

# Interannual Variability of Snowfall Events of Southwest Missouri and Snowfall-to-Liquid Water Equivalents at the Springfield WFO

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## Abstract

*In order to address the difficult issue of forecasting snowfall amounts for the general public, forecasters must be intimately familiar with the climatological behavior of snowfall events and associated snowfall-to-liquid (SL) precipitation ratios that accompany events impacting the region. In Southwest Missouri, an average of 4 to 5 snowfall events of 3 inches or more occurred every year within the period of 1949 to 2002. These events were associated with an average SL ratio of about 12 inches of snow to one inch of rain (12:1).*

*Past studies have also demonstrated relationships between the synoptic environment and SL ratios for a particular locale. Indeed, while many atmospheric and environmental factors contribute to the observed SL ratios in a particular event, quite often recurring synoptic patterns are typically associated with similar SL ratios in Southwest Missouri. This study identified four synoptic patterns which bring heavy snowfalls to Southwest Missouri that are associated predominantly with certain SL ratios. In Southwest Missouri, synoptic disturbances classified as southwest lows or deepening lows processed large amounts of moisture and produced heavy snow. Sixty-seven percent of these events produced SL ratios of 12:1 or less and 90% produced SL ratios of 14:1 or less. Snowfall events (progressive troughs and northwest lows) which brought less snowfall were typically associated with higher SL ratios. There was no significant El Niño-Southern Oscillation (ENSO) related difference in the number of snowfalls per winter season. When the study period was stratified to include interdecadal variability, changes in ENSO-related variability did emerge. Additionally, the SL ratios were smaller during El Niño years and there has been no trend in this tendency.*

## 1. Introduction

A difficult forecasting challenge for Southwest Missouri (SWMO) is determining the arrival and amount of heavy snowfall. Heavy snowfalls occur frequently during the cold season and generally occur in association with synoptic scale cyclones. However, heavy snowfalls occur on time and space scales more consistent with mesoscale phenomena, and may be forced by processes on that scale (e.g., Hakim and Uccellini 1992). Recent studies have detailed the climatological aspects (e.g., Berger et al. 2002) and the dynamic aspects (e.g., Martin 1998; Market and Cissell 2002) of such events.

These snowfalls are a particular challenge for public and private meteorologists in SWMO. Forecasting snowfall amounts requires several considerations including: a) the need to forecast the amount of liquid precipitation [or a "quantitative precipitation forecast" (QPF)]; b) the expected precipitation type(s); c) the potential for snow accumulation (related to, e.g., near surface temperature and ground temperature); and d) the snowfall-to-liquid ratio (Junker 2000). It is proposed here that improvements in snowfall forecasts could be made by studying the association of snowfall-to-liquid ratios that occur with typical synoptic scale snowfall producing regimes.

While certain classes of SL ratios may be associated with particular synoptic scale environments, there are several other factors that govern SL ratio which may depend on where the snow is measured with regard to a cyclone or frontal boundary, or on microphysical considerations. For example, the SL ratio associated with a particular storm may vary widely throughout a storm, with areas near the rain/snow line receiving lower SL ratios, while areas deep into the cold air receive higher SL ratios. The implied dependence of SL ratio to temperature has been studied widely and includes studies by

Magono and Nakamura (1965), Fukuta and Takahashi (1999), and Roebber et al. (2003). For example, Roebber et al. illustrated that dendrites produce higher SL ratios and these form in environments of  $-10^{\circ}$  to  $-20^{\circ}$  C. Additionally, Roebber et al. indicated that for most forecasting applications, useful information can be extracted from the existing radiosonde observational network, in spite of the fact that this network is only capable of resolving features down to the synoptic or meso- $\alpha$  scales.

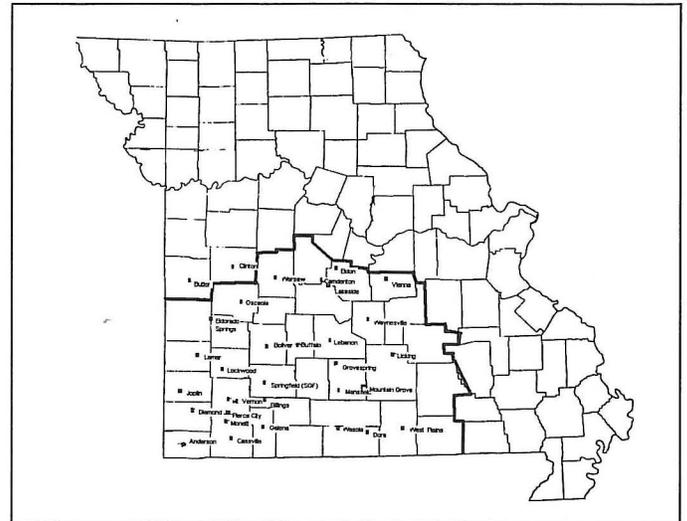
There have been several studies which discuss the relationship between SL ratio and the synoptic scale environment of the embedded storm. Harms (1970) demonstrated that three different storm tracks across the upper Midwest are each associated with a characteristic SL ratio (e.g., "Alberta clippers" are associated with a 20:1 SL ratio). Scofield and Spayd (1984) examined the relationship between the 1000-500 hPa thicknesses and SL ratio for eastern US sites, finding that in general, a higher SL ratio is associated with lower thicknesses. Mote (1991) demonstrated that smaller and larger snowfalls are associated with high and low SL ratios, respectively, in the upper Great Plains region. Several flow regime types are responsible for heavy snowfall across Northwest and Central Missouri (e.g., Berger et al. 1999, 2002), but each may produce different SL ratios, presumably due to different surface and atmospheric horizontal or vertical temperature distributions, as well as other factors that influence SL ratio (e.g., Roebber et al. 2003).

The goal of this study is to: 1) demonstrate that useful information can be extracted from local precipitation observations regarding the climatological character for SL ratios in the NOAA/National Weather Service, Springfield, Missouri (SGF) WFO county warning area; and 2) relate these to the synoptic scale environment. This type of approach to forecasting SL ratios represents the uppermost portion of the "forecast funnel" idea (Snellman 1991), and can be used by forecasters in conjunction with sounding information from SGF as guidance for snowfall forecasting. Information acquired by examining the radiosonde data from SGF and the implications of that data as discussed by Roebber et al. (2003) and others, would be further down in the funnel. In order to accomplish these goals, a snowfall and SL ratio climatology must be developed for SWMO. Next, the climatological representativeness of SGF WFO snowfall event observation data for the SWMO region will be demonstrated. A relationship between the SGF WFO SL ratio and the synoptic scale environments which impact SWMO will be examined (Sections 2, 3, and 4). Finally, the interannual variability of SL ratios at the SGF WFO will be examined (Section 5).

## 2. Data and Methodologies

### a. Data

The data used for this study were acquired from the Missouri Climate Center and the SGF WFO. Several sources were used including cooperative and first order observation station records (32 stations total) from SWMO (Fig. 1), the daily weather map series (published



**Fig. 1.** The Southwest Missouri (SWMO) region of study, which includes all Missouri counties in the Springfield, MO (SGF), WFO county warning area (heavy outline). Each location name is to the right of the marker.

by the National Center for Environmental Prediction [NCEP]), and hourly observations archived at the SGF WFO. A 54 year period was chosen for this study starting with the 1949-1950 snowfall season. This provided a long enough time series to address the issue of interannual variations. Additionally, there have been no substantive changes in the methodology used to measure snowfall or snow depth (using snowboards) and water equivalent (using a core sample) at the SGF WFO during this 54 year period. While the WFO itself moved from Springfield Regional Airport terminal to its present location just outside the airport in 1994, snowfall and snow depth have still been measured using the same areas on the airport grounds. After the implementation of the Automated Surface Observing System (ASOS) instrument, manually derived liquid equivalents have continued. This value has been reported if the ASOS instrument was inoperable or judged to be unrepresentative (subjectively) of the event by the WFO personnel on duty. The report was corrected using the manual reading.

The synoptic flow regime composites were constructed using the National Center for Environmental Prediction (NCEP) gridded analyses archived on CD-ROM (Mass et al. 1987). This data set contains gridded analyses of geopotential height, temperature, u and v wind components, relative humidity, vertical motion, and sea-level pressure stored in 47 x 51 point arrays on the NCEP octagonal grid, which is a polar stereographic grid with a resolution of 381 km at 60° N.

### b. Methodology

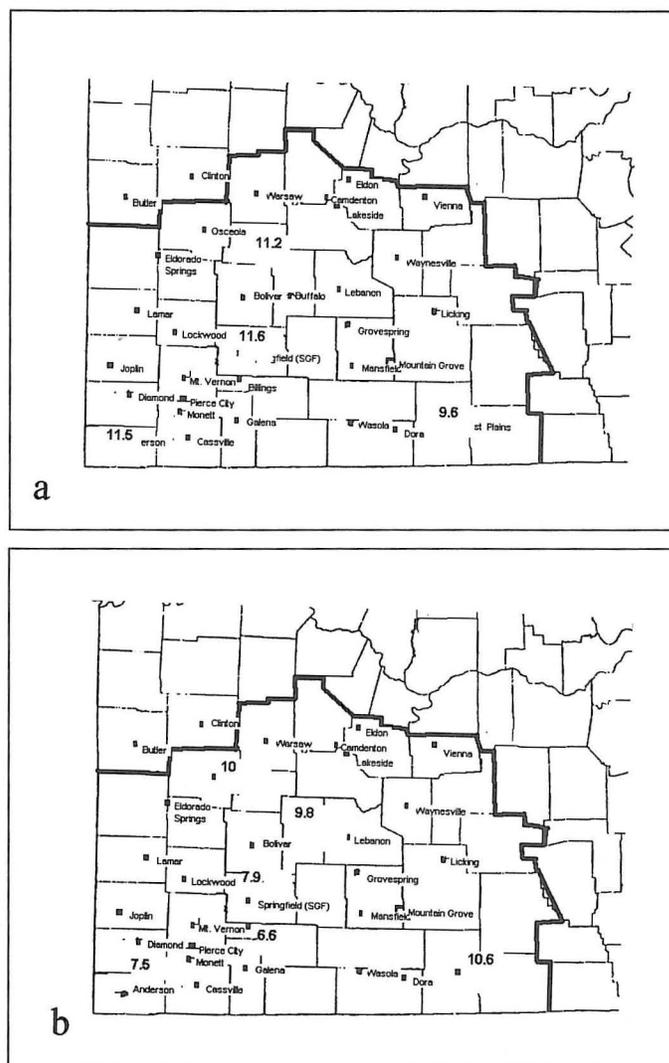
Snowfall events were categorized by intensity as moderate (3-5.9 inches), heavy (6-9.9 inches), and extreme (>10 inches). While most snowfall events in SWMO occurred over a 12 to 24 hour period, events were not limited to a 24 hour time period (e.g., 0000 UTC to 0000 UTC), but instead were classified as any continuous

snowfall occurring in conjunction with a synoptic scale feature. For instance, a slow moving weather system could produce snow in SWMO over a time period covering 2 to 3 calendar days. For the purposes of this study, continuous episodes of precipitation were considered as a single event, even if phase changes occurred. Events that were mostly rain were excluded. In categorizing each event, it was required that only one station in SWMO report a snowfall amount in a particular category, even if all others recorded less snowfall. Thus, if one station recorded 10.5 inches of snow over the course of one event while all others recorded less than 10 inches, the event was categorized as "extreme" because of the potential of the storm to produce these snowfall amounts. This work required that all snowfall reports from first order and cooperative reporting sites be examined. Thus, quality control procedures were applied via subjective map analysis in order to filter out spurious or incorrectly entered reports, or to take into consideration different reporting times that were used by some cooperative observation sites.

Since SGF provides the only reliable and continuous information from which SL ratios could be derived inside SWMO or all of the SGF WFO county warning area, the ability of the SGF snowfall event climatology to represent SWMO was tested by comparing the snowfall event distributions across each category as derived from the cooperative stations. Additionally, the SGF snowfalls could be stratified by SL ratio, with the SL ratio categorizations as follows: a) 10 inches of snow or solid precipitation to 1 inch of liquid precipitation or less (10:1 or less); b) 10:1 - 14:1; c) 14:1 - 18:1; and d) 18:1 or greater inches. This categorization was chosen in order that the mean (12:1) of the overall SL ratio data set reside within a category, a strategy similar to that of Roebber et al. (2003). Four categories were chosen over fewer categories in order to keep one class from becoming too large with respect to more dense or low SL ratio (< 10:1), less dense or high SL ratio (> 18:1) snow categories, and encompassing much of the total dataset. Our methodology could be applied in locales where there may be more high ratio snowfalls than were found here.

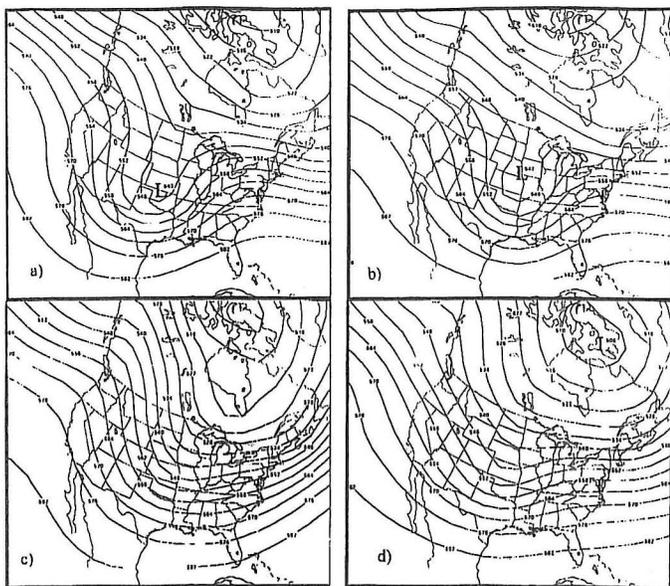
While the moisture (e.g., precipitable water) in a particular environment can be a critical factor in SL ratio (e.g., more moisture, smaller SL ratio), this is not true in every case. Thus the terms "wet" and "dry" are avoided when describing SL ratios. Since the relationship between SL ratio, temperature, and moisture may not be linear, it is possible at colder temperatures to form crystal types that are of greater density, and thus, lead to smaller SL ratios or greater snow densities (e.g., Pruppacher and Klett 1997; Roebber et al. 2003, and/or the references therein). Since these relationships are non-linear and the dataset used not appropriate to the task (17 of 32 stations only report daily information), a detailed discussion about the microphysical implications of these results will not go beyond generalities found in the references cited in this work.

It is conceded here that one SL ratio for the SGF WFO is likely not very representative of a single snowfall event over the entire SWMO since SL ratios can be

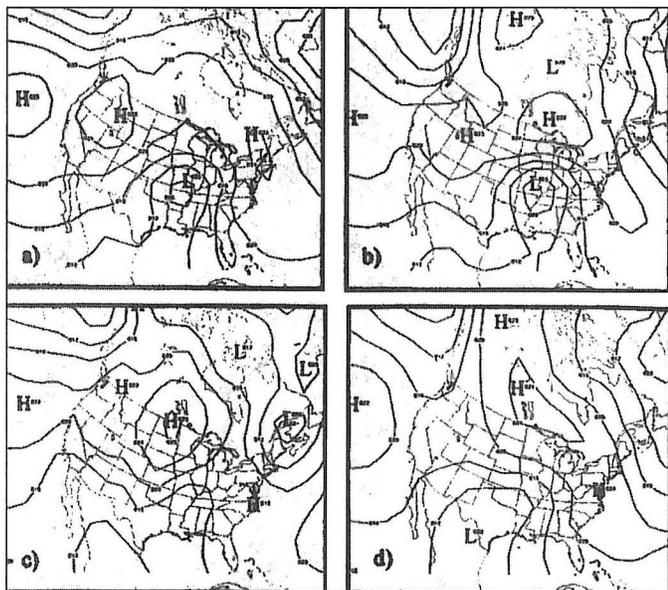


**Fig. 2.** The SWMO region with SL ratios plotted from the SGF WFO and cooperative stations that reported both snowfall amount and liquid precipitation amounts for a) mean values for 20 cases in which snow was reported simultaneously at SGF and three cooperative stations across the region, and b) for the event of 12-14 March 1999.

highly variable in a synoptic event with respect to time and space especially due to the microphysical considerations mentioned above. This may be true even though the long-term climatology for snowfall events themselves are similar for the SGF WFO and SMWO. Thus, the discussion of SL ratios in the following sections will apply to the SGF WFO only and not to SWMO as a whole. In order to support limiting the SL ratio discussion, an examination of 20 snowfall events reporting snow and liquid equivalent at SGF, and three cooperative stations spread across the CWA was examined. Figure 2a shows that the average SL ratios were over 11:1 across the western part of the SWMO region, but less than 10:1 over the eastern part of the region. The variance within individual events, however, could be substantially greater, about 60%, as seen during 12-14 March 1999 by Market and Cissell (2002), and even in events in which there was little or no mixed precipita-

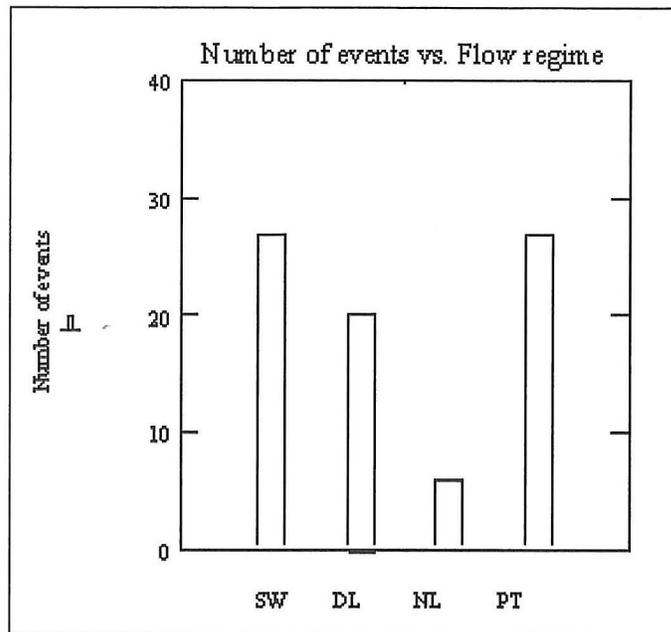


**Fig. 3.** The composite 500 hPa geopotential height maps for the a) southwest low, b) deepening low, c) northwest low, and d) progressive trough categories. Each composite represents the synoptic time closest to maximum snowfall rate as determined subjectively from archived hourly.



**Fig. 4.** As in Fig. 3, except for the surface sea-level pressure maps.

tion at SGF (Fig. 2b). The use of the SGF WFO hourly data enabled rain, and mixed precipitation involving rain, to be filtered out subjectively. This provided a better estimate of the SGF SL ratio. One factor that indicates SGF may be representative of all SWMO is that the elevation is about 387 m above sea level, which is approximately midway between the elevation of the highest and lowest cooperative station in the region. Further, SGF is located a little less than 100 km southwest of the middle of the county warning area in Missouri. However, due to the factors described earlier, the conclusions in this study regarding SL ratio will only apply to SGF, and not all of SWMO.



**Fig. 5.** The total number of snowfall events occurring in each synoptic classification for events impacting SGF, where SW, DL, NL, and PT are southwest lows, deepening lows, northwest lows, and progressive troughs, respectively.

### 3. Snow Producing Synoptic Flow Regimes in SWMO and SL Ratios

Berger et al. (1999, 2002) identified four flow regimes responsible for snowfall in Northwest Missouri (NWMO) (Fig. 3). It was found here that these describe SWMO snowfalls as well. The 500 hPa height composites shown in Fig. 3 were constructed using several randomly chosen, but subjectively appraised, representative events (22 Southwest Lows – Fig. 3a, 24 Deepening Lows – Fig. 3b, 11 Northwest Lows – Fig. 3c, and 29 Progressive Troughs – Fig. 3d) from the NWMO study of Berger et al. (1999). The composites represent the synoptic map time (1200 UTC or 0000 UTC) closest to the maximum snowfall rate as determined subjectively from archived hourly precipitation data. Composites of sea level pressure maps for each type of flow regime are shown in Fig. 4. All 80 snow events that impacted SWMO and the SGF WFO were classified as shown in Fig. 5. Most SGF snow events could be broadly classified into three of the four categories with each bin totaling 20 or more events. Only the “northwest low” category (commonly referred to as “Clipper Lows”) produced very few snow events in SWMO. Each synoptic category will be described briefly below.

Southwest low snowfall events typically evolved out of a deep 500 hPa trough originally located over the Southwest United States. The 500 hPa low center gradually tracks from New Mexico and moves northeastward into Missouri (Fig. 3a). Strong ridging over the Ohio Valley is associated with an arctic high pressure system at the surface centered over the Northeast (Fig. 4a). As the 500 hPa low moves northeast, a well-devel-

oped, extratropical surface cyclone also tracks towards the northeast, but travels south of, or across, SWMO. 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 SWMO on the northwest and west side of the low as it passes, which is a typical synoptic scenario for receiving large amounts of snowfall. 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 produces mesoscale bands of heavy snowfall accounting for much of the total accumulation (e.g., Martin 1998; Market and Cissell 2002). However, light snowfall can precede this type of cyclone as well. This mesoscale banding is marshaled generally by a synoptic scale process such as deformation (Market and Cissell 2002) in the presence of (weak) symmetric instability, or elevated instability (e.g., Schultz and Schumacher 1999).

The Deepening Low typically evolves from a 500 hPa split-flow regime as a strong short wave trough (not shown) in the northern branch phases with the large-scale trough over the Plains (Fig. 3b). The surface low generally moves from southwest to northeast over the southern part of region, or south of the region. The phasing occurs before the time shown in Figs. 3b and 4b. The rapid and synergistic deepening of the mid-tropospheric low and surface cyclogenesis is often a result of the phasing. These events produce significant snowfalls for SWMO (for an example see Lupo et al. 1992). The heaviest snow always fell after rapid deepening had begun. The exact timing of the heaviest snowfall varied from case-to-case, but generally occurred close to the end of the rapid deepening period. These types of systems do not require cold air to be already in place for snow development to occur as is the case for the other three regime categories. Often, and especially with spring season cases, the cooling can result from strong lifting which also may cause thicknesses to rapidly decrease as the cyclone intensifies. Midwestern "bombs" are of this type, especially in the spring and fall seasons (M. Bodner, personal communication, 2000).

The 500 hPa flow regime for the northwest type of snowfall event is characterized by an amplified long-wave trough over the eastern U.S. and an amplified ridge over the western U.S., extending into the eastern Pacific Ocean region (Fig. 3c). This results in meridional flow and arctic air, often originating near the Arctic Circle that moves south or southeastward into the mid-Mississippi Valley. Fast moving shortwave troughs embedded in this flow regime result in "clipper type" storms, producing light to moderate snows in the SWMO region. These events typically move from northwest to the southeast over the middle of the continent, and thus, are not able to ingest much Gulf moisture. The surface composite only shows an elongated trough over the region, possibly corresponding to a cold front (Fig. 4c).

The Progressive Trough pattern is characterized by zonal flow in the 500 hPa flow (Fig. 3d). A short wave trough moves from west to east across SWMO without much change in intensity. At the surface, cold air will

**Table 1.** The total number of snowfall events at SGF stratified by synoptic type for, a) various SL ratios, and b) total snowfall amount.

<b>Number of events for each type</b>					
a) SL Ratio	Southwest	Deepening	Northwest	Progressive	All
< 10:1	12	2	2	4	20
10:1 – 14:1	12	16	2	17	47
14:1 – 18:1	2	1	2	6	11
> 18:1	1	1	0	0	2
<b>Total</b>	<b>27</b>	<b>20</b>	<b>6</b>	<b>27</b>	<b>80</b>

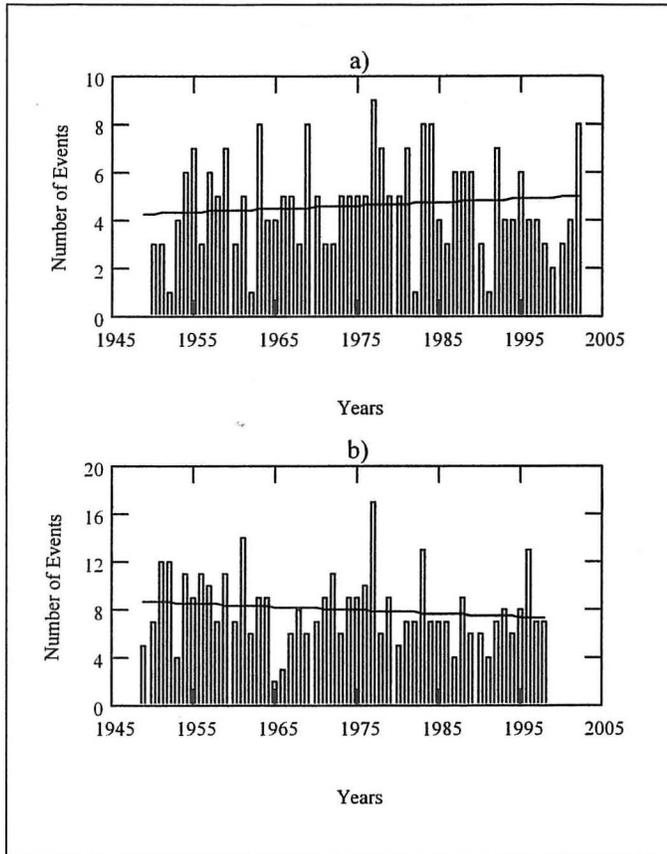
<b>Number of events for each type</b>					
b) snowfall Amount	Southwest	Deepening	Northwest	Progressive	All
Moderate	10	12	5	17	44
Heavy	11	7	1	6	25
Extreme	6	1	0	4	11
<b>Total</b>	<b>27</b>	<b>20</b>	<b>6</b>	<b>27</b>	<b>80</b>

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 (Fig. 4d).

When examining the relationship of snow producing synoptic regimes to SL ratios (Table 1), large majorities of both the southwest (89%) and deepening categories (90%) produce SL ratios of less than 14:1 (Table 1a). Additionally, two thirds of these events produced SL ratios less than the mean SL ratio of 12:1. These events are typically associated with some mixed precipitation, warmer surface temperatures, and warmer air aloft than the other two categories. As stated in the introduction, these environments can be associated with low SL ratios due to snow microphysics. However, southwest lows are also the most prolific snow producers for SWMO (Table 1b) as 63% of these snow producing events produce heavy or extreme snowfall amounts. The deepening lows also produce heavy or extreme snowfall amounts, but produce moderate amounts more often than the southwest lows. For many progressive trough and northwest low cases, cold air is already in place and the surface low may even be well to the south. If cold air is already in place, as discussed above, and the environment in which the snow forms is colder, then a higher SL ratio snowfall may be expected. These cases were associated with higher SL ratios as often as they were with lower SL ratios (Table 1a), and were generally not prolific snow producing events (Table 1b).

#### 4. Trends and Variations in SL Ratio

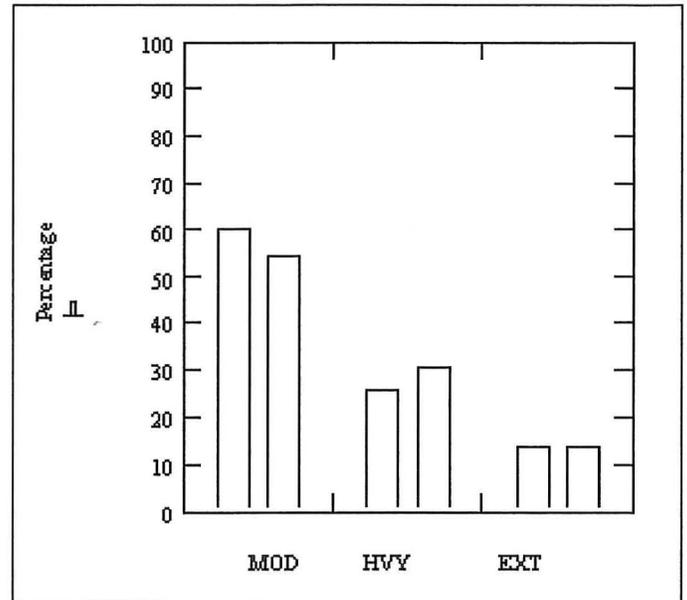
A total of 250 snowfall events which met the criteria in Section 2a occurred within the SWMO region over the 54 year period, which compares to 398 (in 51 years) for the NWMO region (Berger et al. 2002). This represents an average of 4.6 events per year. The finding of fewer events in the SMWO region is consistent with the climatological results of Kunkel and Angel (1999), whose



**Fig. 6.** The total annual number of snowfall events for a) SWMO and b) NWMO vs. year. Also the linear trend is represented by the solid black line.

study shows that the annual snowfall totals decrease rapidly toward the south across the mid-Mississippi Valley region. Most of these events were of moderate intensity (151 or 60% of all – compare with Table 2) and occurred in the winter (December – February) (186 or 74%). As in northwest Missouri (Berger et al. 2002), there were more spring (March and April) events (20% of all) than there were fall (October and November) events (6%) in SWMO. The interannual variation in the number of snowfall events, using one standard deviation as a measure of variability, was two events. Out of 51 snowfall seasons, 16 (32%) of these were associated with a number of events greater (9 seasons) or less (7 seasons) than one standard deviation from the mean. Thus, the sample is close to being normally distributed. There was a slight upward, long-term trend in SWMO snowfalls (Fig. 6a). However, this trend is not statistically significant at even the 90% confidence level and using the F-test (e.g., Neter et al. 1988). This compares to a slight downward trend for the annual number of northwest Missouri snowfalls (Fig. 6b). However, that trend was also not statistically significant at the 90% confidence level.

In order to determine whether or not the snowfall event climatology derived from the SGF WFO observations was representative of SWMO, case studies were examined as shown in Fig. 2 and discussed in Section 2.



**Fig. 7.** The total percentage of snowfall events in SWMO (left bar) and for SGF WFO (right bar) classified as moderate, heavy, or extreme.

A statistical approach, however, also shows that the distribution of the 80 snowfall events (Table 2a) that were recorded at the SGF WFO were very similar to that of all SWMO snowfalls (Table 2b) by percentage. Using the chi-square goodness-of-fit test for the total samples demonstrates that the distributions are similar at the 90% confidence level. The most substantial differences between the SGF sample and the SWMO climatology represent the seasons (fall and spring) in which snowfalls are comparatively rare. However, even if the SGF subset was distributed in a similar manner to SWMO snowfalls (Figs. 2 and 7), it cannot be assumed that the climatological dis-

**Table 2.** The a) total number of seasonal and overall snowfall events for the SGF WFO stratified by snowfall category, and the b) the ratio of the number of SGF events in each category, compared to the total number of events (in parenthesis), expressed as a percentage, and broken down by season for the SWMO region. The seasons are defined in a conventional sense (e.g., Fall – September, October, November).

a)	Fall	Winter	Spring	All
Moderate	4	35	5	44
Heavy	3	17	5	25
Extreme	0	7	4	11
Total	7	59	14	80
b)	Fall	Winter	Spring	All
Moderate	5% (2.5%)	44% (47%)	6% (11%)	55% (60%)
Heavy	4% (2.5%)	21% (18%)	6% (6%)	31% (26%)
Extreme	0% (1%)	9% (9%)	5% (3%)	14% (14%)
Total	9% (6%)	74% (74%)	17% (20%)	100%

**Table 3.** The number of snowfall events for the SGF WFO by season (columns 2-4) and total (column 5).

SL Ratio	Fall	Winter	Spring	All
< 10:1	1	15	4	20
10:1-14:1	4	34	9	47
14:1-18:1	1	9	1	11
> 18:1	1	1	0	2
Total	7	59	14	80

**Table 4.** The total number of snowfall events for each synoptic type with SL ratios larger than 12:1 and a surface temperature less than 28° F (first number / first row) and SL ratios larger than 14:1 (first number / second row). The second number in each cell is the total number of events for each type with an SL ratio larger than 12:1 (first row) and larger than 14:1 (second row).

a) SL Ratio	Southwest	Deepening	Northwest	Progressive	All
> 12:1	1 / 8	4 / 7	1 / 4	12 / 12	18 / 31
> 14:1	0 / 3	2 / 2	0 / 2	6 / 6	8 / 13

tribution of SGF SL ratios would adequately represent all of the SWMO region.

A majority (61%) of the snowfall events were associated with a SL ratio at SGF of 12 inches of snow or solid precipitation to 1 inch of liquid (12:1) or less (not shown), and 59% of the total number of storms produced SL ratios in the 10:1 - 14:1 category (Table 3). The median SL ratio was 11:1 for SGF. Winter snowfall events were more evenly distributed with respect to the mean of 12:1 than other seasons as 57% of events had SL ratios less than this value. Spring and fall events were skewed more heavily toward smaller SL ratios, with 70% of these snow events producing SL ratios 12:1 inches of snow or less. An examination of the total sample by decade (not shown) reveals there was no statistically significant trend toward low or high SL ratio events.

In Table 4, surface temperature was related to SL ratio and synoptic type. In this analysis, all storms with an SL ratio larger than 12:1 and 14:1 were examined in order to determine if colder surface temperatures could be associated with SL ratio and synoptic type. The surface temperatures were examined during the storm, and if the mean temperature was less than 28° F during the time that a majority of the storm total was accumulated, it was counted (first number in the table). A majority of the high SL ratio storms are associated with surface temperatures at SGF of less than 28° F, including all progressive trough events. Again, Figs. 3 and 4 showed that in the case of progressive troughs, there tended to be cold air in place to the north and east of SWMO, and the surface low tends to pass well to the south and east of SWMO.

Further, if the 500-1000 hPa and 850-1000 hPa mean thicknesses are examined, as these represent a surrogate for the atmospheric temperature profile, the 18 snowfall events in which the SL ratio was larger than 12:1 and

surface temperatures were less than 28° F were associated with the lowest values. Recall that using the hypsometric equation, one can calculate that a 10 m difference in thickness for two comparable 500-1000 hPa (850-1000 hPa) columns represents an average temperature difference between the columns of approximately 0.5°C (2.0°C). The average values for the 18 events were 5401 m and 1286 m for the 500-1000 hPa and 850-1000 hPa thicknesses, respectively. These thicknesses were averaged over the entire time each synoptic event tracked through the SGF WFO. For the 13 events in which the SL ratio was larger than 12:1 and the surface temperature greater than 28° F, the comparative thickness values averaged 5425 m and 1304 m, respectively. For all 31 events in the higher SL ratio category, the overall mean thicknesses were 5411 m and 1294 m, respectively. Examining the 49 snowfall events in which the SL ratio was smaller than 12:1, the corresponding thickness values were 5432 m and 1304 m, respectively. These 49 events were stratified by surface temperature as well, and for the 24 colder surface temperature events thicknesses were 5423 m and 1299 m, respectively. Meanwhile, the warmer surface temperature events were associated with thicknesses of 5440 m and 1309 m, respectively. Thus, as expected, smaller SL ratios were associated with a warmer atmosphere. Additionally, the correlation between thickness and SL ratio was -0.19, which given the sample size, is significant at the 90% confidence level. These results were similar across each synoptic category of snowfall events. Finally, given the testing methods here, it is difficult to determine whether the surface temperature had an impact on the SL ratio.

### 5. Interannual Variability of SL Ratios

#### a. Definitions used

Berger et al. (2002) found that certain snowfall producing synoptic types were favored in NWMO depending on the El Niño-Southern Oscillation (ENSO) phase. Thus, SWMO snowfall events can also be stratified by ENSO phase to determine if there are any statistical or causal relationships between synoptic type or SGF SL ratio and ENSO phase. Snowfall data were stratified into El Niño, ENSO-neutral, and La Niña phases of the ENSO in order to determine whether large-scale flow regime variations associated with sea surface temperature (SST) variations in the Pacific Ocean basin are reflected in the SWMO snowfall climatology. The data were also stratified by phase of the Pacific Decadal Oscillation (PDO). The definitions of ENSO and PDO, and the methodologies for performing the analysis are outlined in Berger et al. (2002) and will be described briefly below.

For labeling a winter season with respect to ENSO, the Japan Meteorological Agency (JMA) ENSO Index was used in this study (see COAPS Web site: [www.coaps.fsu.edu/products/jma\\_index.php](http://www.coaps.fsu.edu/products/jma_index.php)). 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

**Table 5.** A list of years examined in this study separated by ENSO phase.

La Niña (LN)	Neutral (NEU)	El Niño (EN)
1949	1950	1951
1954-1956	1952-1953	1957
1964	1958-1962	1963
1967	1966	1965
1970-1971	1968	1969
1973-1975	1977-1981	1972
1988	1983-1985	1976
1998-1999	1989-1990	1982
	1992-1996	1986-1987
	2000-2001	1991
		1997
		2002

**Table 6.** The phase of the Pacific Decadal Oscillation (PDO).

PDO PHASE	PERIOD OF RECORD
Phase 1	1933 - 1946
Phase 2	1947 - 1976
Phase 1	1977 - 1998
Phase 2	1999 -

and Landsea 1999). A list of El Niño (EN), La Niña (LN), and ENSO-neutral (NEU) years is included in Table 5. In summary, the index classifies years as EN, LN, and NEU based on 5 month running mean Pacific Ocean basin sea surface temperature (SST) anomaly thresholds bounded by the region 4° N, 4° S, 150° W, and 90° W, encompassing both the Niño 3 and 3.4 regions (see NOAA/CPC Web site: [www.cpc.ncep.noaa.gov/products/analysis\\_monitoring/en\\_sostuff/nino\\_regions.shtml](http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/en_sostuff/nino_regions.shtml).) in the central and eastern tropical Pacific. The SST anomaly thresholds used to define EN years are those greater than +0.5° C, less than -0.5° C for LN years, and NEU for anomalies between +0.5° and -0.5° C. For classification as an EN or LN year, these values must persist for 6 consecutive months including October, November, and December. The JMA ENSO criterion defined an El Niño year as beginning on 1 October of the previous year. Thus, the year "1970", which in Table 5 is labeled a La Niña year, begins in October of 1970 and ends in September 1971.

The PDO is a longer term SST oscillation occurring over a 50 to 70 year time period (Minobe 1997) within the eastern Pacific Ocean basin. As defined by Gershonov and Barnett (1998), the positive phase of the PDO is characterized by a deeper Aleutian Low. Cold western and central north Pacific waters, warm eastern Pacific coastal waters, and warm tropical Pacific waters also characterize this phase of the PDO which we refer to as PDO1. The reverse conditions characterize the negative phase of PDO which we refer to as PDO2. The period for each phase of the PDO is shown in Table 6. Gershonov and Barnett found a correlation between PDO phase and the intensity of ENSO as they both affect the atmospheric climatological flow regimes over the United States simultaneously. In particular, they found that the PDO serves to

**Table 7.** The total number (first number) and average number per year (second number) of snowfalls versus El Niño / La Niña phase for the SWMO sample, PDO2 (1949-1976, 1999-), and PDO1 (1977 - 1998) period.

	All	Moderate	Heavy	Extreme
<b>(La Niña)</b>				
Total	59 / 4.2	32 / 2.3	16 / 1.1	11 / 0.8
PD02	53 / 4.1	30 / 2.3	13 / 1.0	10 / 0.8
PD01	6 / 6	2 / 2	3 / 3	1 / 1
<b>(Neutral)</b>				
Total	131 / 4.9	84 / 3.1	34 / 1.3	13 / 0.5
PD02	44 / 3.7	28 / 2.4	12 / 1.0	4 / 0.3
PD01	87 / 5.4	56 / 3.5	22 / 1.4	9 / 0.6
<b>(El Niño)</b>				
Total	60 / 4.6	35 / 2.7	16 / 1.2	9 / 0.7
PD02	37 / 5.3	19 / 2.7	12 / 1.7	6 / 0.9
PD01	23 / 3.3	16 / 2.3	4 / 0.6	3 / 0.4
<b>All</b>				
Total	250 / 4.6	151 / 2.8	66 / 1.2	33 / 0.6
PD02	134 / 4.2	77 / 2.4	37 / 1.2	20 / 0.6
PD01	116 / 4.8	74 / 3.1	29 / 1.2	13 / 0.5

either enhance or weaken the ENSO phenomenon, and thus, the strength of the influence of the ENSO phenomenon (depending on the PDO phase). During PDO1 (PDO2), the intensity of El Niño and its impacts on North American atmospheric climatological flow regimes and circulation features tends to be greater (weaker), with a less (more) intense La Niña impact. Additionally, many others have found that the intensity of the ENSO phenomena varies on the interdecadal timescale in both observational (Gu and Philander 1995) and theoretical studies.

#### *b. Interannual variations in SWMO snowfalls and SL ratios*

Examining Table 7 reveals that there is little interannual variability associated with ENSO in SWMO snowfalls. None of these variations were statistically significant at the 90% confidence level or higher. Note that the whole SWMO data set is used in this section in order to allow for statistical testing using larger samples. In SWMO there were 14% (6%) fewer events during La Niña (El Niño) years than there were during neutral years (almost all accounted for in the moderate snowfall category). As was shown for NWMO snowfalls (Berger et al. 2002), however, examining only ENSO variability over an entire 50 year period may not be adequate since the frequency and intensity of ENSO events may change on longer time scales (e.g., Mokhov et al. 1998, 2000; Fedorov and Philander 2000). We postulate that the frequency and amplitude of the ENSO phases may be impacted by the PDO phase, and that the PDO and ENSO phases may modulate the frequency of snowfall events in SWMO. Statistical analysis performed on this data

**Table 8.** The number of snowfall events for each SL ratio category separated by El Niño / La Niña phase for the SGF WFO.

	< 10:1	10:1-14:1	14:1-18:1	> 18:1	All
La Niña	4	13	1	1	19
Neutral	7	24	9	1	41
El Niño	9	10	1	0	20
Total	20	47	11	2	80

(Table 7) shows that during the earlier half of the 54 year time period, plus the last five years (the years characterized by PDO2), El Niño years averaged at least 29% more snowfall events annually than La Niña or neutral years. During the PDO1 portion of this study, however, there were 67% more snowfalls in the combined category of La Niña and neutral years (significant at the 90% confidence level when testing versus the mean) than during El Niño years. Thus, the PDO1 (PDO2) snowfall seasons in SWMO experienced ENSO variability similar to (different from) that of Northwest Missouri (Berger et al. 2002). In NWMO roughly 8 events were observed per year in PDO2 regardless of ENSO phase, while in PDO1 8.5 events were observed in La Niña and neutral years, and 5.8 events in El Niño years. As was the case for the general statistical character of SGF winters (Section 4), the observations from the snowfall events in the SGF WFO area showed ENSO variability that was remarkably similar to that of SWMO (not shown). Next, we will examine the interannual variability of the SL ratio data for the SGF WFO, but as stated earlier, this only applies to the SGF station data.

When SL ratio data were stratified by ENSO year, the majority of La Niña and neutral year snowfalls were associated with SL ratios of less than 12:1 (60% of all events). However, during El Niño years, 75% of the snowfall events were associated with SL ratios of less than 12:1. None of these distributions are significantly different from the total sample, but it should be cautioned here that the sample sizes for El Niño and La Niña years are small. Further, a large fraction (approximately 85%) of these events regardless of category have an SL ratio of less than 14:1 (Table 8). When stratifying the data by PDO phase and then ENSO phase, there were no remarkable differences in the ENSO SL ratio distributions between PDO1 and PDO2 years (not shown).

#### c. ENSO variations in SL ratio and synoptic scale flow regime.

Table 9 shows the number of SGF snowfall events categorized by synoptic scale flow regime and ENSO phase. While each synoptic type can be expected to occur in an individual year, there was a greater tendency toward the occurrence of more southwest low events during El Niño years. This corresponds with the observation that the large scale flow over the North America trends toward a more zonal pattern or that weak troughing (ridging) was

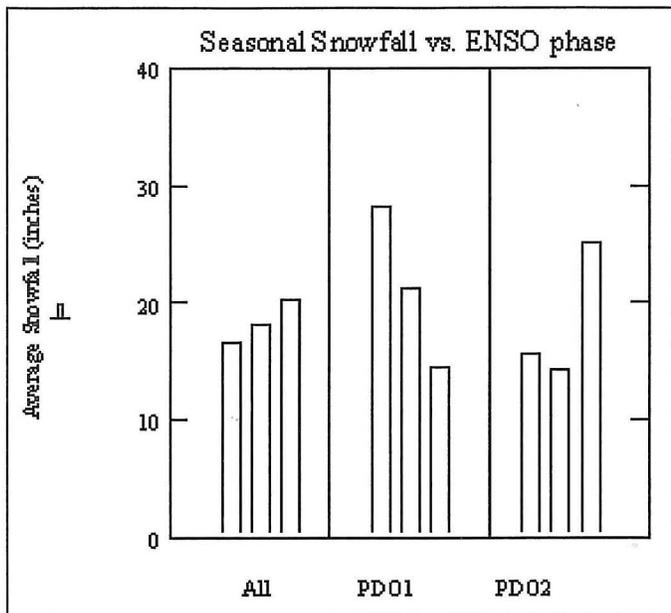
**Table 9.** The raw number of snowfalls produced by each synoptic-scale flow regime versus ENSO phase (first number), the average number of events per year (second number – dividing the first number by the total number of, for example, El Niño years), and percentage difference (in parenthesis) from the expected frequency if each type were equally likely in any year.

ENSO					
Phase (yrs)	Southwest	Deepening	Northwest	Progressive	All
La Niña (14)	7/0.5 (0.0)	6/0.4 (4.0)	2/0.2 (7.0)	4/0.3 (-11.0)	19/1.4
Neutral (27)	11/0.4 (-9.0)	11/0.4 (5.0)	3/0.1 (0.0)	16/0.6 (9.0)	41/1.5
El Niño (13)	9/0.7 (9.0)	3/0.2 (-9.0)	1/0.1 (-7.0)	7/0.5 (2.0)	20/1.5
Total	27	20	6	27	80

more typical over southwestern (eastern) North America during El Niño (La Niña) years (e.g., Keables et al. 1992). We speculate here that during El Niño years there may be less cold air available in place preceding these events, and possibly more mixed or liquid precipitation at some point during the storm. These events may also bring warmer and moister air into the SWMO region at least initially, and may be more likely to be associated with lower SL ratios (as discussed in Sections 2b, 5b; see Table 8), but higher storm total snowfalls (Table 1b) due to the larger amount of moisture available to the system. In spite of the small sample or relatively rare occurrence, the opposite appears to be true for northwest lows. Even though the findings showed fewer snowfall events during non-neutral years in SGF, and especially for El Niño years from the late 1970s through the 1990s, the seasonal snowfall amounts may not necessarily be much less given a greater likelihood of the occurrence of southwest lows characterized by a low SL ratio, but larger snow totals. The other interesting results indicated on Table 9 were that there were fewer deepening storms during El Niño years, but these were evenly distributed across the La Niña and neutral categories, and there were fewer progressive troughs during La Niña years. Fewer progressive troughs during La Niña years would be consistent with the Weidenmann et al. (2002) study, which showed a greater tendency toward East Pacific blocking.

Using these analyses above, more heavy snow producing, low SL ratio southwest lows occurring in El Niño years would suggest that these seasons may be associated with larger annual snowfall totals even though fewer events are observed. If the annual average snowfall data for SGF is stratified by ENSO phase, the total annual average snowfall amounts are similar across the El Niño and neutral phases (Fig. 8), even though there are nearly 20% more snowfall events in neutral years. This supports the findings above that a larger proportion of snowfall events were southwest lows (larger snowfall totals, lower SL ratio) during El Niño years. Thus, examining the interannual variability of snowfall by looking at annual snowfall amounts only can be misleading.

Additionally, we stratified seasonal snowfall totals by ENSO phase by the phase of the PDO (Fig. 8). This demonstrated that EN years observed greater than 60% more snowfall annually than La Niña and neutral years in PDO2, but roughly 33% less snowfall during PDO1



**Fig. 8.** The average seasonal snowfall (inches, October-May) for the SGF WFO for the entire 51-year period (All) by El Niño / La Niña phase, and the PDO2 (1949-1976, 1999-) and PDO1 (1977 - 1998) periods. The left, middle, and right bars represent La Niña, Neutral, and El Niño snowfall seasons.

years. These numbers correspond to roughly only 25% more (roughly 40% fewer) snowfall events than La Niña and neutral years in PDO2 (PDO1) years, but roughly 40% fewer events during El Niño PDO1 years. This suggests, again, that El Niño season snowfall events were generally more productive snowfall events.

## 6. Summary and Conclusions

The climatological character of SWMO snowfalls was examined using archived hourly observations obtained from the WFO in the Springfield, Missouri, and the cooperative weather observation program (COOP) stations for the SGF WFO county warning area. This examination included a study relating SL ratios and the synoptic scale flow regime provided more detail about the climatological character of SWMO snowfall events for operational forecasters than is available through routinely available climatological information. It is important for the effectiveness of forecasting and local public relations in a particular region that meteorologists become intimately familiar with the climatological character of that region. Such information as provided by this study represents information for the upper part of the "forecast funnel" and can be used as guidance for local forecasters. The methodologies used here were similar to those of Berger et al. (2002), wherein the interannual variability of snowfall events as associated with ENSO and PDO were characterized.

These results demonstrate that, as expected, there were fewer snowfall events per year in SWMO than in Northwest Missouri, and that most of these events were moderate snowfalls and winter season events. There was no statistically significant long term trend noted toward fewer

or more snowfall events in the region. An examination of the SGF WFO SL ratios showed that 60% of the snowfall events in the climatology were associated with a low (< 12:1) SL snowfall ratio. Winter season snowfalls were more evenly distributed between lower and higher SL ratios than were spring or fall season events since presumably winter season synoptic events are associated with colder and drier air. The synoptic scale flow regimes associated with SWMO snowfall events were the same as those in Northwest Missouri (Berger et al. 1999). Snowfalls in SWMO are primarily associated with three flow regimes (southwest lows, progressive troughs, and deepening lows) which occur with approximately equal frequencies. A fourth flow regime, northwest lows or "clipper-type storms", infrequently produce significant snowfalls. Lower SL ratios, but larger snowfall amounts, were associated with southwest lows and deepening lows, especially for the latter. Progressive troughs and northwest lows were associated with more moderate snowfalls, but were equally likely to be associated with higher or lower SL ratios. This suggests that there may be an indirect relationship between the atmospheric dynamics and thermodynamics, and cloud microphysical properties to SL ratios within a regime. These other environmental factors (e.g., vertical temperature distributions of temperature and humidity) also contribute to snow densities or SL ratios. However, in SWMO snowfall events, the dynamics may favor large precipitation amounts while the microphysics and environmental factors favor lower SL ratios. Conversely, there were no snowfall events that were accompanied by large snowfall amounts and high SL ratios. However, it is conceded that more detailed studies would be needed to affirm these assertions.

An examination of the interannual variability of SGF snowfall SL ratios reveals that there was variability with respect to ENSO phase, and no variability or trends with respect to longer term climatic variability and/or climate change. This ENSO variability was manifested by a much higher number of low SL ratio snowfall events during El Niño years than during non-El Niño years. Stratifying the synoptic scale flow regimes by ENSO phase suggested that southwest lows occurred more often during El Niño and neutral years, while the few northwest low events that occurred, occurred most often in La Niña and neutral years. These findings are supported by other studies that have examined the prevailing planetary scale regimes over North America and their variability (e.g., Keables 1992; Weidenmann et al. 2002). There appears to be little correlation between the yearly snowfall accumulation and the number of snowfall events. It is further suggested that SWMO snowfall seasons with fewer events may produce as much total snowfall as years with more events. A SWMO snowfall season with few events may be associated with more southwest low-type storms which have a lower SL ratio, but larger storm totals. However, after determining that the snowfall data from the SGF WFO was adequately representative of the climatological character of SWMO, including the interannual variability, it was determined that the SL ratios from SGF may not be adequately representative of the region.

An examination of the interannual variability of SWMO snowfalls revealed that ENSO-neutral winters produced more snowfall events than the El Niño or La

Niña snowfall seasons, but the result was not statistically significant. When winter seasons were further stratified by phase of the PDO, the interannual variability of snowfall events associated with ENSO changed when comparing the earlier years in the data set with the later years. During the PDO2 period (1949-1976, and 1999 - 2003), El Niño winters produced more snowfalls. La Niña and neutral winters produced more snowfalls during the later period (PDO1 - 1977-1999). This result was significant at the 90% confidence interval when testing the means.

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