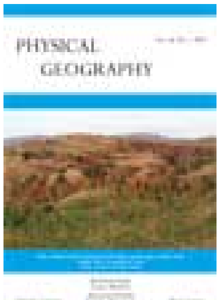

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A Climatology of Northwest Missouri Snowfall Events: Long-Term Trends and Interannual Variability

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A CLIMATOLOGY OF NORTHWEST MISSOURI SNOWFALL EVENTS: LONG–TERM TRENDS AND INTERANNUAL VARIABILITY

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Abstract: The goal of this study was to develop a 50-yr. statistical climatology of snowfall occurrences using data from a dense network of cooperative station observations covering northwest and central Missouri, and these records were provided by the Missouri Climate Center. This included a study of the long-term trends and interannual variability in snowfall occurrence as related to sea surface temperature variations in the Pacific Ocean basin associated with the El Niño and Southern Oscillation (ENSO) and the North Pacific Oscillation (NPO). These trends and variations were then related to four synoptic-scale flow regimes that produce these snowfalls in the Midwest. The results demonstrate that during the snowfall season (Oct–April) the northwest Missouri region can expect about eight snowfall events which produce $\geq$3 in. (>7.5 cm) of accumulation. While no significant long-term trend in overall snowfall occurrence was found, a decrease in the number of extreme events ($\geq$10 in., >25 cm) was noted. Also, fewer snowfall events were found during El Niño years, while more heavy snowfall events occurred during "neutral" years, and these results could be related to synoptic-scale variability. A closer examination of the results demonstrated that El Niño/La Niña related variability in snowfall occurrence was superimposed on longer-term NPO-related variability. [Key words: Interannual variability, snowfalls, climatology, El Niño.]

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INTRODUCTION

In recent decades, climatic fluctuations due to natural variability inherent in the earth-atmosphere system have been examined extensively (e.g., Wallace and Gutzler, 1981; Blackmon et al., 1984; Gray, 1984, 1998; Mo and Livezey, 1986; Wunsch, 1992, 1999; Hurrell, 1995, 1996; Schmitz, 1996; O'Brien et al., 1996; Bove et al., 1998). In particular, interannual variability in climates within the United States Midwest has been linked to coupled ocean-atmosphere phenomena such as the El Niño and Southern Oscillation (ENSO; e.g., Kung and Chern, 1995; Changnon et al., 1999), and the North Pacific Oscillation (NPO; or the Pacific Decadal Oscillation, PDO; e.g., Gershunov and Barnett, 1998). These phenomena have been shown to influence the mean structure of midlatitude atmospheric circulations on time scales from seasons (e.g., McPhaden, 1999) to a few years (e.g., ENSO related variability) to decades (e.g., NPO related variability: Gershunov and Barnett, 1998). Additionally, many other studies have shown the importance of sea surface temperature (SST) variations in forcing an atmospheric response on both short and long time and space scales (e.g., Namias, 1982; Hoskins et al., 1983; Kung et al., 1990, 1992, 1993; Nakamura et al., 1997; Lau, 1997; Lupo and Bosart, 1999). Recently, Livezey et al. (1997), Hu et al. (1998), and Berger et al. (1999) have noted ENSO related variability in midwestern U.S. precipitation. Hu et al. (1998) also showed variability in midwestern precipitation on longer time scales as well as a general upward trend in precipitation amounts. Karl and Knight (1998) noted these general trends for heavy precipitation events nationwide, and Karl et al. (1993) and Karl et al. (1996) also have shown long-term trends in U.S. temperatures.

One of the more difficult forecasting challenges for Northwest Missouri (NWMO) is the arrival of heavy snowfalls, which can occur frequently during the cold season. There is anecdotal evidence demonstrating that heavy snow events and their timing can affect communities in many ways, including the slowing down or halting of air and ground traffic flow, which in turn can have a large economic impact on the region. An early snowfall event in October could adversely affect the late season harvest. A late snowfall event in the spring could also affect the agricultural industry by delaying the planting of crops and saturating the ground.

Heavy snowfalls are events that typically occur in association with synoptic scale transients. However, these snowfalls often occur on time and space scales more consistent with those of mesoscale phenomena (e.g., Martin, 1998; Market and Cissell, 2002). Therefore, identifying the common climatic, synoptic-, and meso-scale patterns that produce heavy snowfall is essential for the improvement of heavy snowfall forecasting. Some studies (e.g., Kunkel and Angel, 1999; Smith and O'Brien, 2001) have examined the interannual variability in snowfall amounts for various regions of the country. The Smith and O'Brien (2001) study did not extend into the NWMO region but did discuss adjacent regions of the country, while the Kunkel and Angel (1999) did extend across this study region. There have been a few recent local studies that discuss the climatological (e.g., Metze and Glass, 1998; Berger et al., 1999) characteristics of snowfalls in NWMO. However, these studies do not provide the necessary detail needed to understand comprehensively the climatological behavior and interannual variability of snowfall occurrence in the NWMO region.

A climatology of snowfall events and snowfall-producing flow regimes is presented here using a dense station observation network covering NWMO and part of central Missouri. A statistical analysis was performed in order to find long and short-term trends and study the seasonal and intraseasonal variability, as well as interannual variability in snowfall occurrences and their relationship to ENSO and NPO variability. This study will extend similar studies, such as those by Kunkel and Angel (1999) and Smith and O'Brien (2001), by examining the climatological character of snowfall events in this region, and by examining and classifying the climatological occurrence of snowfall-producing flow regimes. A synoptic climatology of the snowfall-producing regimes for the lower Midwestern region of the country is unique to this study.

DATA AND METHODOLOGY

Data Sources

Snowfall data were taken from the Missouri Climatological Data (MCD), which are archived in periodical format at the Missouri Climate Center (MCC) on the University of Missouri–Columbia campus. These data can be made available through MCC. These archives include a variety of climatological parameters including temperature and precipitation records at weather observation stations throughout Missouri. The Hourly Precipitation Data (a companion publication with the MCD) at 17 cooperative observing stations, the daily 500 hPa, and surface weather maps archived in atlas format and on microfilm were also examined in order to verify whether multiple-day snowfalls were in fact single snowfall events. These maps were also used for determining the type of flow regime in which each event occurred, and for subjectively filtering out spurious reports. These data are also available through the MCC. The daily weather map series is a weekly publication available through the National Centers for Environmental Prediction (NCEP).

Definitions

A 50-yr. period was chosen for this study starting with the 1949–1950 snowfall season. This period was chosen because it was sufficiently long to describe significant interannual variability. A longer period was not chosen because the local snowfall records may be less reliable prior to the late 1940s, as there were far fewer cooperative observation sites that were operational and/or possessed a complete record available for use. A snowfall season is defined as starting on October 1 and ending with April 30. The annual snowfall season was then subdivided into calendar seasons, with fall, winter, and spring season snowfalls occurring within the months of October and November, December through February, and March and April, respectively. Snowfall events were categorized as moderate (3 to <6 in.; ~7.5 to <15 cm), heavy (6 to <10 in., ~15 to 25 cm) and extreme (10+ in., >25 cm). This categorization roughly corresponds to the description of snowfall events used by the Pleasant Hill National Weather Service Office when considering the total snowfall. This classification scheme does not correspond to text used in a forecast

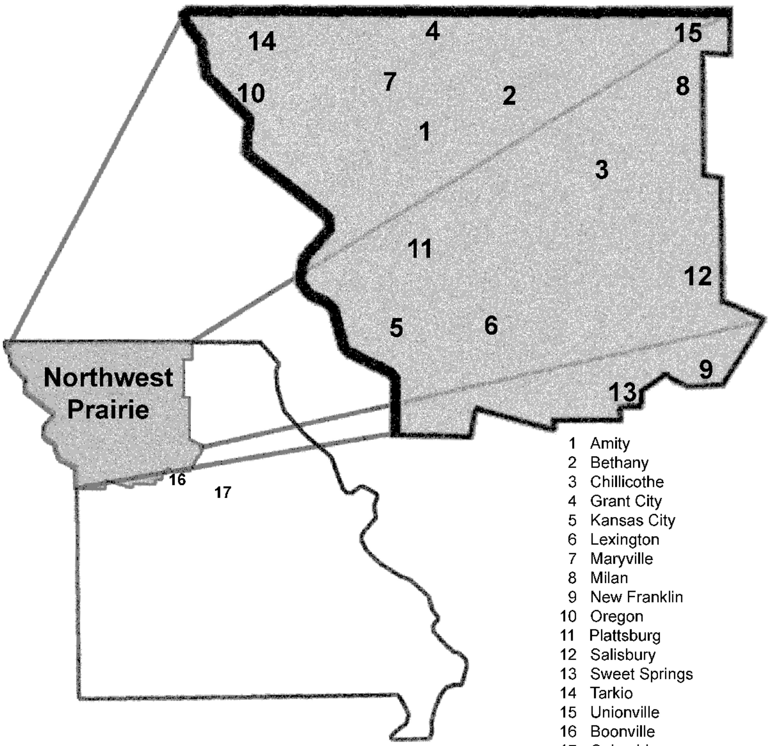

Fig. 1. Northwest Missouri showing the study region.

since in that context the words "heavy" or "moderate" refer to snowfall rates as well.

Snowfall events were not limited to, for example, a 24-hr. time period from 0000 GMT to 0000 GMT (e.g., Glass, 1998; Metze and Glass, 1998), but instead were classified as any continuous snowfall occurring in association with a larger-scale feature. For instance, a slow moving weather system could have produced snow in NWMO (see Fig. 1 for a map of the region) over a time period covering 2 to 3 calendar days. For the purpose of this study it was considered one event. In the summer, isolated rainfalls would need to be eliminated in a study such as this because of their nonorganized nature (e.g., Glass, 1998), however, winter storms in NWMO tended to occur over a more widespread area. In categorizing events, it was required that only one station in our region of study report a snowfall amount in a particular category, even if all others recorded less snow. Thus, if one station recorded 10.5 in. (26.67 cm) of snow over the course of one event while other stations recorded less than 10 in. (25.4 cm), the event was categorized as extreme because of the storm potential to produce extreme snowfall amounts and the limited spatial resolution of the network.

ENSO was defined in this study according to the Japan Meteorological Agency (JMA) ENSO Index. A complete description can be found on the Center for Ocean

Table 1. A List of Years Used in This Study Separated by ENSO Phase

La Niña (LN)	Neutral (NEU)	El Niño (EN)
1949	1950	1951
1954	1952	1957
1955	1953	1963
1956	1958–1962	1965
1964	1966	1969
1967	1968	1972
1970	1974	1976
1971	1977–1981	1982
1973	1983	1986
1975	1984	1987
1988	1985	1991
1998	1989	1997
	1990	
	1992–1996	

and Atmospheric Prediction Studies (COAPS) website (http://www.coaps.fsu.edu), and only a brief outline of this definition is provided here. The index classifies years according to sea surface temperature (SST) anomaly thresholds. The SST anomalies derived from 5 month running means are used within the area covering the tropical Pacific from 4°S–4°N, 150°W–90°W. A year is classified as El Niño (EN; La Niña, LN) if the index values are 0.5°C (-0.5°C) or higher (lower) for 6 consecutive months, of which the six months must begin before October of the previous year and continue through December. Values between -0.5°C and 0.5°C (but not inclusive) would be considered neutral (NEU). The "El Niño" year is defined as starting in October of the previous year and continuing through the following September. A list of these years as separated by ENSO phase is found in Table 1, which is also borrowed from COAPS. This ENSO definition has been used in many published studies (e.g., Bove et al., 1998; Lupo and Johnston, 2000; Smith and O'Brien, 2001; Weidenmann et al., 2002), and is similar to other definitions used by other investigators (e.g., Pielke and Landsea, 1999).

The North Pacific Oscillation, or NPO, is a long-term SST oscillation occurring over a 50- to 70-yr. time period (e.g., Minobe, 1997) within the eastern Pacific Ocean basin. This oscillation is also called the Pacific Decadal Oscillation (PDO). As defined by Gershunov and Barnett (1998), the high (positive) phase of NPO is characterized by an anomalously deep Aleutian low. Cold western and central north Pacific waters and warm eastern Pacific Ocean coastal waters and tropical Pacific waters also characterize this phase of the NPO. We referred to this phase as NPO1. The reverse conditions characterize the low (negative) phase of NPO and we referred to these conditions as NPO2. Table 2 defines the period of record for each phase of the NPO since period 1933. These are based on the findings of

Table 2. Phases of the North Pacific Oscillation (NPO)

NPO PHASE	PERIOD OF RECORD
Phase 1	1933–1946
Phase 2	1947–1976
Phase 1	1977–1998
Phase 2	1999–

Gershanov and Barnett (1998) and described by Kerr (1999) and Weitlich et al. (2003).

Statistical Testing

After classifying years as El Niño, La Niña, and neutral, simple means were calculated to examine and compare decadal, ENSO, and NPO related variability. Comparisons of means were examined using a two-sided "simple standardized test statistic" (z*; Neter et al., 1988, pp. 310–366). Means for the entire 50-yr. period sample served as the "expected" frequency of occurrence. Since the distributions were not known beforehand, a two-tailed test was used, which resulted in a more stringent criterion for significance. In order to find long-term trends over the length of the data set, simple regression lines were constructed. The significance of trends was examined using an analysis of variance approach (ANOVA; *F* test, see Neter et al., 1988). All statistical tests assumed the null hypothesis, or that there was no a priori relationship between the two variables being tested. Histograms for subsets of snowfall frequency plotted versus category (discrete distributions) were tested using the chi-square goodness of fit test. For this test, total observed (unapproximated) sample distributions served as the "standard" or "expected" frequency (Lupo et al., 1997). This is preferable to using an approximated distribution since these may not represent observed distributions reasonably well. It should be cautioned that this test was carried out using the minimal number of categorizations (three or four) permitted for this test since the synoptic categorization for each snowfall event precluded a finer-scale breakdown of the snowfall frequencies.

Snow Producing Synoptic Flow Regimes for NWMO

Four large-scale flow regimes were identified as being responsible for snowfalls in the western Missouri region (Berger et al., 1999; Lupo et al., 2002). All snow events that impacted NWMO were classified as shown in Table 3. Each synoptic category will be described briefly below (see also Lupo et al., 2002).

Southwest low snowfall events typically evolved out of a deep 500hPa trough originally located over the southwest United States. The 500-hPa low center gradually tracks from New Mexico and moves northeastward into Missouri (Fig. 2A). Strong ridging over the Ohio Valley is associated with an arctic high pressure system at the surface, centered over the Northern Plains (not shown). As the 500 hPa low

Table 3. The Total Number of Snowfall Events Occurring in Each Synoptic Classification for Events Impacting NWMO

Synoptic classification of snow event	Percent of total number of events
Progressive trough	47.7
Southwest low	26.9
Northwest low	16.9
Deepening low	8.5

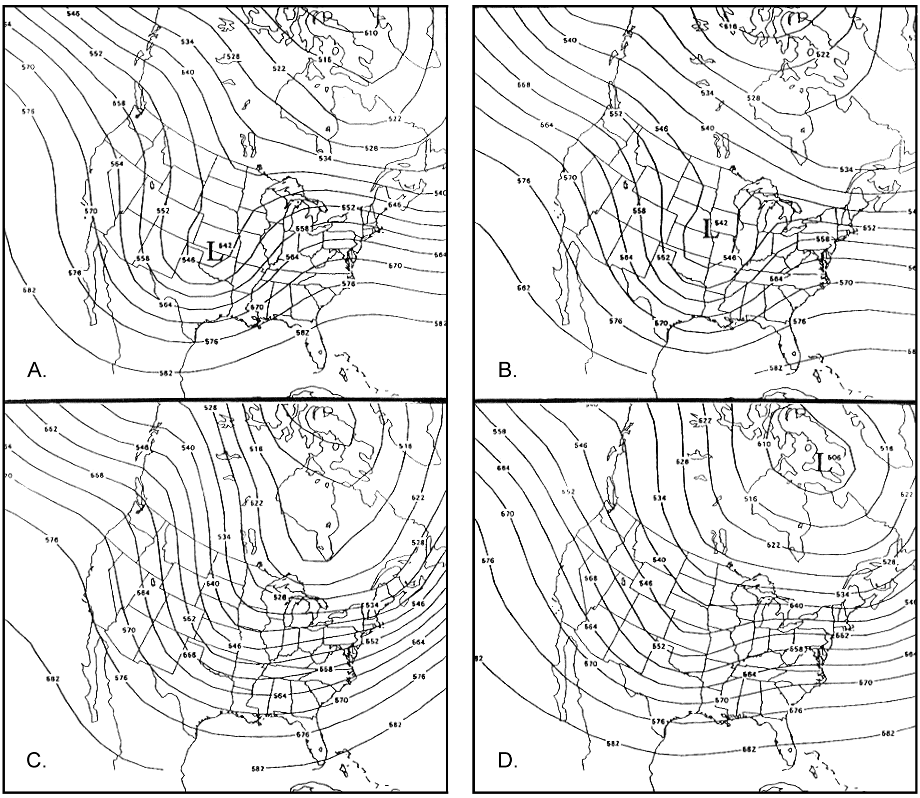

Fig. 2. The composite 500-hPa geopotential height maps for the (A) southwest low, (B) deepening low, (C) northwest low, and (D) progressive trough categories. Each composite represents the synoptic time closest to maximum snowfall rate as determined subjectively from archived hourlies.

lifts northeast, a well-developed surface extratropical cyclone also tracks towards the northeast, but propagates southeast of NWMO. The cyclone may already be occluded and a TROWAL (TROugh of Warm air Aloft) feature (e.g., Martin, 1998) may extend over the region. This places NWMO on the northwest and west side of the low as it passes, which is a typical synoptic scenario for receiving large amounts of snowfall and the case study of Market and Cissell (2002) was classified as this type of storm. Snowfall occurring in the northwest quadrant of the cyclone typically

Table 4. The Total Number of Seasonal and Overall Snowfall Events over Northwest Missouri

	Fall	Winter	Spring	All
Moderate	22	173	47	242
Heavy	10	86	30	126
Extreme	1	23	6	30
Total	33	282	83	398

produces bands of heavy snowfall accounting for much of the total accumulation; however, light snowfall can precede this type of cyclone as well.

The deepening low typically evolves within a 500-hPa split-flow regime as a strong short wave (not shown) in the northern branch phases with the large-scale trough over the plains region (Fig. 2B). This phasing occurs before the time shown in Figure 2B. The rapid and synergistic deepening of the midtropospheric low and the surface feature is often a result of the phasing, and these events produce significant snowfalls for NWMO. This type of system does not require cold air to be in place for snow development to occur, as is the case for the other three flow regimes. Often, and especially with spring season cases, the cooling can result from strong lifting and rapidly decreasing 1000–500 hPa thicknesses as the cyclone intensifies. Midwestern "bombs" are of this type, especially those occurring in the spring and fall seasons.

The 500 hPa flow regime for the northwest low snowfall event is characterized by an amplified long wave trough over the eastern United States and an amplified ridge over the western United States extending into the eastern Pacific Ocean region (Fig. 2C). The result of this pattern is highly meridional flow over the midcontinent, and arctic air moving south or southeastward into the mid–Mississippi Valley. Fast moving shortwave troughs embedded in this flow regime result in "clipper type" storms, which produce light to moderate snows in the NWMO region.

The progressive trough pattern is characterized by zonal flow in the 500-hPa flow (Fig. 2D). A short wave trough moves from west to east across NWMO without much change in intensity. At the surface, cold air will already be in place and the surface cyclones may be well to the south along a surface front located across or over the Gulf Coast region. The progressive trough snowfall events were the most frequent visitors to the NWMO region, followed by southwest lows, northwest lows, and deepening cyclones (Table 3).

CLIMATOLOGICAL ANALYSIS

Seasonal Variations and Decadal Trends

The results demonstrated that snowfall events occurred between the months of October and April and totaled 398 for the 50-yr. period (Table 4), which represented an average of 8 events per year over the region of study. As expected, most of the events were categorized as moderate (242 events or 61%), and there were few extreme events (30 or 7%). While the majority of these events occurred in the

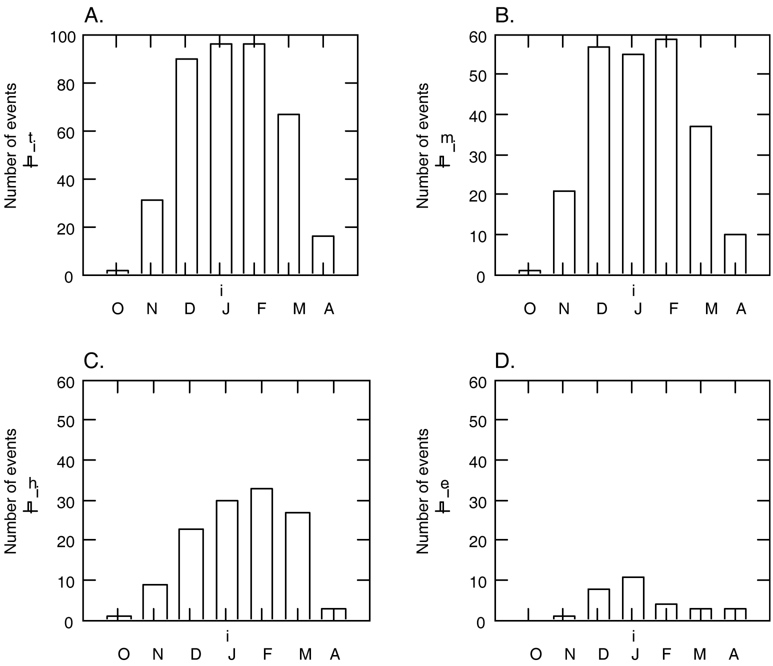

Fig. 3. The monthly distribution of snowfall events versus snowfall season month for the (A) 50-yr. sample, (B) moderate, (C) heavy, and (D) extreme events.

winter season (December–February: 282 events), there were more events that occurred in the spring months (83 events or 21%) rather than in the fall (33 events or 8%; Table 4). A monthly distribution (Fig. 3A) shows that the distribution was nearly normal with a peak occurrence of 2 events per year for both January and February. Figures 3B, 3C, and 3D break down the monthly distribution into snowfall categories. Moderate snowfall events have a distinct peak in occurrence from December to February. Heavy snowfalls were skewed slightly toward a peak in February, while the peak occurrence for extreme snowfalls was during January.

Long-Term Trends

The interdecadal variability of snowfall occurrence was also examined season-by-season (Table 5). A slight upward trend was found in the total number of fall events, with a higher frequency of these snowfalls in the last 3 decades, especially when comparing the moderate events alone (Table 5). The winter season snowfalls showed a slight downward trend in the total occurrence of events (Table 5), though the trend was strongest over the late 1980s and 1990s. This trend was most evident in the extreme category. Heavy (moderate) snowfalls showed a peak occurrence in the 1970s (1950s). The examination of heavy plus extreme winter events revealed that the majority of events were found in the 1960s and 1970s, with a downward trend occurring thereafter. A downward trend was found in total spring snowfalls,

Table 5. Snowfalls Separated by Calendar Decade and Season[a]

Category	1950s	1960s	1970s	1980s	1990s
Moderate					
Fall	5/(0.5)	1/(0.1)	4/(0.4)	7/(0.7)	5/(0.5)
Winter	43/(4.3)	28/(2.8)	31/(3.1)	37/(3.7)	33/(3.3)
Spring	10/(1.0)	13/(1.3)	11/(1.1)	7/(0.7)	6/(0.6)
Heavy					
Fall	0	2/(0.2)	5/(0.5)	0	3/(0.3)
Winter	12/(1.2)	20/(2.0)	22/(2.2)	17/(1.7)	15/(1.5)
Spring	11/(1.1)	6/(0.6)	5/(0.5)	5/(0.5)	3/(0.3)
Extreme					
Fall	1/(0.1)	0	0	0	0
Winter	6/(0.6)	4/(0.4)	6/(0.6)	2/(0.2)	3/(0.3)
Spring	0	1/(0.1)	3/(0.3)	0	3/(0.3)
Total					
Fall	6/(0.6)	3/(0.3)	9/(0.9)	7/(0.7)	8/(0.8)
Winter	61/(6.1)	52/(5.2)	59/(5.9)	56/(5.6)	51/(5.1)
Spring	21/(2.1)	20/(2.0)	19/(1.9)	12/(1.2)	12/(1.2)

[a] The numbers represent total number of snowfalls (left) and the average snowfalls per year (right).

Table 6. Snowfalls for the Total 50-Year Sample Separated by Calendar Decade[a]

Category	1950s	1960s	1970s	1980s	1990s
Moderate	58/(5.8)	42/(4.2)	46/(4.6)	51/(5.1)	43/(4.3)
Heavy	23/(2.3)	28/(2.8)	32/(3.2)	22/(2.2)	21/(2.1)
Extreme	7/(0.7)	5/(0.5)	9/(0.9)	2/(0.2)	7/(0.7)
Total	88/(8.8)	75/(7.5)	87/(8.7)	75/(7.5)	71/(7.1)

[a] The numbers represent total number of snowfalls (left) and the average snowfalls per year (right).

as well as within each category (Table 5). These trends were especially evident when comparing moderate-plus-heavy, and heavy-plus-extreme events. Only the downward trend in total and heavy spring snowfall events proved to be significant at the 95% level when using the *F* test.

Examining the decadal variability within the entire 50-yr. period showed that the first three decades (1950s, 1960s, and 1970s) averaged 8.3 snowfall events per year, while the last two decades (1980s and 1990s) have averaged 7.3 events per year (Table 6). The trend was most severe in the extreme snowfall category. The first three decades averaged 7 extreme snowfalls per decade, while for the past two decades the average has been 4 events per decade. There also was a downward trend in the

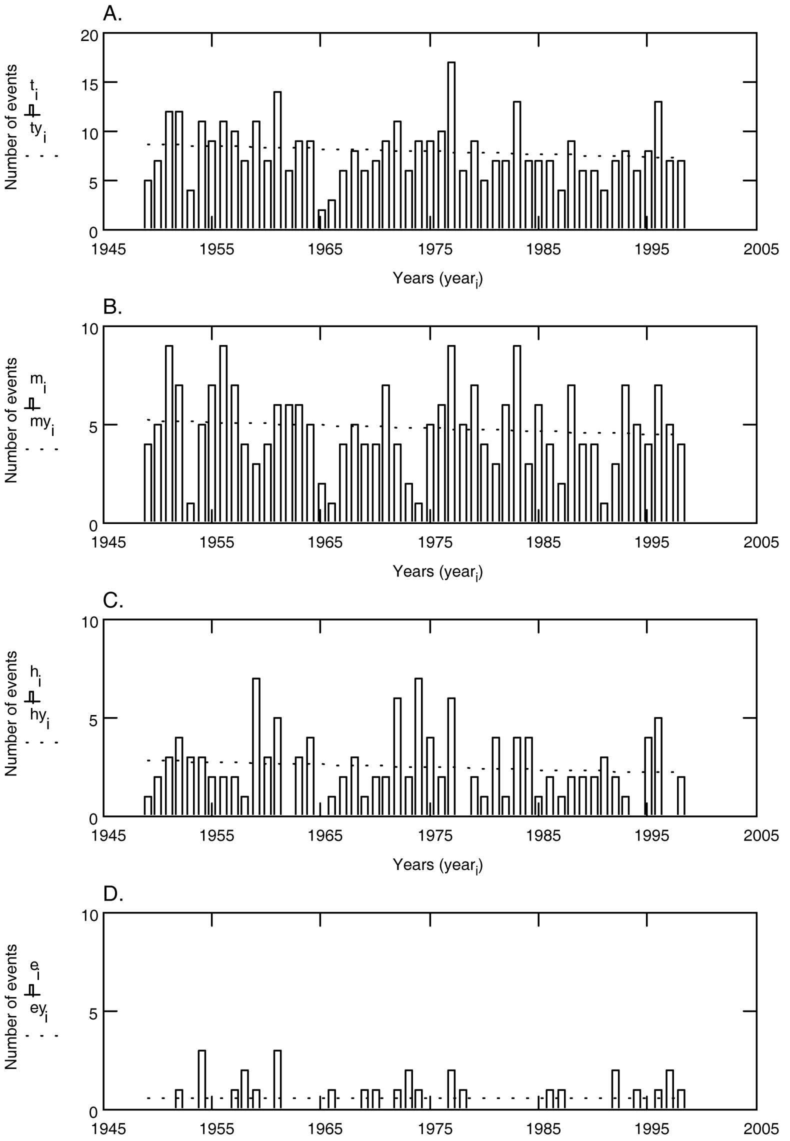

Fig. 4. The (A) total 50-yr. distribution of snowfalls per year (bars, number of events) and regression line (dashed). The distribution of (B) moderate, (C) heavy, and (D) extreme events are also shown.

number of heavy snowfall events (2.8 events per year in the first three decades vs. 2.1 events per year in the final two).

The total number of annual snowfall events were plotted with respect to time in Figure 4A, and the regression analysis shows that there was a slight downward trend in the total annual number of snowfall events. This trend did not prove to be

Table 7. The Total Number (Left) and Average Occurrence (Right) of Snowfalls Versus El Niño/La Niña Phase

	All	Moderate	Heavy	Extreme
Cold (LN)	98/8.3	63/5.3	28/2.3	7/0.6
Neutral (NEU)	213/8.2	123/4.7	74/2.8	16/0.6
Warm (EN)	87/7.3	56/4.7	24/2.2	7/0.6
Total	398/8.0	242/4.9	126/2.5	30/0.6

significant at the 95% level using the *F* test. Figures 4B, 4C, and 4D show the distribution of snowfalls divided into the three subcategories defined in section 2. The trend was also downward, but to varying degrees in each separate category, though none of these trends proved to be significant at the 95% level. There was little trend in the total number of snowfall events in spite of a general increase in precipitation (Hu et al., 1998; Karl and Knight, 1998) in the Midwestern United States over the last 30 yr. Some evidence supporting the decreasing snowfall trend may be provided by the study of Zishka and Smith (1980), which showed downward trends in the number of winter and summer season cyclones over the United States from the 1950s through the late 1970s. Also, Key and Chan (1999) found similar downward trends in the number Northern Hemisphere midlatitude cyclones through the late 1990s.

ENSO AND NPO-RELATED VARIABILITY

El Niño Versus La Niña Years

Table 7 displays the number of snowfall events stratified by El Niño/La Niña phase. A majority of snowfall events occurred during the NEU phase, as was expected. The total sample included 26 NEU, 11 LN, and 13 EN years. During EN years, 7.3 events occurred on average, and this compared to 8.3 events for LN and 8.2 for NEU years. While there was no difference in the mean number of extreme events per year for any category, there were more moderate events in LN years compared to NEU and EN years, and more moderate plus heavy events in LN and NEU years compared to EN years. Thus, the more frequent occurrence of El Niño events over the past two decades (Table 1, 1980s and 1990s) may partially explain the general decrease in overall snowfall events shown in section 3. The lower mean occurrence of snowfalls during El Niño years was not significant at standard levels of confidence (90% or greater). However, the distributions of snowfall events versus category were tested using the chi-square goodness-of-fit test. Only the distribution for El Niño year snowfalls was different from the total snowfall distribution as described above, a result significant at the 90% confidence level.

Also, slightly fewer EN season snowfall events correspond with the results of Kunkel and Angel (1999) and Smith and O'Brien (2001) who found that seasonal snowfall amounts were smaller during EN years, but in adjacent regions such as the upper Midwest and Ohio Valley regions. These results also concur with those of

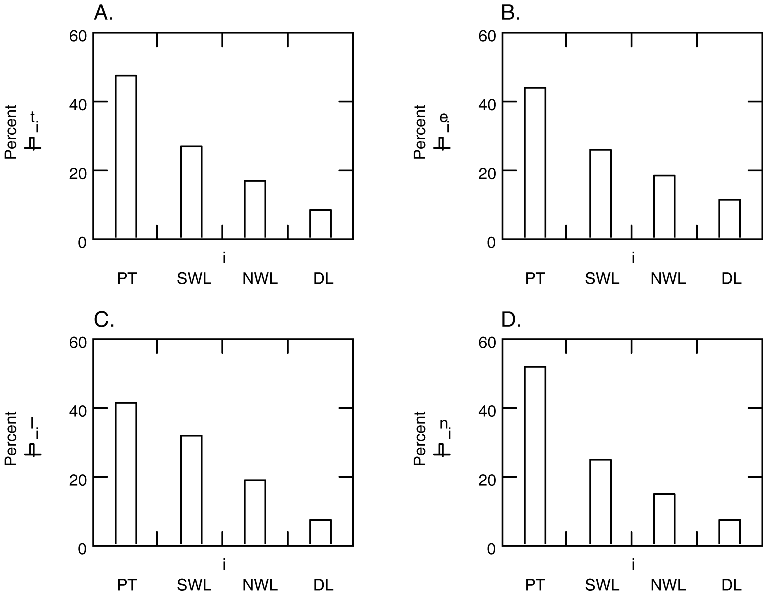

Fig. 5. The total number by percentage of progressive tough, southwest low, northwest low, and deepening low snow events for (A) the 50-yr. sample, (B) EN years, (C) LN years, and (D) NEU years.

Key and Chan (1999) and Martins and Smith (2003). Key and Chan (1999) found that there were fewer (more) cyclones in the Northern Hemisphere midlatitudes during EN (LN) years, and Martins and Smith (2003) found that there were fewer cyclones (but deeper) over the eastern two-third of the United States during EN years in the winter season. Martins and Smith found their result despite showing that the mean storm track for NEU and EN seasons were similarly positioned.

The Key and Chan (1999) results for LN years would also support the above results, but Smith and O'Brien (2001) find decreased snowfall amounts in LN years in the adjacent Midwest region. Kunkel and Angel (1999) found that strong LN years produced more snowfall over the mid-Missouri region. Thus, examining the type of snowfall events that occur in this region may bridge the gap between the results of this study and the published results described above. Figure 5A shows the number of snowfall events for each of the four flow regimes discussed in section 2 (by percentage) that occurred during the 50-yr. period, as well as for EN, LN, and NEU seasons (Figs. 5B to 5D, respectively). The distributions of EN, LN, and NEU snowfall-producing flow regimes do not depart significantly from the distribution of the total sample. However, the distributions of EN and LN snowfall-producing regimes were similar to each other, and different from that of the NEU snowfall seasons. This difference was significant at the 90% confidence interval.

During NEU years, there were more progressive troughs (52% NEU versus 44 and 42% for EN an LN years, respectively), and these events produced more heavy and extreme snowfall events over the NWMO region (not shown here). Thus, in LN years there may have been more snowfall events than in EN years and a similar

Table 8. Total (Left) and Average Occurrence (Right) of Snowfalls Versus ENSO Phase for Each Season

	All	Moderate	Heavy	Extreme
Cold (LN)				
Fall	6/0.5	4/0.3	2/0.2	0
Winter	73/6.1	47/3.9	19/1.6	7/0.6
Spring	19/1.7	12/1.1	7/0.6	0
Neutral (NEU)				
Fall	17/0.7	11/0.4	5/0.2	1/0.1
Winter	149/6.0	86/3.4	51/2.0	12/0.5
Spring	47/1.9	26/1.1	18/0.7	3/0.1
Warm (EN)				
Fall	10/0.8	7/0.6	3/0.2	0
Winter	53/4.1	35/2.7	16/1.2	2/0.2
Spring	17/1.3	9/0.7	5/0.4	3/0.2
Total				
Fall	33/0.7	22/0.5	10/0.2	1/0.0
Winter	282/5.5	173/3.3	86/1.7	23/0.4
Spring	83/1.7	47/1.0	30/0.6	6/0.1

number to NEU years, but more of LN season events were moderate snowfall producers (see also Table 7). Additionally, more northwest flow snow events, which produce more moderate snowfalls, occurring over the central United States in LN years (19% in LN years versus 15% in NEU years) would agree with an increase in east Pacific blocking during these winter seasons (Wiedenmann et al., 2002).

Snowfall occurrence results were then broken down by season. During the fall months (Table 8) it was found that more snows occurred overall during EN years. The spring results (Table 8) were similar to the overall results, showing fewer snowfalls in EN years compared to LN and NEU years with the exception of the extreme category. However, the spring and fall snowfall samples were smaller in size and, thus, no statistical tests were applied to these seasons. Fewer snowfall events were found in EN winter months (Table 8), which was evident across all snowfall categories. In the winter season analysis, the lower mean occurrence of EN winter snowfalls was not significant at the 90% level. However, testing their distributions demonstrated that the distribution of El Niño and La Niña season snowfalls were different from the total distribution and from each other at the 95% confidence interval.

Variability with Respect to the NPO

More attention has been focused lately on longer-term oceanic oscillations that impact on atmospheric circulations such as the North Atlantic Oscillation, and more recently the North Pacific Oscillation. Gershunov and Barnett (1998) found a correlation between NPO phase and the intensity of ENSO as it affects the

Table 9. Total Number (Left) and Average Occurrence (Right) of Snowfalls Stratified by ENSO Phase during the Negative NPO Phase (NPO2: 1949–1976, 1999–)

	All	Moderate	Heavy	Extreme
Cold (LN)	89/8.1	56/5.1	26/2.2	7/0.7
Neutral (NEU)	88/8.0	43/3.9	36/3.3	9/0.8
Warm (EN)	58/8.2	38/5.4	17/2.4	3/0.4
Total	235/8.1	137/4.7	79/2.7	19/0.65

atmospheric climatological flow regimes over the United States. They find that the NPO serves either to enhance or to weaken the ENSO phenomenon, and thus the influence of the ENSO phenomenon, depending on the NPO phase. During the high NPO phase (NPO1), the intensity of El Niño and its impacts on North American atmospheric flow regimes tends to be greater, with a less intense La Niña related impact. The opposite is true for the low NPO phase (NPO2), which is indicative of stronger La Niña and weaker El Niño events. Thus, during NPO2, the El Niño has less impact on typical North American circulation features.

Snowfall variability with respect to ENSO phase was examined in conjunction with the NPO. The negative phase (NPO2) showed little ENSO-related variability in the overall number of snowfall events when stratified by ENSO years (Table 9). Snowfall events occurring during neutral years were distributed more evenly across each category than during EN and LN years. During the NEU phase, fewer average occurrences were found in the moderate category, while a higher average occurrence was found within the heavy events. The distribution of NEU events was different from the total sample at the 99% confidence interval. The occurrence of extreme events was least in EN years, but this result was not significant.

An examination of the distribution of snowfall-producing flow regimes for NPO2 years (Fig. 6A) reveals that the distributions across each phase of ENSO were slightly different than the total distribution, but these differences did not rise to the level of statistical significance. The important difference was that there were more progressive trough events in NEU years (49%) than in EN (43%) and LN (41%) years (Figs. 6B to 6D), and this may partially account for the increased number of heavy snowfall events cited earlier. The dearth of progressive trough occurrences in EN and LN years is somewhat evenly spread across the other categories.

Key differences were found in the results when examining snowfall occurrences during NPO1 (Table 10). LN and NEU years experienced more snowfall events both overall and within the moderate and heavy categories. In NPO1, La Niña and neutral years together had a similar average occurrence of snowfalls per year (8.4) as was found for NPO2. However, fewer snowfall events were found to occur during El Niño years, with an average of only 5.8 snowfalls per year. This result is significant at the 80% confidence level (90% when considering total NPO1 as the base). Also, the distribution of snowfalls during El Niño years was different from that of the total sample (and when considering NPO1 as the base) at the 99% confidence

Table 10. Total Number (Left) and Average Occurrence (Right) of Snowfalls Stratified by ENSO Phase during the Positive NPO Phase (NPO1: 1977–1998)

	All	Moderate	Heavy	Extreme
Cold (LN)	9/9.0	7/7.0	2/2.0	0/0.0
Neutral (NEU)	125/8.3	80/5.3	38/2.5	57/0.46
Warm (EN)	29/5.8	18/3.6	7/1.4	4/0.8
Total	163/7.75	105/5.0	47/2.25	11/0.56

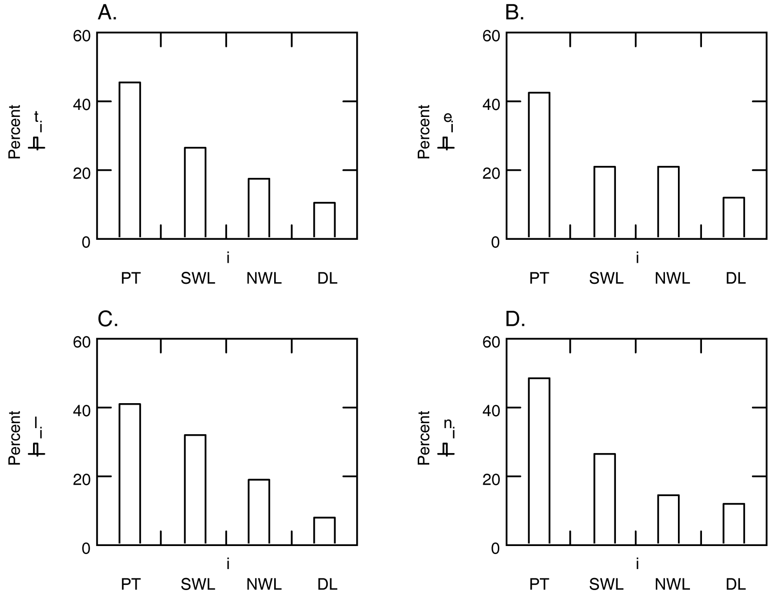

Fig. 6. Same as in Figure 5, except for NPO2 years (Table 2).

interval. Thus, the reduced number of snowfalls in the warm phase of ENSO may be related to the enhancement of El Niño-related variability over North America by the NPO1. Categorically, moderate events exhibited the largest decline from cold plus NEU to warm phase, and the decline in heavy events was more consistent with the decline in the total sample by percentage (significant at the 77% confidence level). The occurrence of extreme events was not consistent with the other categories, with more extreme events being found in EN years during the NPO1 phase. Thus, it appeared that ENSO-related variability in the 50-yr. sample was confined to, and reflects, ENSO related variability in NPO1. This is confirmed by the fact that there was little ENSO-related variability in NPO2 as compared to NPO1.

The distribution of snowfall-producing regimes during NPO1 years is shown in Figure 7. While the distribution of NPO1 snowfall-producing events was not significantly different from that of the 50-yr. sample (Fig. 7A), the distribution of

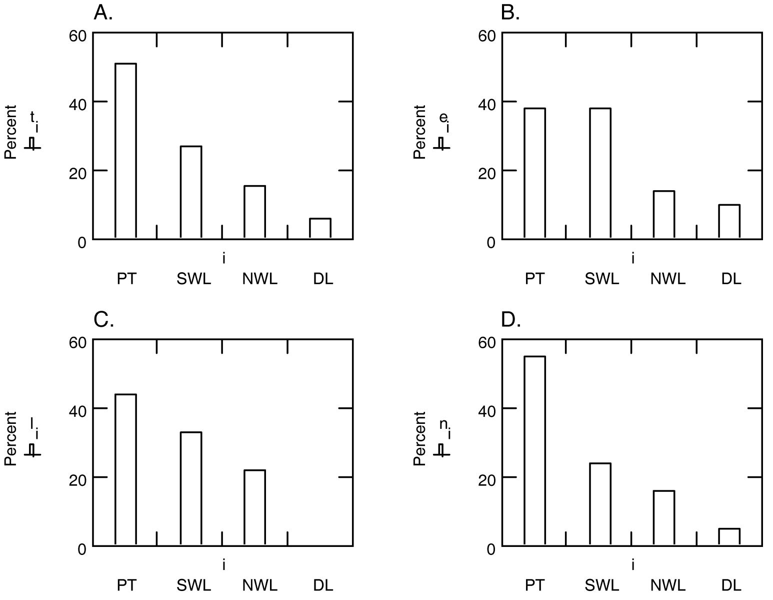

Fig. 7. Same as in Figure 5, except for NPO1 years (Table 2).

snowfall-producing events in EN years was significantly different from the total sample at the 99% confidence level (Fig. 7B). There were many fewer progressive trough events (38%) in these years compared to those of NEU years (55%; Fig. 7D). There were more southwesterly and deepening low events during EN years (38% and 10%, respectively) than in NEU years (24% and 5%, respectively), which would be consistent with the predominance of the negative PNA pattern over the United States during these years—troughing (ridging) over the western (eastern) United States (Keables et al., 1992; Kung and Chern, 1995). More NEU year events which produce heavier snow fall events during the NPO1 time period is also consistent with the results of Kunkel and Angel (1999). Also, fewer, but deeper, EN snowfall-producing events found here are consistent with those of Martins and Smith (2003), and the time period they study mostly contains the NPO1 period.

SUMMARY AND CONCLUSIONS

Heavy snowfalls are a phenomenon that can greatly affect communities where they commonly occur. Understanding the long-term climatological characteristics of heavy snowfalls in northwest Missouri, including the climatological occurrence of various snowfall-producing flow regimes, can aid in the forecasting process, which in turn may provide more accurate weather forecasts to the general public. In this study, several climatological trends and some important characteristics of long and short-term interannual variability for snowfall occurrence in northwestern Missouri have been identified using simple methodologies and data provided by the Missouri Climate Center.

When examining seasonal variations, it was shown that the majority of snowfall events occurred in the winter months of December, January and February. More events were found to occur in the spring months than during the fall months. There was also a long-term trend favoring the occurrence of more fall and fewer spring snowfall events. Only trends in total and heavy spring snowfall events were found to be significant at the 95% level. Also, the overall occurrence of snowfalls in NWMO and by extension the region (e.g., Lupo et al., 2002) could be classified into four distinct types. Snowfall events classified as progressive troughs occurred most frequently, followed by southwest lows, northwest lows, and deepening lows.

Overall, there was a downward trend in snowfall events. Some studies have shown a decrease in the frequency of North American cyclones in the winter season, a result that is consistent with the weak trends in snowfall occurrence found here. Also, an examination of snowfall occurrence by decade revealed that more snowfall events occurred during the first three decades of this study, and that the number of events has decreased in the last two decades. This trend was most severe in the extreme category. None of these results were found to be significant at the 90% level.

Variability related to the El Niño and Southern Oscillation has been the topic of many studies in recent years. It was found that there were more snowfalls in LN and NEU years than during EN years, a result that is consistent with other studies of seasonal snowfall totals in the NWMO region and/or adjacent regions. This difference was noted primarily in the occurrence of the moderate and moderate-plus-heavy events. The distribution of snowfalls occurring in EN years was different from that of the total sample at the 90% confidence interval, confirming that there were fewer events in these years. It was also shown that the distribution of the occurrence of snowfall-producing regimes was similar in EN and LN years, but different from that of NEU years in that there were fewer progressive trough cases.

Seasonal ENSO-related variability was examined as well. Similar results to the 50-yr. period were shown for the winter season snowfall events, but were shown to be more pronounced (statistical significance was stronger). During El Niño years, more snowfall events were found to occur in fall months. Also, the weak decreasing trend found in overall snowfall events over the 50-yr. period may partially be explained by the more frequent occurrence of El Niño years during the past two decades.

Examining variability associated with another long-term oscillation, the North Pacific Oscillation, has been of more recent interest. Other studies have shown that the positive phase of NPO, or NPO1, tends to enhance the effects of El Niño events, and the negative phase, NPO2, tends to enhance La Niña events. In our study it was found that there was little variation in the total number of snowfall occurrences between NPO1 and NPO2. However, it was found that there was a significant difference between ENSO-related variability within each phase of the NPO. Thus, longer-term NPO-related variability was superimposed on shorter-term ENSO variability. More specifically, it was found there was little ENSO-related variability in the number of snowfalls and the occurrence of snowfall-producing flow regimes during NPO2. But during NPO1, there were significantly (at the 80% confidence level) fewer snowfall events during El Niño years. The distribution of EN year snowfall occurrences and the snowfall-producing regimes differed from the total sample and this result was significant at the 99% confidence level.

Thus, these results demonstrate that the tendency for more (less) snowfalls to occur during La Niña (El Niño) years may not apply to an entire data set of a certain climatological parameter, but may also depend on interaction with other longer-term oscillations (e.g., Gershunov and Barnett, 1998).

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