the time of the year these cases occur. The New Mexico Upper Low cases in this study occurred from mid November to early April. It is possible that the elevation bias over the West Central region in combination with the upper low location and cold air source may aid in dynamical cooling, which may help to explain the lack of a seasonal signal.

c. Detaching Upper Trough

The Detaching Upper Trough regime is similar to the previous New Mexico Upper Low pattern except that it is more progressive. This is because the ridge across the northwestern Pacific Ocean does not expand into the northern Rocky Mountains. In this setup, the shortwave trough responsible for the Texas snowfall comes ashore in the Pacific Northwest two to three days before the event. The shortwave trough digs southward and intensifies,

Fig. 6-a

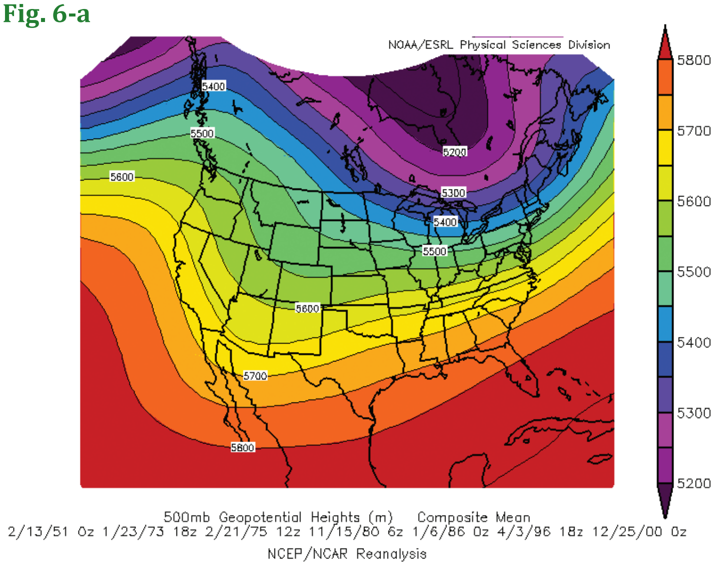


Fig. 6-b

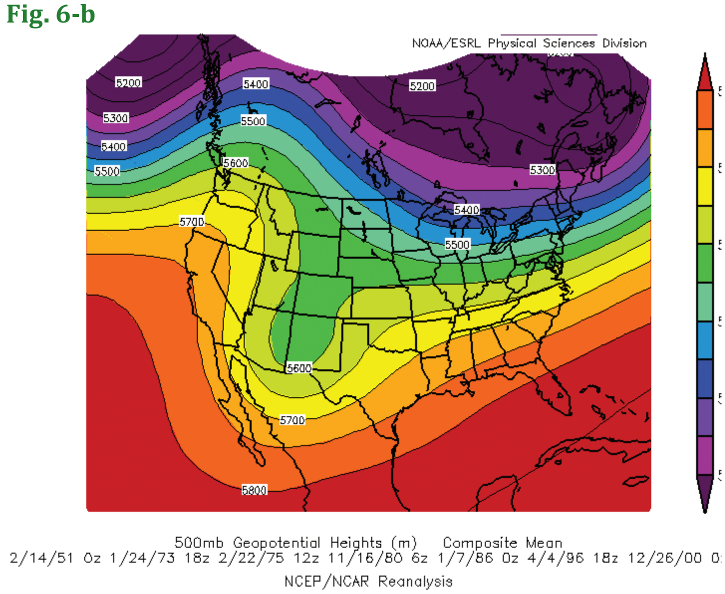


Fig. 6-c

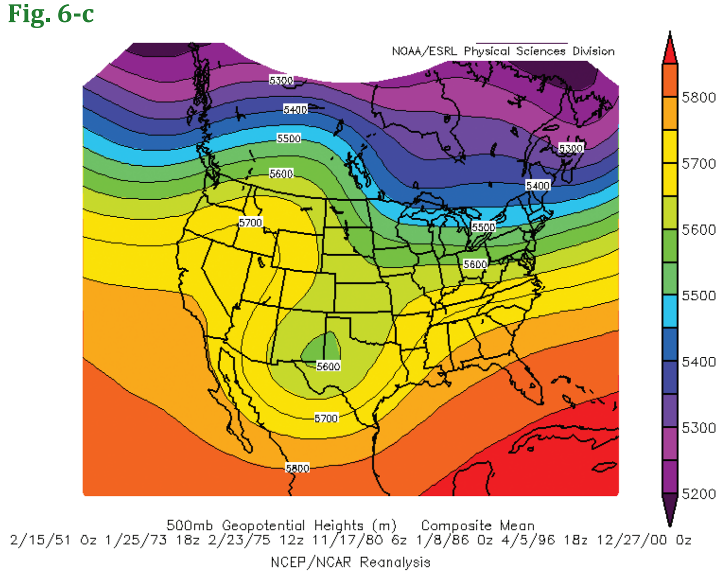


Fig. 6. Same as Fig. 4, except for the New Mexico Upper Low cases.

evolving into a split flow regime. The faster eastward progression of the northern upper trough allows continental polar air to move south into Texas, arriving in the study area a day or so ahead of the upper level disturbance, which by this time has evolved into a closed upper low or pronounced shortwave trough. Figure 8 illustrates the synoptic pattern evolution.

The Detaching Upper Trough regime was responsible for (40%) of all snowfall events studied, with 18 cases identified. Most of the events occurred in the months of December, January, or February. It produced the second highest areal coverage of four-inch snowfall totals, with many cases showing a long narrow band from west to east where the disturbance tracked across the state.

The 500-mb height anomaly in the Detaching Upper Trough pattern was usually significant, averaging almost two standard deviations below normal. Figure 9a depicts a 500-mb height and anomaly map typical of these types of cases. Temperature anomalies at 500 mb (Fig. 9b) were significant and averaged over two standard deviations below normal; however the 700-mb temperature anomalies were relatively weak. The distribution of temperature anomalies suggests an environment with relatively steep mid level lapse rates and perhaps mid-level instability. Mixing ratio anomalies at 500 mb and 700 mb were approximately one standard deviation above normal. A favorable combination of mid-level instability coupled with moisture could create conditions favorable for intense precipitation.

Fig. 7-a

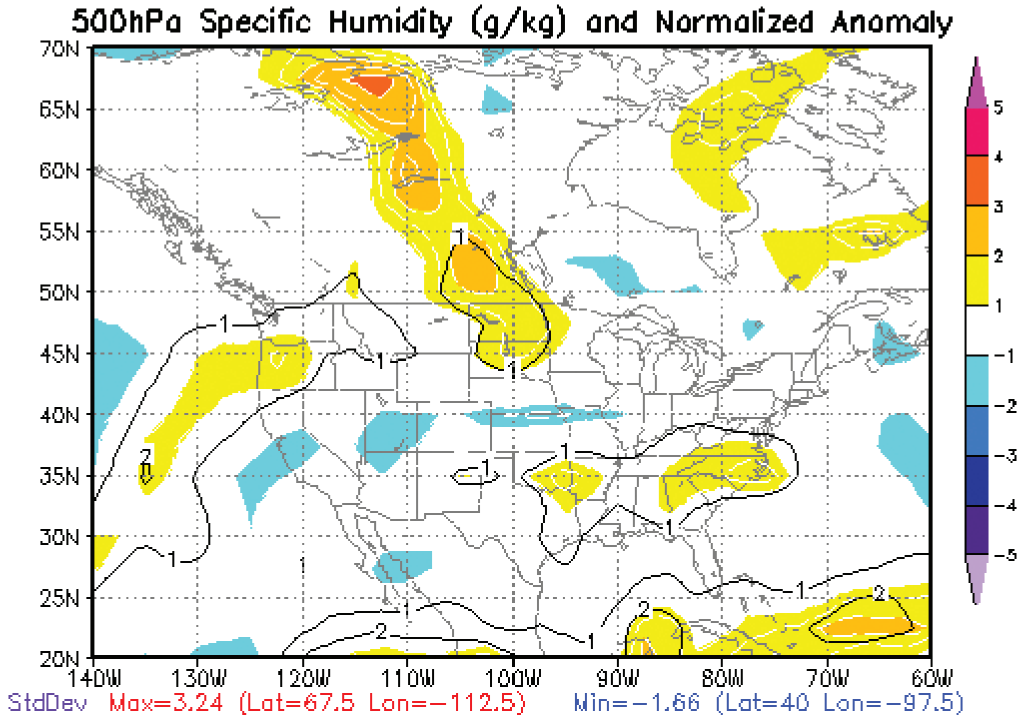


Fig. 7-b

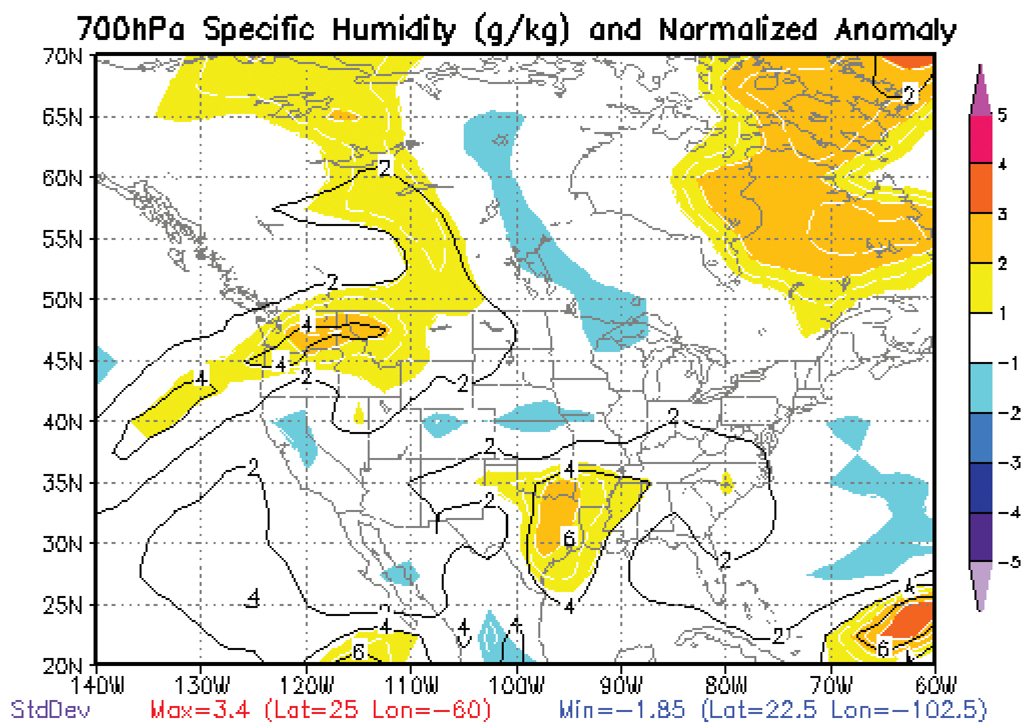


Fig. 7. Same as Fig. 5, except taken from a New Mexico Upper Low case on 27 December 2000. Notice the anomalously high 700-mb moisture over north Texas.

Fig. 8-a

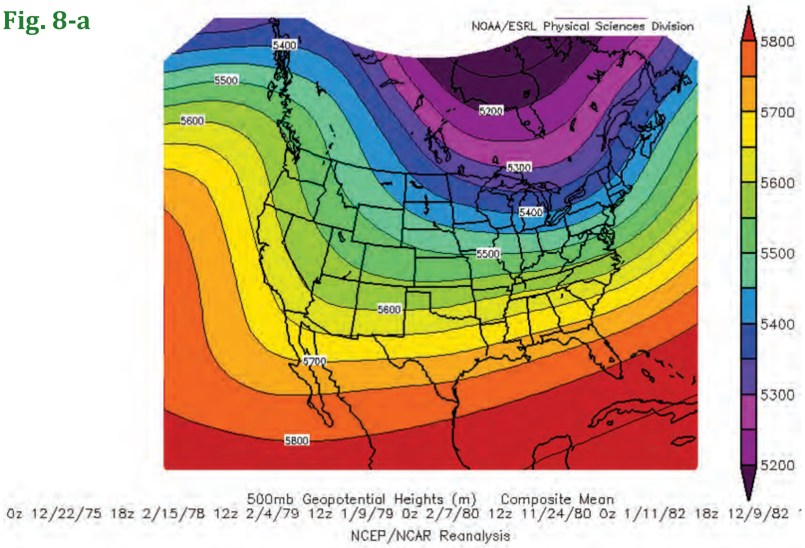


Fig. 8-b

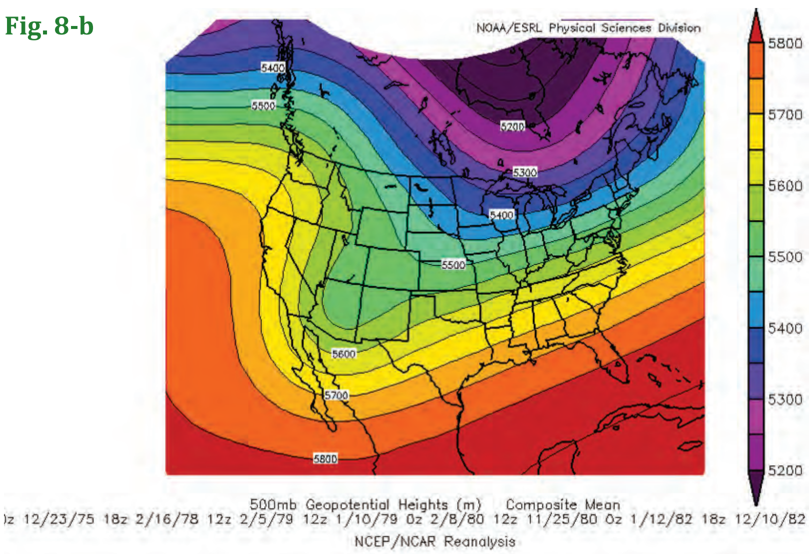


Fig. 8-c

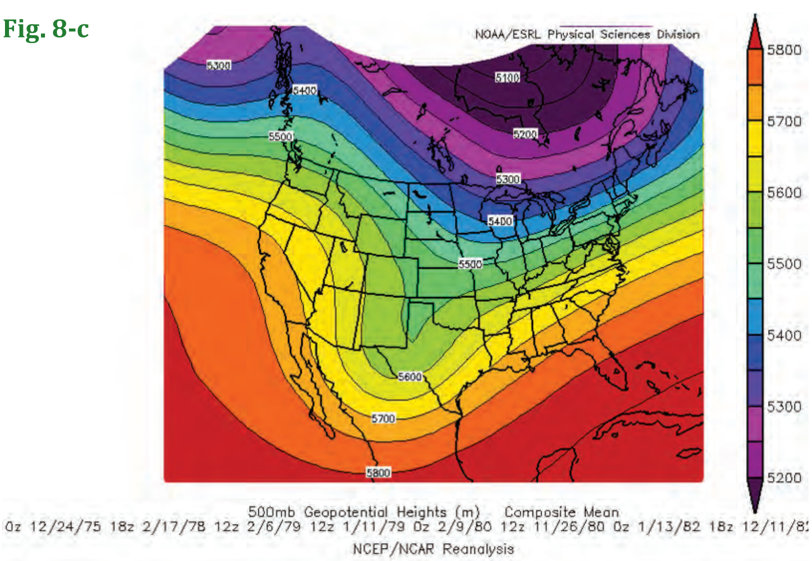


Fig. 8. Same as Fig. 4, except for the Detaching Upper Trough cases.

Because of the frequency of snowfall events associated with the Detaching Upper Trough, it is one of the most important synoptic configurations for forecasters to recognize. The synoptic setup has the ability to bring cold air south first, and then allows large amounts of moisture to be drawn north from the Gulf of Mexico in the mid levels, which is then lifted ahead of the upper level low. This is a climatologically favored pattern and it may be possible for forecasters to see the potential for snow several days in advance. However, the exact location where significant snow will occur is very hard to forecast due to the typically narrow west to east swath. Because the north-south placement of the band of four inch or greater snowfall is critically dependent on the track of the disturbance, forecasters may obtain better forecast accuracy using ensemble prognosis.

d. Subtropical Split Flow

The Subtropical Split Flow pattern is dominated by zonal split flow embedded within an active subtropical branch of the jet stream. A fast-moving shortwave trough within the southern branch acts as the catalyst for these snow events. In the series of composite mean 500-mb height charts shown in Figure 10, the southern stream shortwave trough from the Pacific Ocean moves east through the Sonora Desert with the split in the flow maximized one day before the snow event begins. The specific snowfall-producing synoptic features were weak and subtle, somewhat similar to the Baja Closed Low pattern.

Anomalies of geopotential height and temperature at 500 mb and 700 mb were weak and in some cases non-existent. Moisture was just a little more than one standard deviation above normal at both 500 mb and 700 mb, with 500-mb mixing ratio anomalies averaging the second highest of all the synoptic types (Fig. 11). Just as it did with the Baja Closed Low pattern, this indicates the presence of subtropical Pacific moisture in Texas. The 500-mb temperatures were the warmest of all the groups, and 700-mb temperatures were the second warmest. The warm temperatures and overall lack of synoptic forcing suggest that significant dynamic or microphysical cooling does not occur with this pattern. Therefore any snow which makes it to the ground requires sub-freezing temperatures throughout the column prior to the event.

The Subtropical Split Flow synoptic pattern suggests that once the split flow is in place, deep cold air would not be able to move south into Texas, and therefore would already have to be present well before the southern stream energy moves across the region. This synoptic type produced the second highest average maximum snowfall amount. Almost all the cases occurred in either the North or Northwest regions, with no heavy snows recorded in the South Central region.

The clustering of events in the coldest months of the winter and across the northern portions of the study area suggests that cold air is the main limiting factor in producing snow in this kind of regime. Null events for this regime would primarily occur due to an unfavorable temperature profile and have little to do with moisture. When the Subtropical Split Flow pattern appears, forecasters should focus on whether temperature profiles will be cold enough to produce snowfall.

e. Pacific Coast Ridge

This Pacific Coast Ridge regime features an upper ridge along the Pacific Coast of the United States and Canada with a positively tilted (northeast to southwest) upper level trough along the front range of the Rocky Mountains. The progression of the upper level features in Figure 12 shows the ridge across the western United States translating eastward, placing the research area in the track of the lee-side trough. This highly amplified pattern often is associated with the disintegration of an omega block as the eastern-most upper level low moves slowly southeastward.

Fig. 9-a

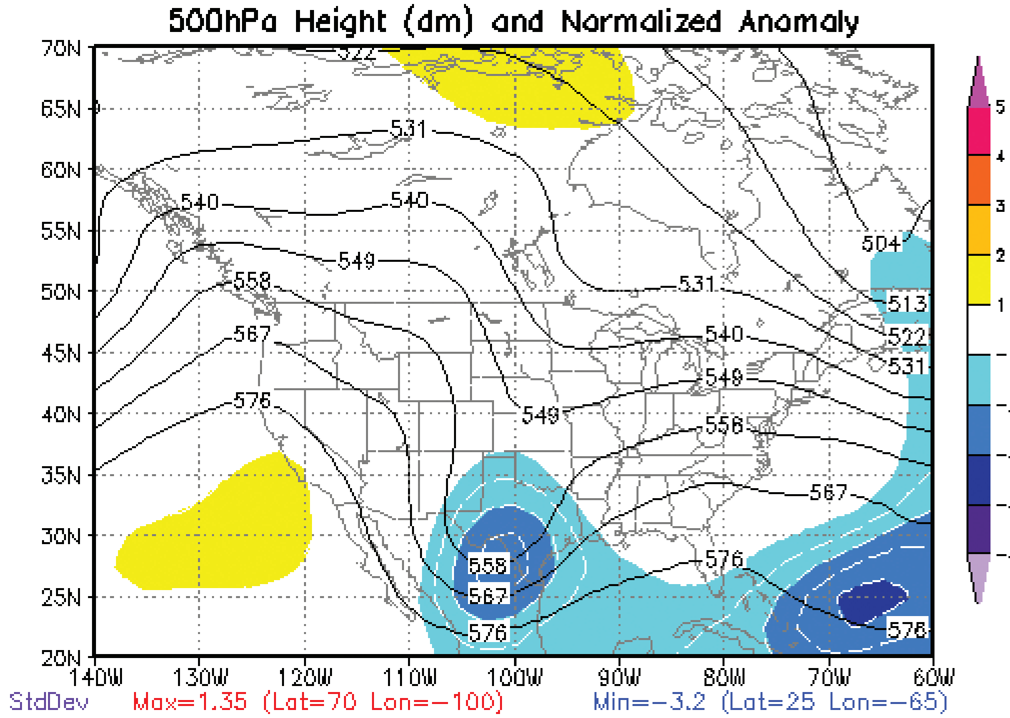


Fig. 9-b

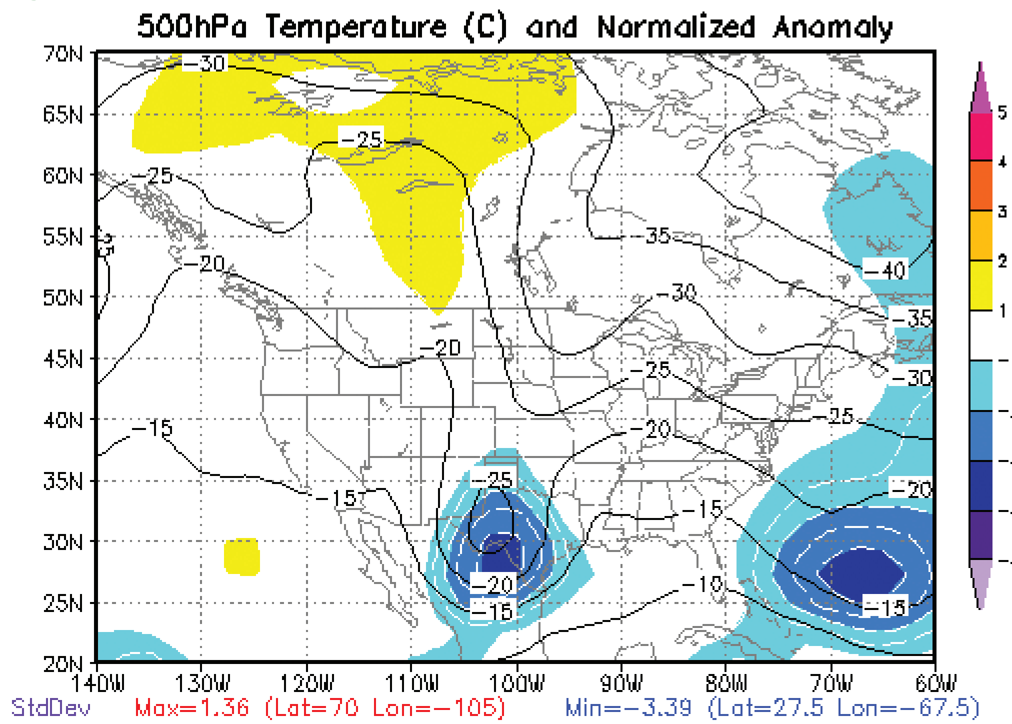


Fig. 9. a.) Geopotential heights (solid black lines in decameters) and b) temperatures (solid black lines in degrees C) at 500 mb and their associated normalized anomalies (shaded) from a Detaching Upper Low case at 0000 UTC on 25 December 1975. Notice the -25°C 500 mb temperatures across West Texas.

Fig. 10-a

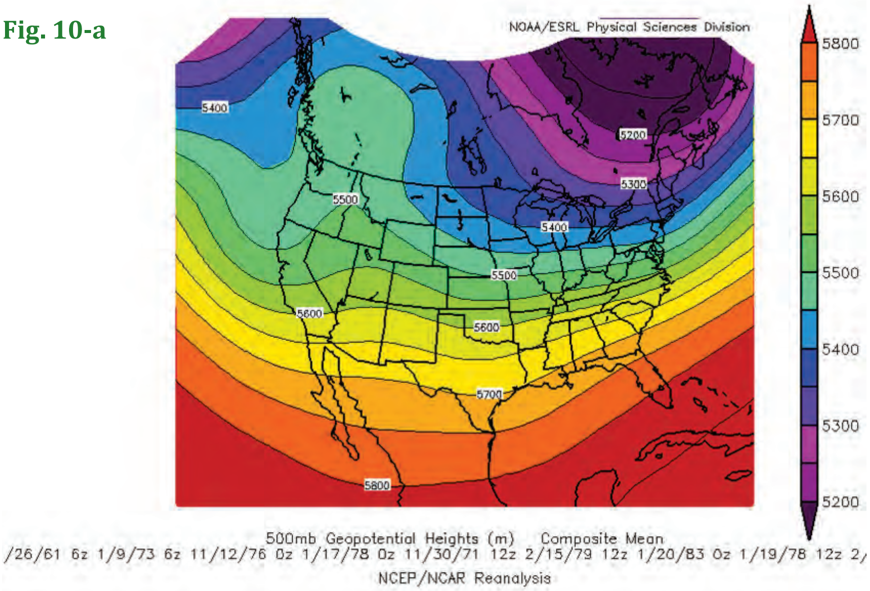


Fig. 10-b

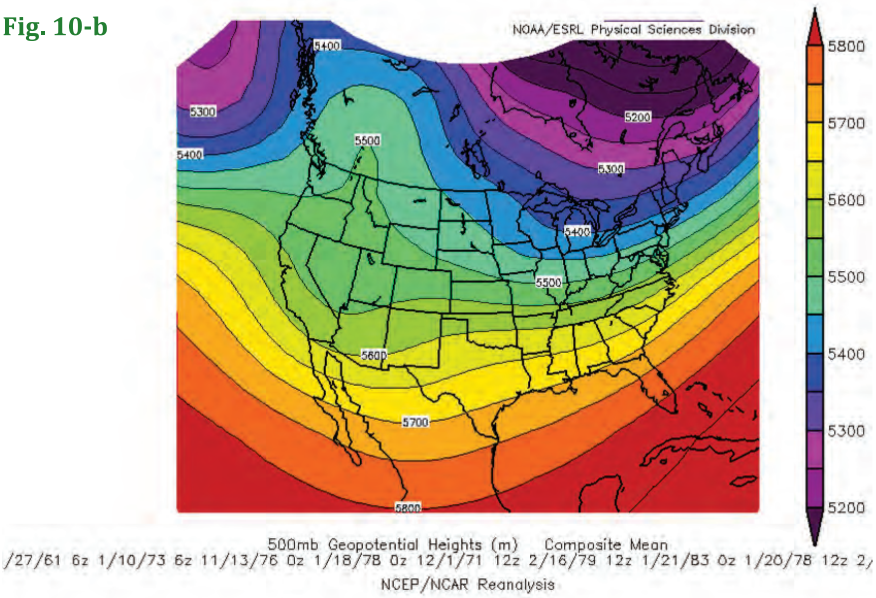


Fig. 10-c

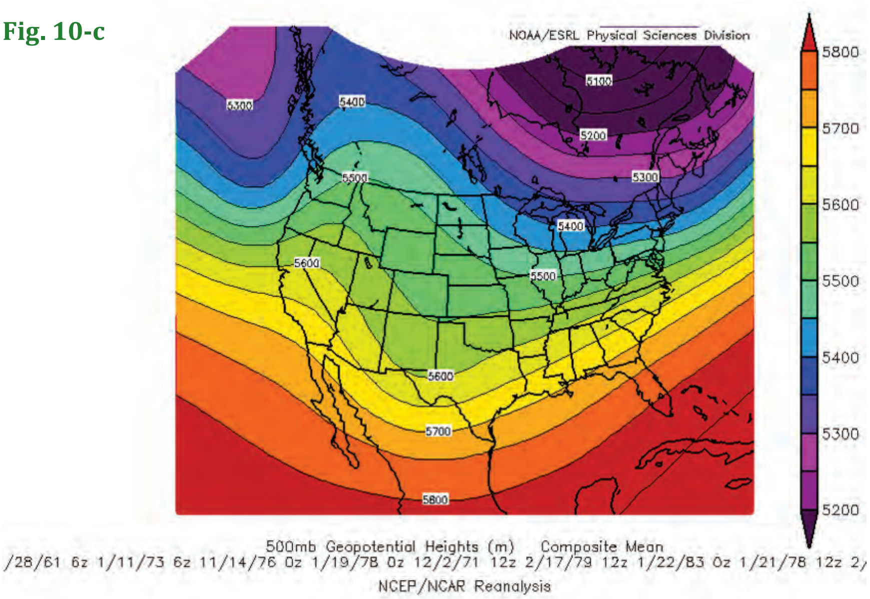


Fig. 10. Same as Fig. 4, except for the Subtropical Split Flow cases.

The resulting polar fetch allows cold air to plunge southward into Texas; however there is less available moisture to work with because the moisture is shunted northeast as the upper level trough approaches from the northwest.

The 500-mb height anomaly maps from a typical Pacific Coast Ridge case (Fig. 13) show significant positive anomalies over western Canada. Much weaker negative anomalies were associated with the upper level trough, averaging 1.5 standard deviations below normal. Temperatures at 500 mb were the coldest of all of the synoptic types, while the 700-mb and 850-mb temperatures were second coldest. Temperature anomalies both at 500 mb and 700 mb were nearly two standard deviations below normal. Moisture with these cases was low, which is to be expected with northwesterly flow aloft. Mixing ratio anomalies were only one standard deviation above normal at 700 mb with essentially no deviation from normal at 500 mb. The lack of significant moisture could lead to a null event where snowfall accumulations total less than four inches.

Only four cases fell into this classification, and therefore statistical correlation and ranking may have little significance. This upper level setup is one of the coldest and had less moisture than most of the other synoptic categories. The average maximum snowfall amount was the second lowest of all of the synoptic types which may be expected with a progressive system such as this. The heaviest snows associated with all four cases fell across the North region of the study area.

f. North American Trough

The North American Trough pattern is characterized by a deep and potent upper trough across central North America. There were eight significant storm cases associated with this synoptic pattern, with all but two of the events occurring with either stationary or retrograding troughs. The main synoptic feature of interest was the anomalous southern location of the Hudson Bay polar low, which often was stationary across the Northern Plains during the time snow was falling in the study area.

These events were associated with very cold temperatures, and this regime ranked as the coldest of all the synoptic types at 700 mb and 850 mb. The North American Trough case depicted in Figure 14 had 500-mb height and temperature anomalies of three standard deviations below normal. Both the 500-mb and 700-mb temperature anomalies averaged two standard deviations below normal. With such cold air in place, it follows that the 500-mb and 700-mb mixing ratio anomalies were not impressive and averaged less than one standard deviation above normal. These were the lowest mixing ratio anomalies for all of the synoptic types.

The North American Trough pattern also produced the lowest average maximum snowfall amount of all of the synoptic categories studied. This is likely because the flow associated with this setup has an inability to bring moisture northward. However, the deep cold air aloft allows snowfall production to be maximized in the limited moisture environment, resulting in low water-equivalent snowfalls.

The mean 500-mb height charts two days prior to the snowfall event (Fig. 15) show little change, with basically the same broad longwave trough over the central United States. Forecasters should watch for longwave troughs that are slow moving, very cold, and are able to utilize mixing ratios of at least 2.0 g kg^{-1} at 700 mb and 1.0 g kg^{-1} at 500 mb. Systems containing less moisture at these levels may result in null cases in which little or no precipitation falls.

4. Discussion

Grumm and Hart (2001) found that significant East Coast and Plains snow storms had a propensity for high standardized anomalies in several fields such as temperature, moisture, geopotential height, as well as the u and v wind component speeds. Although the use of anomalies can help forecasters classify the type of synoptic pattern, this research shows little to no correlation between the severity of the event and the strength of the anomalies across our study region. The rarity of snow events across Texas is most likely not a

Fig. 11-a

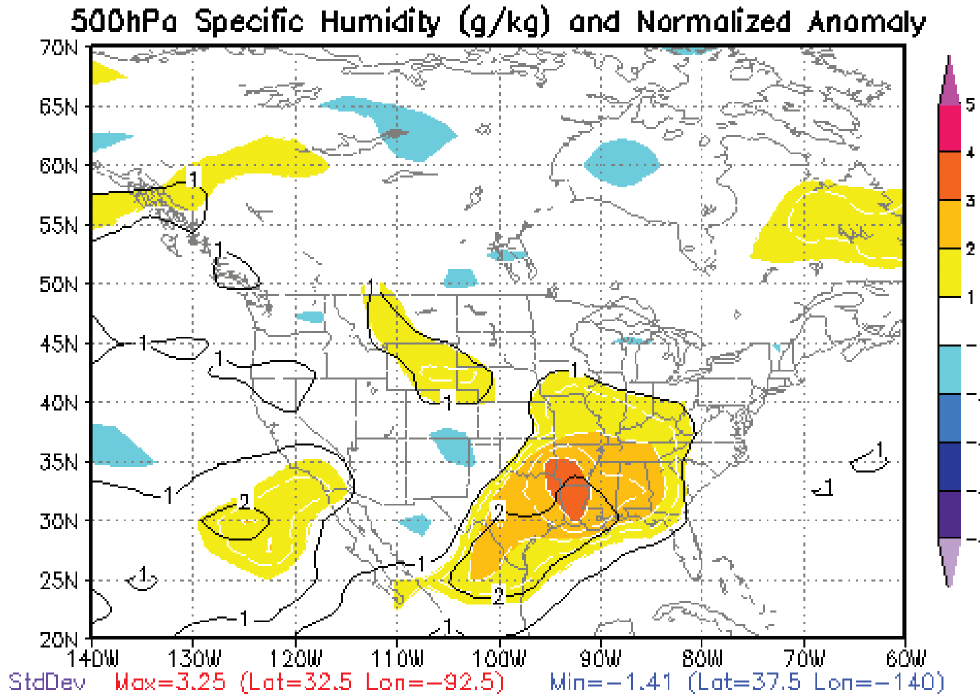


Fig. 11-b

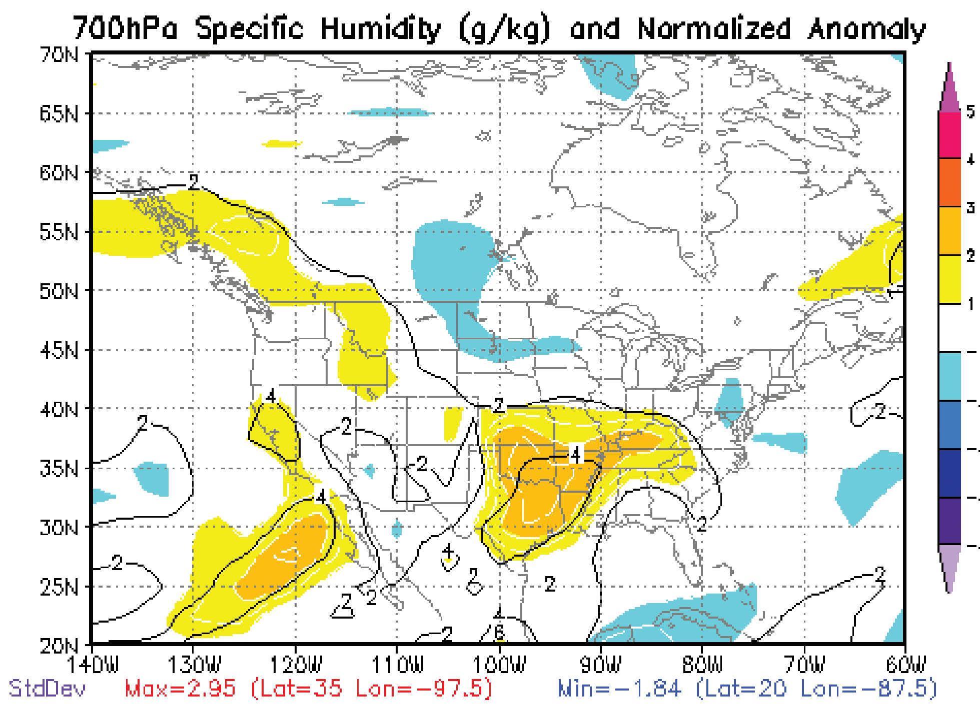


Fig. 11. Same as Fig.5, except taken from a Subtropical Split Flow case on 16 January 1978. Notice the injection of upper level Pacific moisture at these levels over north Texas.

result of a lack of major storm systems, but rather a rarity of synoptic, thermodynamic, and cloud microphysical processes that combine to produce conditions favorable for heavy snow. With some synoptic patterns, such as the Subtropical Split Flow, few significant standardized anomalies were detected. Certain regimes had tendencies for considerable anomalies, such as cold temperatures in the North American Trough cases and high moisture in the Baja Closed Low pattern.

Dendritic crystal growth is a necessary requirement for snow and often the layer from -10° C to -20° C is saturated. According to Wallace and Hobbs (1977), saturation at temperatures colder than -10°C is indicative of ice activation in a cloud the majority of the time. Analysis of the 500-mb and 700-mb temperatures and mixing ratios for each event would give a reasonable guess as to whether the dendritic growth layer was saturated. In cases where the 700-mb temperatures are warmer than -10°C, the dendritic growth layer must be higher than 700 mb. One would therefore assume that the layer near 500 mb could represent the dendritic layer and postulate that 500-mb mixing ratios would on average be higher for these events than for events with which dendrites are allowed to form at 700 mb. Our research supports this theory; 500-mb mixing ratios were almost 0.5 g kg^{-1} higher when 700-mb temperatures were warmer than -10°C. Therefore, 500-mb moisture may not be a critical parameter for significant snow in cases where 700-mb temperatures are colder than -10°C.

Fig. 12-a

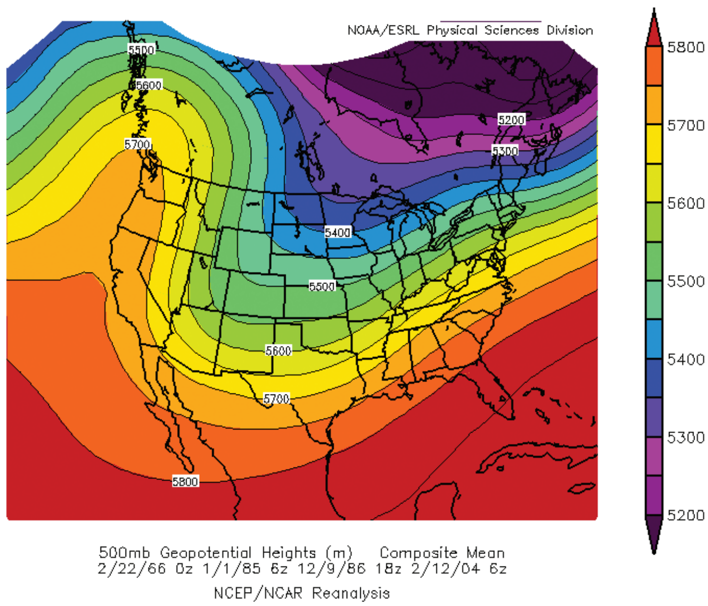


Fig. 12-b

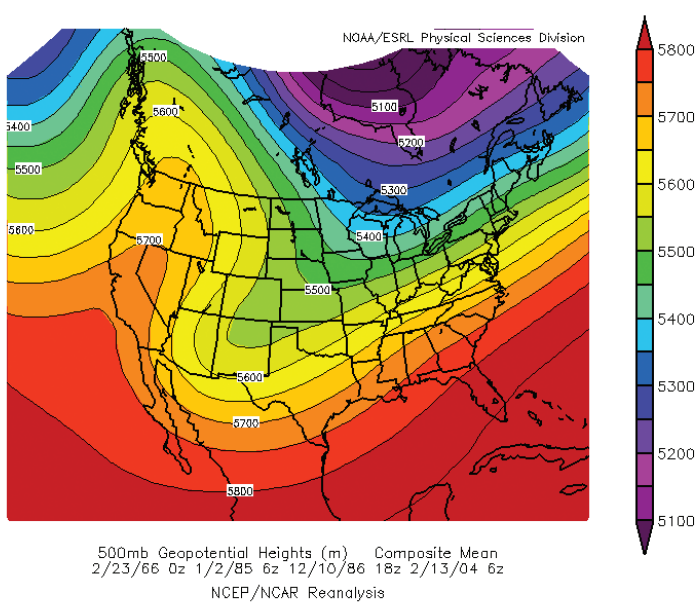


Fig. 12. Same as Fig. 4, except for the Pacific Coast Ridge cases.

5. Conclusion and Proposed Future Research

With the use of model guidance, this research can be integrated into the forecast process to enhance accuracy and increase lead times of snowfall events. When a synoptic setup favorable for winter precipitation is forecast to develop, forecasters should first try to classify the regime as one of the six categories presented. Comparison of key geopotential height, temperature, and moisture parameters between the model forecasts and the climatological averages for the particular synoptic type can aid in pattern recognition. This can provide the forecaster improved anticipation and situational awareness as to whether a pending snowfall event is climatologically favorable or unfavorable. If model forecasts are

Fig. 12-c

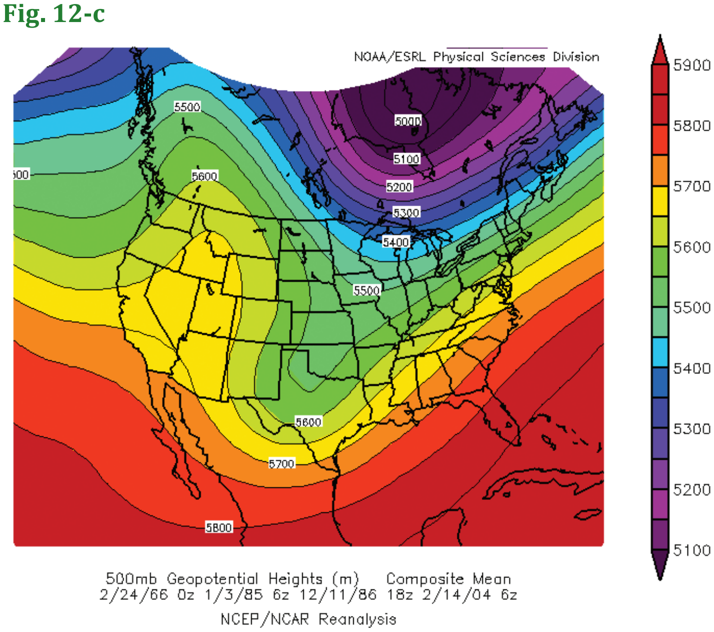


Fig. 13-a

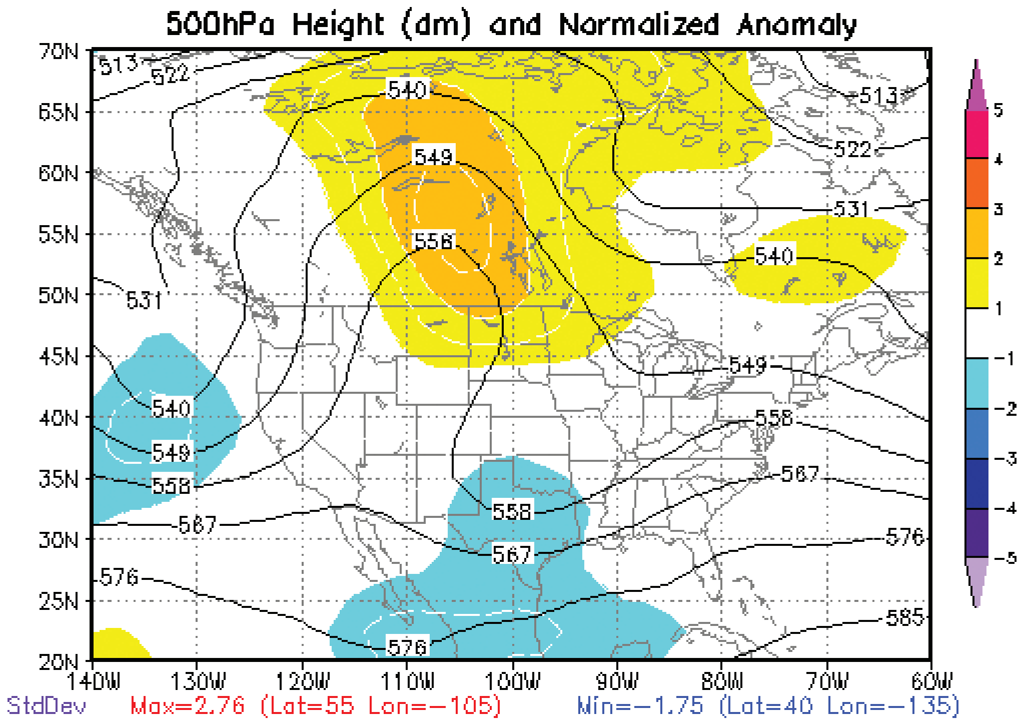


Fig. 13-b

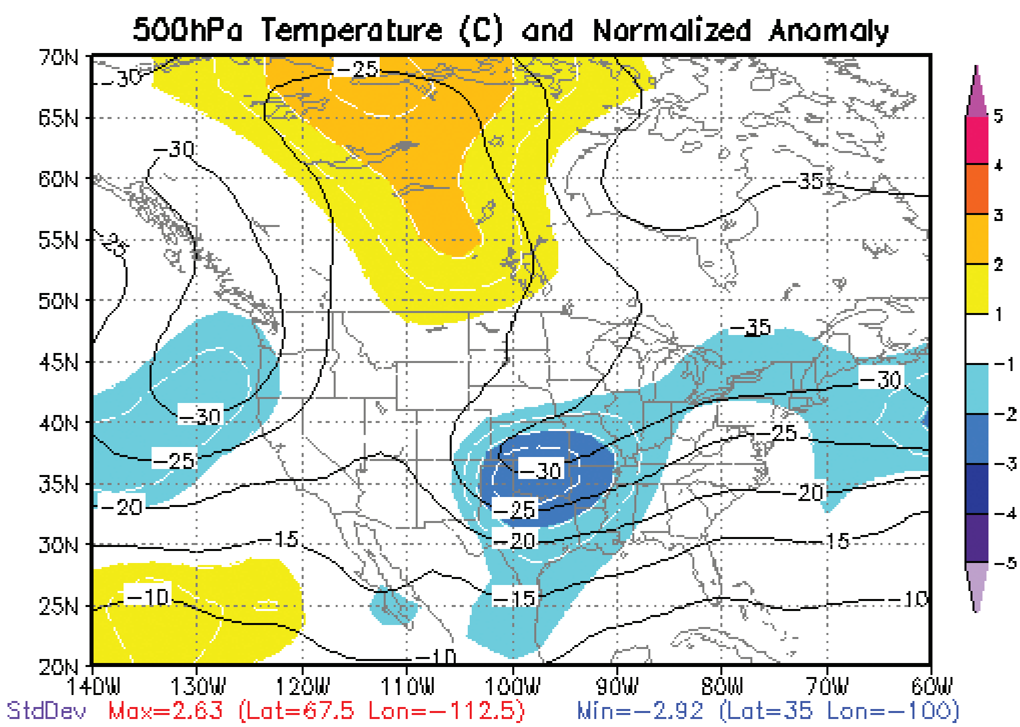


Fig. 13. Same as Fig. 9, except taken from a Pacific Coast Ridge case at 0000 UTC on 24 February 1996. Notice the -30°C analyzed with the upper level trough at 500 mb. However, the height anomalies are not that significant over this same area.

climatologically unfavorable, forecasters will be able to key in on what parameter(s) must change in model forecasts or observed data in order to make the conditions more favorable.

All cases in which significant snowfall occurred were researched; however occurrences of these patterns which did not produce four or more inches of snowfall were not investigated. Further examination of the climatological frequency of the six synoptic types presented in this paper could generate operationally useful statistics such as probability of detection and false alarm rates. Additionally, an event which produces any amount of measurable frozen precipitation may still be significant to residents of the study region. Therefore it may be helpful to classify the remaining synoptic events as those which produced no winter precipitation and those that produced accumulations of less than four inches. This method would complement the database of research in this study.

As a result of this research, the authors believe that improvement to snowfall forecasting skill in Texas and perhaps other regions in the southern and central U.S. will occur. An improvement of forecast skill will allow better lead times and result in substantial economic and safety benefits to residents within the study area.

Fig. 14-a

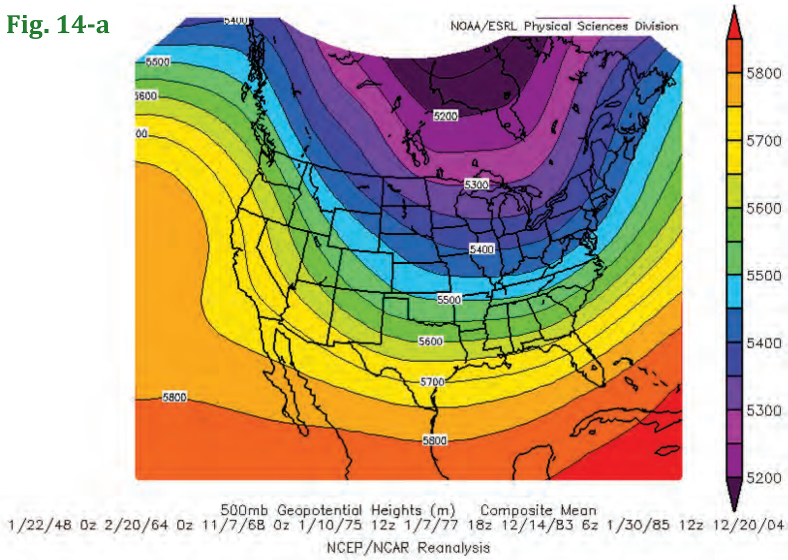


Fig. 14-b

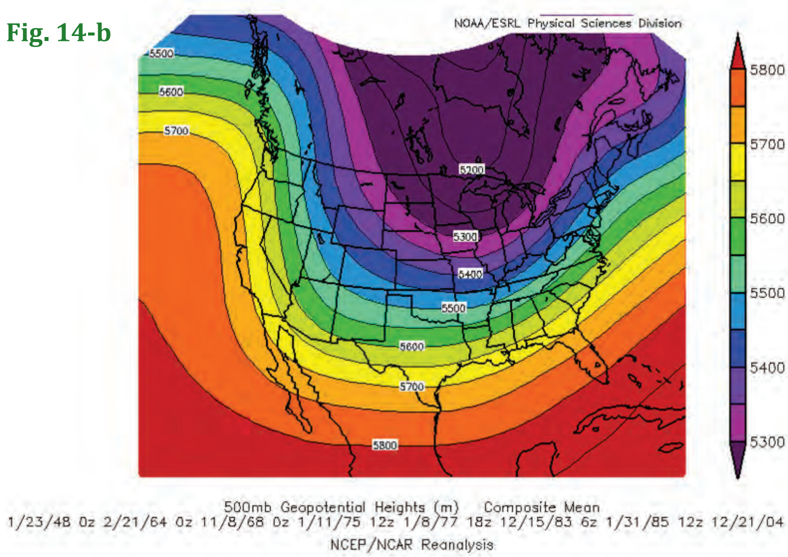


Fig. 14-c

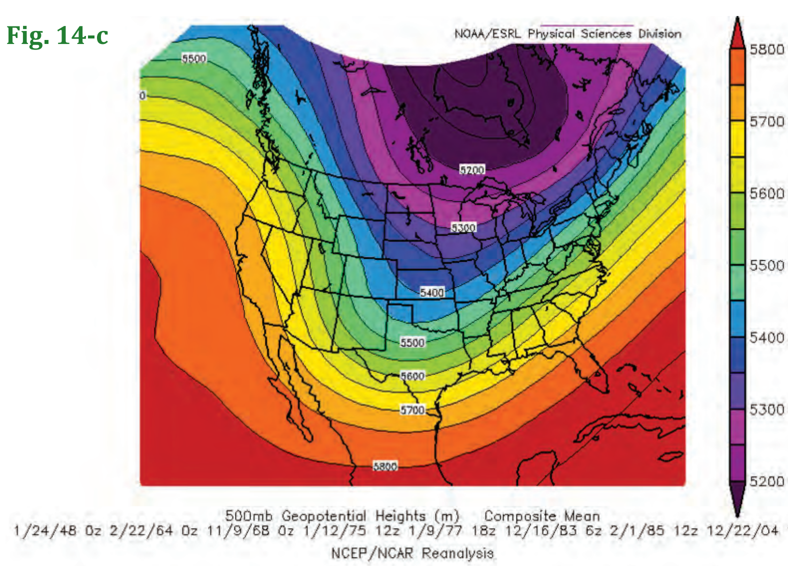


Fig. 14. Same as Fig. 4, except for the North American Trough cases.

Authors

Ted Ryan is a Senior Forecaster at the NWS Forecast Office in Fort Worth, Texas. Ted graduated from Texas A & M University with a degree in meteorology (2002). His duties include issuing forecasts, warnings, and advisory products for 46 counties in north Texas. Ted's interests include all aspects of operational forecasting, ranging from hazardous convective weather to winter storms.

Stacie Hanes is a forecaster at the NWS Forecast Office in Fort Worth, Texas. Stacie is a B.S. graduate from the University of Georgia (2004). Prior to working in Fort Worth, Stacie was a student intern at the NWS Forecast Office in Peachtree City, Georgia from 2000 - 2004. Stacie is a member of the national and local chapters of the National Weather Association (NWA) and the American Meteorological Society (AMS).

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Fig. 15-a

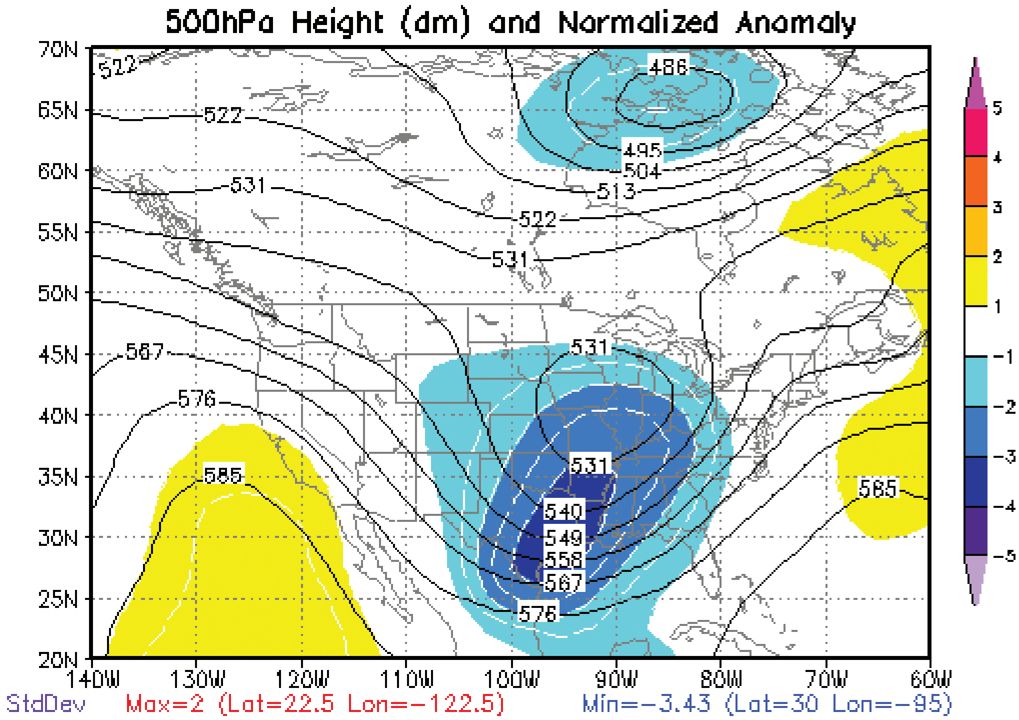

Fig. 15-b

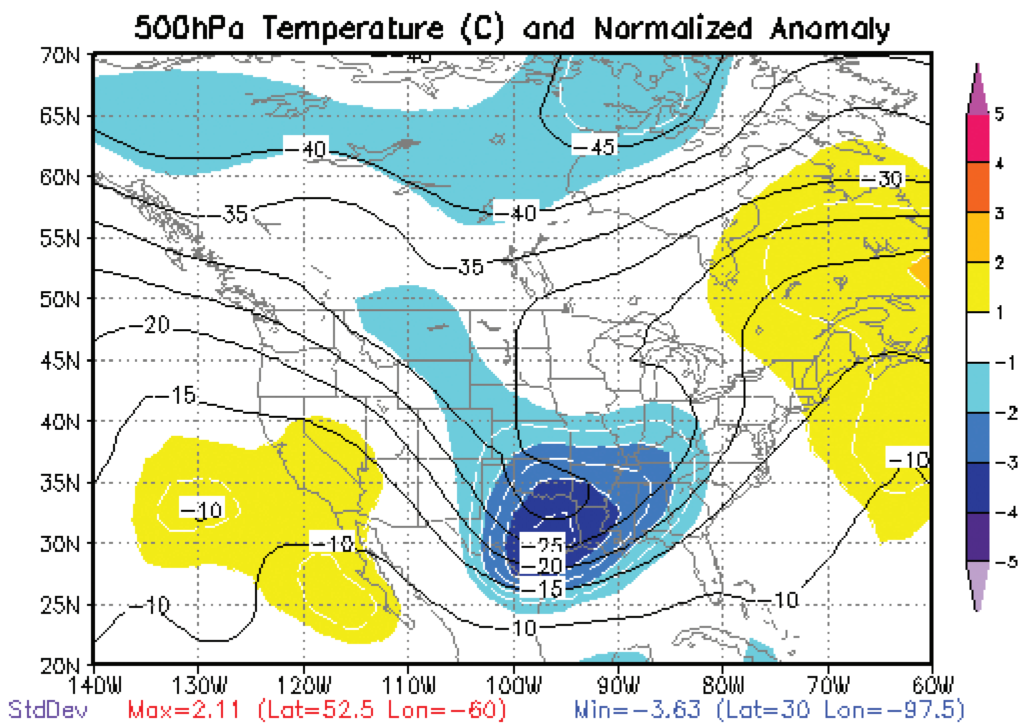

Fig. 15. Same as Fig.5, except taken from a North American Trough case at 0000 UTC on 15 December 1983. Notice the large anomaly values in both the height and temperature fields at 500 mb over East Texas.

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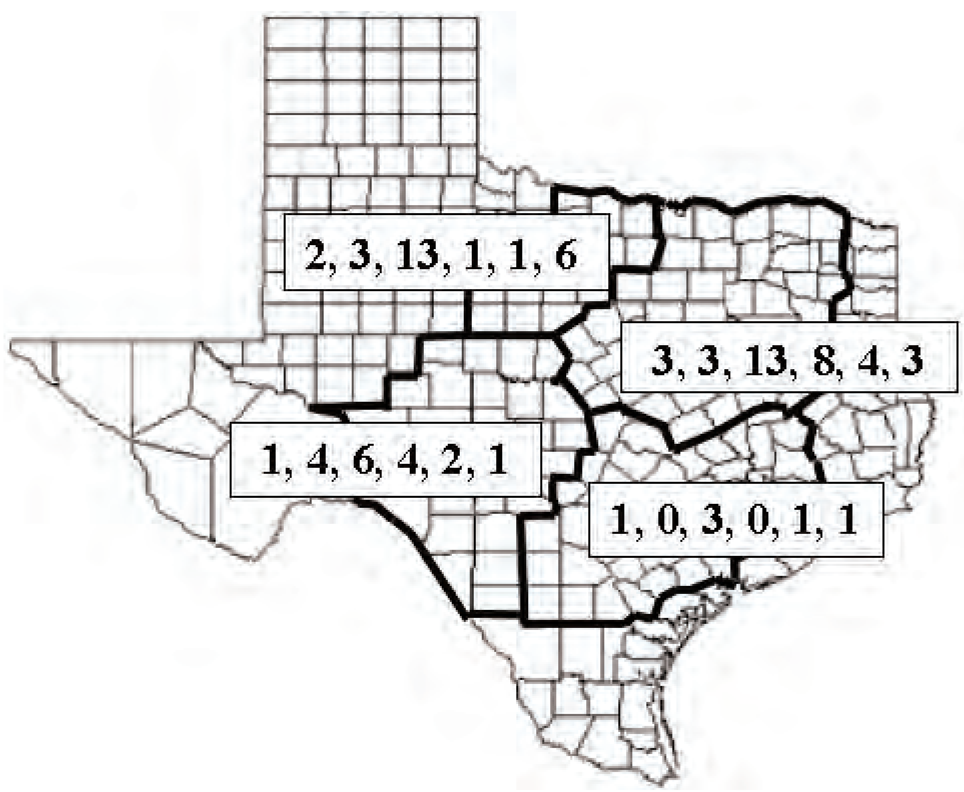
Appendix A

Shown at right is a map with the research areas outlined and the number of cases per synoptic type for each region. The synoptic types are listed as follows: Baja Closed Low, New Mexico Upper Low, Detaching Upper Trough, Subtropical Split Flow, Pacific Coast Ridge, North American Trough. Also, tables list all the cases and their snowfall characteristics by synoptic type. Snowfall areas were estimated using maps of the events and include the region within the four-inch snowfall isoline. Asterisks in the snowfall area column indicate that only a rough approximation was obtainable (due to missing data). Locations of maximum snowfall amounts are designated using the regions depicted in Fig. 1c., and are abbreviated as follows: North – N, Northwest – NW, West Central – WC, South Central – SC. The 'Regions Affected' column indicates areas where four or more inches of snow fell.



Baja Closed Low

Date	Max Snow Amount (in)	Region of Max Snow Amount	Regions Affected	Orientation of Snow Band	Snowfall Area (mi^2)
30-31 JAN 1977	11	N	N, NW	SW to NE	25,310
12-13 JAN 1985	14	WC	WC, SC	W to E	50,900
6-7 JAN 1997	6	N	N	SW to NE	2,600
24-27 FEB 2003	5	N	N, NW	SW to NE	2,850
AVG	9.0				20,415

New Mexico Upper Low

Date	Max Snow Amount (in)	Region of Max Snow Amount	Regions Affected	Orientation of Snow Band	Snowfall Area (mi^2)
13-15 FEB 1951	4.2	N	N	Unknown	300*
25 JAN 1973	4.9	WC	WC	SW to NE	3,400
22-23 FEB 1975	3.7	N	N	WSW to ENE	300
16-17 NOV 1980	12	NW	NW, WC	SW to NE	4,245
7-8 JAN 1986	8.2	WC	WC	Unknown	2,600
5 APR 1996	9.3	NW, WC	NW, WC	W to E	2,070
25-27 DEC 2000	8	N	N, NW	N to S	4,045
AVG	7.2				2,823

Detaching Upper Trough

Date	Max Snow Amount (in)	Region of Max Snow Amount	Regions Affected	Orientation of Snow Band	Snowfall Area (mi^2)
30-31 JAN 1949	7	SC	N, WC, SC	WSW to ENE	65,740
17-18 JAN 1956	6	N	N	SW to NE	5,028
15-16 JAN 1964	12	N	N, NW	SSW to NNE	28,057
28-30 DEC 1969	5.4	NW	NW	WSW to ENE	1,127
19-21 MAR 1970	6.2	NW	N.NW	W to E	6,800
23-25 DEC 1975	4	NW	N, NW	WSW to ENE	1,120
15-18 FEB 1978	12	N	N,NW	W to E	26,830
10-11 JAN 1979	4	N	N,NW	W to E	1,950
5-7 FEB 1979	9.5	N	N,NW	W to E	4,768
8-10 FEB 1980	6	NW	N, NW	SW to NE	4,420
25-26 NOV 1980	4	WC	WC	NW to SE	300
31 DEC 1982-02 JAN 1983	7.5	NW	NW, WC	SW to NE	9,844
12-14 JAN 1982	8.1	N	N, NW, WC,SC	W to E	43,160
11-12 DEC 1982	4	N	N, NW	SW to NE	850
4 MAR 1989	6.3	NW	N, NW, WC	WSW to ENE	20,030
28 NOV 2001	4	NW	NW, WC	SW to NE	7,776
5-6 FEB 2002	5	N	N	W to E	4,690
24-25 DEC 2004	12	SC	SC	WSW ENE	6,324
AVG	6.8				13,267

Subtropical Split Flow

Date	Max Snow Amount (in)	Region of Max Snow Amount	Regions Affected	Orientation of Snow Band	Snowfall Area (mi^2)
27-28 JAN 1961	6	N	N	SW to NE	3,170
1-2 DEC 1971	4.2	NW	NW	Unknown	927
10-12 JAN 1973	7.5	NW	N, NW, WC	W to E	7,350
12-14 NOV 1976	13	N	N, NW, WC	WSW to ENE	24,035
17-19 JAN 1978	4.5	N	N, NW	W to E	3,500
20-22 JAN 1978	8.8	WC	N, WC	SW to NE	4,080
6-9 FEB 1978	8	N	N, NW	NW to SE	13,171
16-18 FEB 1979	4.3	N	N	SW to NE	700
21-22 JAN 1983	5.5	N	N, NW, WC	NW to SE	8,485
AVG	6.9				7,269

Pacific Coast Ridge

Date	Max Snow Amount (in)	Region of Max Snow Amount	Regions Affected	Orientation of Snow Band	Snowfall Area (mi^2)
22-23 FEB 1966	4.8	N	N	Unknown	3,000*
1-3 JAN 1985	8	N	N, WC, SC	SW to NE	27,150
11 DEC 1986	6	N	N, WC	WSW to ENE	3,800
14 FEB 2004	5	N	N, NW	W to E	9,584
AVG	6.3				10,884

North American Trough

Date	Max Snow Amount (in)	Region of Max Snow Amount	Regions Affected	Orientation of Snow Band	Snowfall Area (mi^2)
24 JAN 1948	4	NW	N, NW	WNW to ESE	4,100
21 FEB 1964	4	SC	SC	Unknown	300*
8-9 NOV 1968	5.8	WC	WC	W to E	4,150
12 JAN 1975	6	NW	NW	WSW to ENE	1,965
9-10 JAN 1977	6	NW	NW	W to E	2,377
15-17 DEC 1983	7	N	N, NW	W to E	18,884
31 JAN 01-FEB 1985	8.1	NW	NW	S to N	3,117
22 DEC 2004	4	N	N, NW	W to E	2,850
AVG	5.6				4,718