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

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1. *See "Operational challenges of forecasting snowfall" authored by Mr. Norman W. Junker* at: http://www.eas.slu.edu/CIPS/Presenations/CIPSworkshop/junkersnow.

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 precipitation (SL) 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 that bring heavy snowfalls to Southwest Missouri and these 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 Nino-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[1]. It is proposed here that improvements in snowfall forecasts could be made by studying the association of snowfall-to-liquid (SL) 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 (e.g., Magono and Nakamura, 1965; Fukuta and Takahashi, 1999; Roebber et al., 2003) (e.g, dendrites have been shown to produce higher SL ratios and

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these form in environments of -10 to -20^{o} C, see Roebber et al. 2003 and references therein). Roebber et al. (2003) 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-α scales.

There have been several studies which discuss the relationship between SL ratio and the synoptic-scale environment of the embedded storm (e.g., Harms 1970; Scofield and Spayd 1984; Mote 1991; Super and Holroyd, 1997). 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 SGF WFO county warning area, and then 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. Then, 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 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 and 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^{o} 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-h period, events were not limited to a 24-h 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. Also, 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) and less dense or high SL ratio (> 18:1)" snow categories and encompassing much of the total dataset. Also, 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 and 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.[1] (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 highly variable in a synoptic event with respect to time and space especially due to 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. Fig. 2a showed 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%) (e.g., 12-14 March 1999 – see also Market and Cissell (2002)) even in events in which there was little or no mixed precipitation 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. Also, SGF is located a little less than

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[1] *See "Operational challenges of forecasting snowfall" authored by Mr. Norman W. Junker* at: http://www.eas.slu.edu/CIPS/Presentations/CIPSworkshop/junkersnow.

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.

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 (Fig. 3 adapted from Berger et al. (1999, 2002)). 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-developed 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 synoptic-scale process such as deformation (see 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, and 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, and 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 longwave 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 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 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 – see 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. 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 distribution 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^{o} 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^{o} 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^{o} 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 0.5 ^{o}C (2.0 ^{o}C) approximately. 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^{o} 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 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 Nino, neutral and La Nina 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. (2003) 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. 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). A list of El Nino (EN), La Nina (LN), and Neutral (NEU) years is included in Table 5. (A more detailed description of the JMA ENSO Index, can be found by accessing the Center for Ocean and Atmospheric Prediction Studies (COAPS) website[2].) 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^{o} N, 4^{o} S, 150^{o} W, and 90^{o} W (encompassing both the Nino 3 and 3.4 regions - e.g., see Climate Diagnostics Bulletin[3]) in the central and eastern tropical Pacific. The SST anomaly thresholds used to define EN years are those greater than $+0.5^{o}$ C, less than -0.5^{o} C for LN years, and NEU otherwise. 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 Nino year as beginning on 1 October of the previous year. Thus, the year '1970' which in Table 5 is labeled a La Nina 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 (e.g., Minobe 1997) within the eastern Pacific Ocean basin. As defined by Gershanov 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

[2] The COAPS website is at: http://www.coaps.fsu.edu

[3] The Climate Diagnostics Bulletin is a monthly publication issued through the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Centers for Environmental Prediction. Much of this bulletin is online at: http://www.cpc.ncep.noaa.gov

Pacific waters also characterize this phase of the PDO, which we refer to as PDO1. The reverse conditions characterize the negative phase of PDO and we refer to these conditions as PDO2. The period for each phase of the PDO is shown in Table 6 (see Gershanov and Barnett, 1998; Weitlich et al., 2003). Gershanov and Barnett (1998) 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 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 Nino and its impacts on North American atmospheric climatological flow regimes and circulation features tends to be greater (weaker), with a less (more) intense La Nina impact. Additionally, many others have found that the intensity of the ENSO phenomena varies on the interdecadal timescale in both observational (e.g., 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, and 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 Nina (El Nino) years than there were during neutral years (almost all accounted for in the moderate snowfall category). As was shown for Northwest Missouri 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 7), shows that during the earlier half of the 54 year time period, plus the last five years (the years characterized by PDO2), El Nino years averaged at least 29% more snowfall events annually than La Nina or Neutral years. During the PDO1 portion of this study, however, there were 67% more snowfalls in the combined category of La Nina and neutral years (significant at the 90% confidence level when testing versus the mean) than during El Nino years. Thus, the PDO1 (PDO2) snowfall seasons in SWMO experienced ENSO variability similar to (different from) that of Northwest Missouri (see 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 Nina and Neutral years and 5.8 events in El Nino 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 showed ENSO variability that was remarkably similar to that of SWMO (not shown). Next, we will also 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 LN and Neu year snowfalls were associated with SL ratios of less than 12:1 (60% of all events). However, during El Nino 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 Nino and La Nina years are small. Also, 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 EN years. This corresponds with the observation that the large-scale flow over the North America trends toward a more zonal pattern (see website from footnote 3) or that weak troughing (ridging) was more typical over southwestern (eastern) North America during El Nino (La Nina) years (e.g., Keables et al. 1992). We speculate here that during El Nino years, there may be less cold air available in place preceding these events, and thus 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, thus, may be more likely to be associated with lower SL ratios (as discussed in section 2b, 5b, see also 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 Nino 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 which are characterized by a low SL ratio, but larger snow totals. The other interesting results indicated on Table 9 was that there were fewer deepening storms during El Nino years, but these were evenly distributed across the La Nina and Neutral categories, and there were fewer progressive troughs during La Nina years. Fewer progressive troughs during La Nina 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 Nino 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 Nino 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 EN 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 Nina and neutral years in PDO2, but roughly 33% less snowfall during PDO1 years. These numbers correspond to roughly only 25% more (roughly 40% fewer) snowfall events than La Nina and neutral years in PDO2 (PDO1) years, but roughly 40% fewer events during El Nino PDO1 years. This suggests, again, that El Nino season snowfall events were more productive snowfall events generally.

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, providing more detail about the climatological character of SWMO snowfall events for WFO personnel 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" produce significant snowfalls infrequently. 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 Nino years than during non-El Nino years. Stratifying the synoptic-scale flow regimes by ENSO phase suggested that southwest lows occurred more often during El Nino and neutral years, while the few northwest low events that occurred, occurred most often in La Nina 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, for example; 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 Nino or La Nina 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 Nino winters produced more snowfalls. La Nina and neutral winters produced more snowfalls during the later period (PDO1 - 1977-1999), and this result was significant at the 90% confidence interval when testing the means.

7. Acknowledgements

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Table Captions

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

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).

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

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^{o} 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).

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

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

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

Table 8. The total number and average occurrence of snowfalls versus El Nino / La Nina phase.

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 Nino years), and percentage difference (in parenthesis) from the expected frequency if each type were equally likely in any year.

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

Number of events for each type

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
Total	27	20	6	27	80

Number of Events for each type

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
Total	27	20	6	27	80

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^{o} 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).

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

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

La Nina (LN)	Neutral (NEU)	El Nino (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-

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

	All	Moderate	Heavy	Extreme
(La Nina) Total PDO2 PDO1	 59 / 4.2 53 / 4.1 6 / 6	 32 / 2.3 30 / 2.3 2 / 2	 16 / 1.1 13 / 1.0 3 / 3	 11 / 0.8 10 / 0.8 1 / 1
(Neutral) Total PDO2 PDO1	 131 / 4.9 44 / 3.7 87 / 5.4	 84 / 3.1 28 / 2.4 56 / 3.5	 34 / 1.3 12 / 1.0 22 / 1.4	 13 / 0.5 4 / 0.3 9 / 0.6
(El Nino) Total PDO2 PDO1	 60 / 4.6 37 / 5.3 23 / 3.3	 35 / 2.7 19 / 2.7 16 / 2.3	 16 / 1.2 12 / 1.7 4 / 0.6	 9 / 0.7 6 / 0.9 3 / 0.4
All Total PDO2 PDO1	 250 / 4.6 134 / 4.2 116 / 4.8	 151 / 2.8 77 / 2.4 74 / 3.1	 66 / 1.2 37 / 1.2 29 / 1.2	 33 / 0.6 20 / 0.6 13 / 0.5

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

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

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 Nino years), and percentage difference (in parenthesis) from the expected frequency if each type were equally likely in any year.

ENSO phase (years)	Southwest	Deepening	Northwest	Progressive	All
La Nina (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 Nino (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

Figure Captions and Footnotes

Figure Captions

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

Figure 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.

Figure 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 hourlies.

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

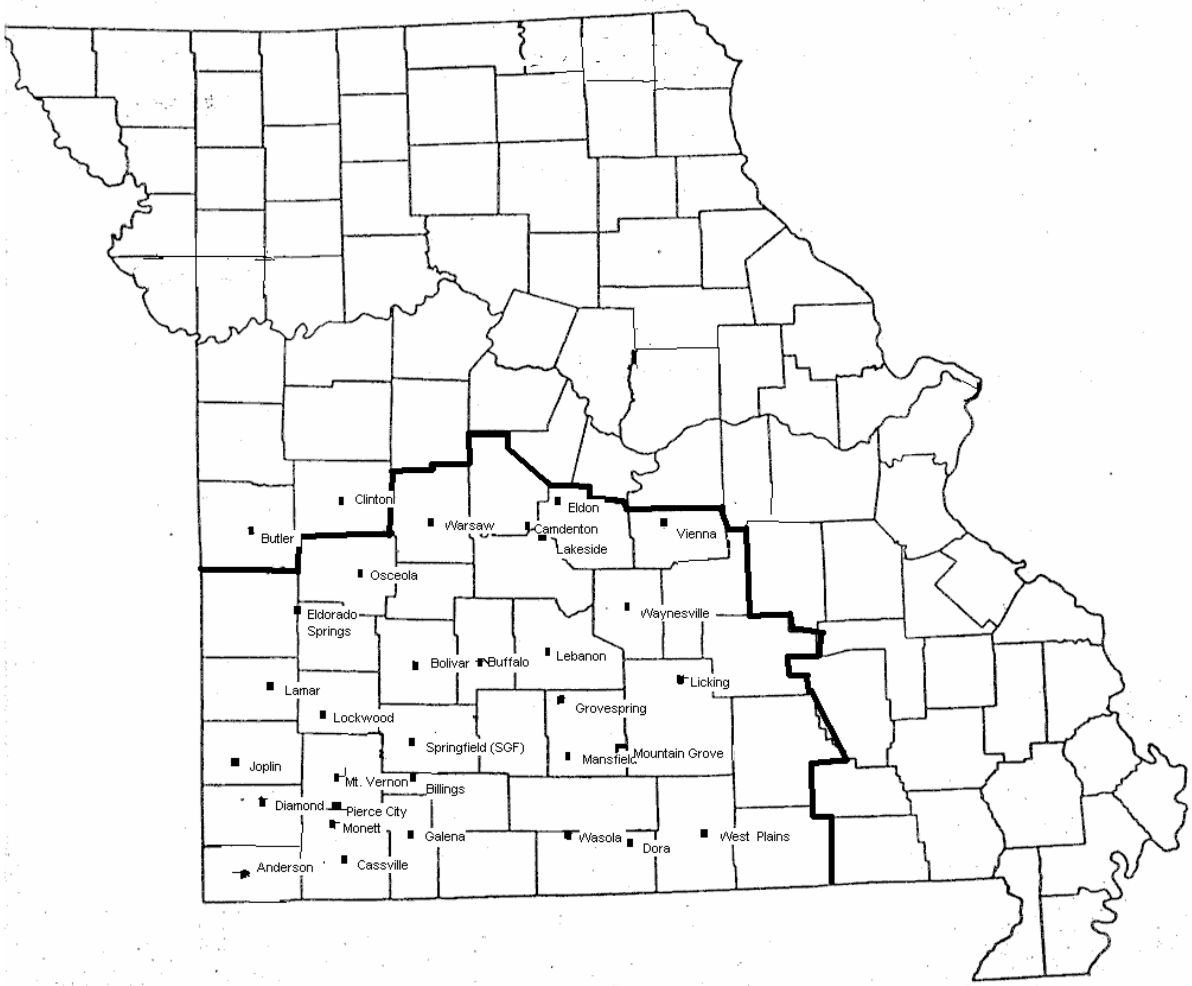
Figure 5. The total number of snowfall events occurring in each synoptic classification for events impacting SGF, where SW, DL, NL, and PT are southwest lows, deepening lows, northwest lows, and progressive troughs, respectively.

Figure 6. The total annual number of snowfall events for a) Southwest Missouri and b) Northwest Missouri vs. year. Also the linear trend is represented by the solid black line.

Figure 7. The total percentage of snowfall events in Southwest Missouri (left bar) and for the Springfield, MO, WFO (right bar) classified as moderate, heavy, or extreme.

Figure 8. The average seasonal snowfall (inches, October – May) for the SGF WFO for the entire 51-year period (All) by El Nino / La Nina phase, and the PDO2 (1949-1976,

1999-) and PDO1 (1977 - 1998) periods. The left, middle, and right bars represent La Nina, Neutral, and El Nino snowfall seasons.



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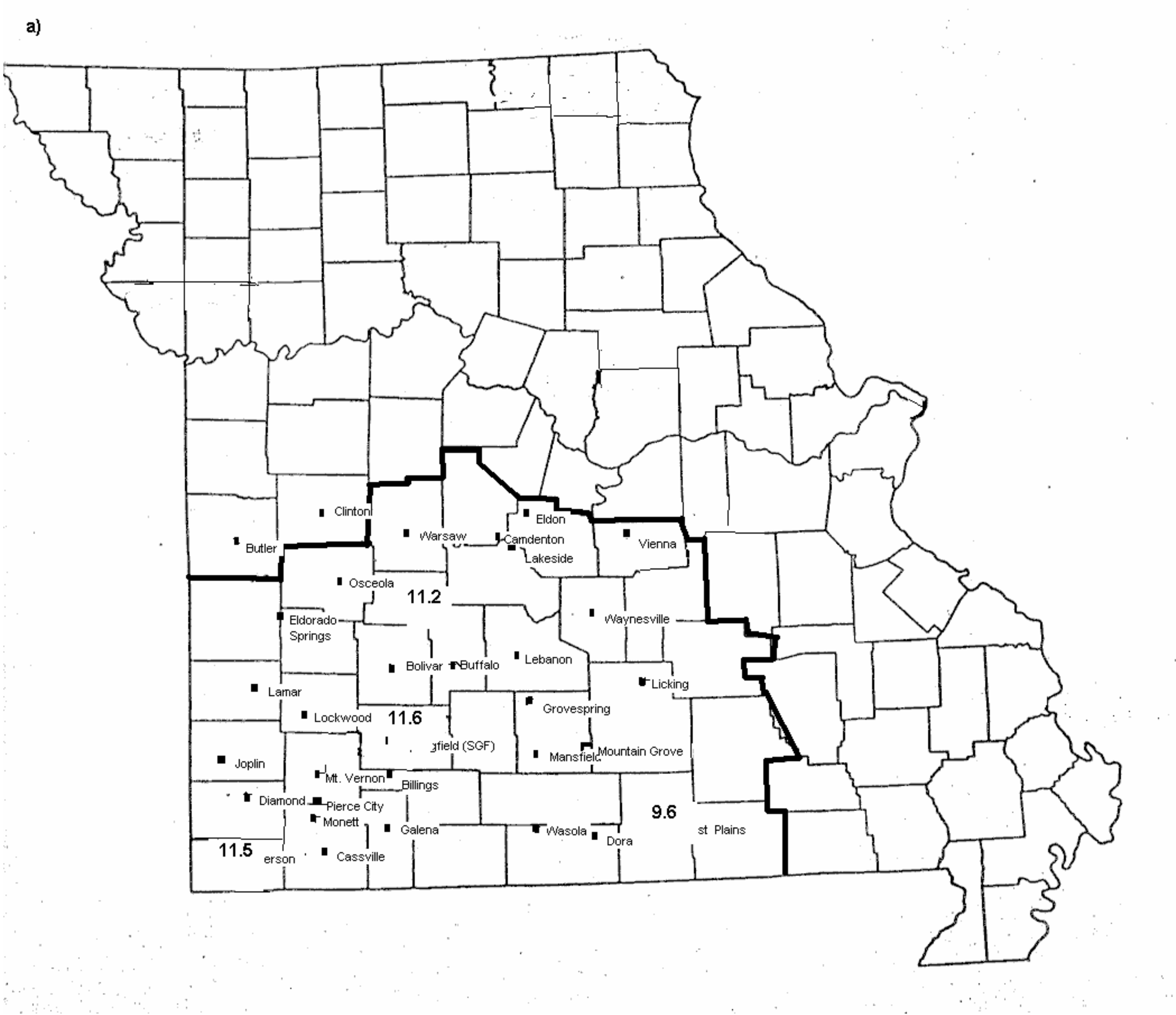
2a)


a)
Clinton
Butler
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Buffalo
Lebanon
Licking
Lamar
Lockwood
11.6
Grovespring
Joplin
gfield (SGF)
Mansfield
Mountain Grove
Mt. Vernon
Billings
Diamond
Pierce City
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Wasola
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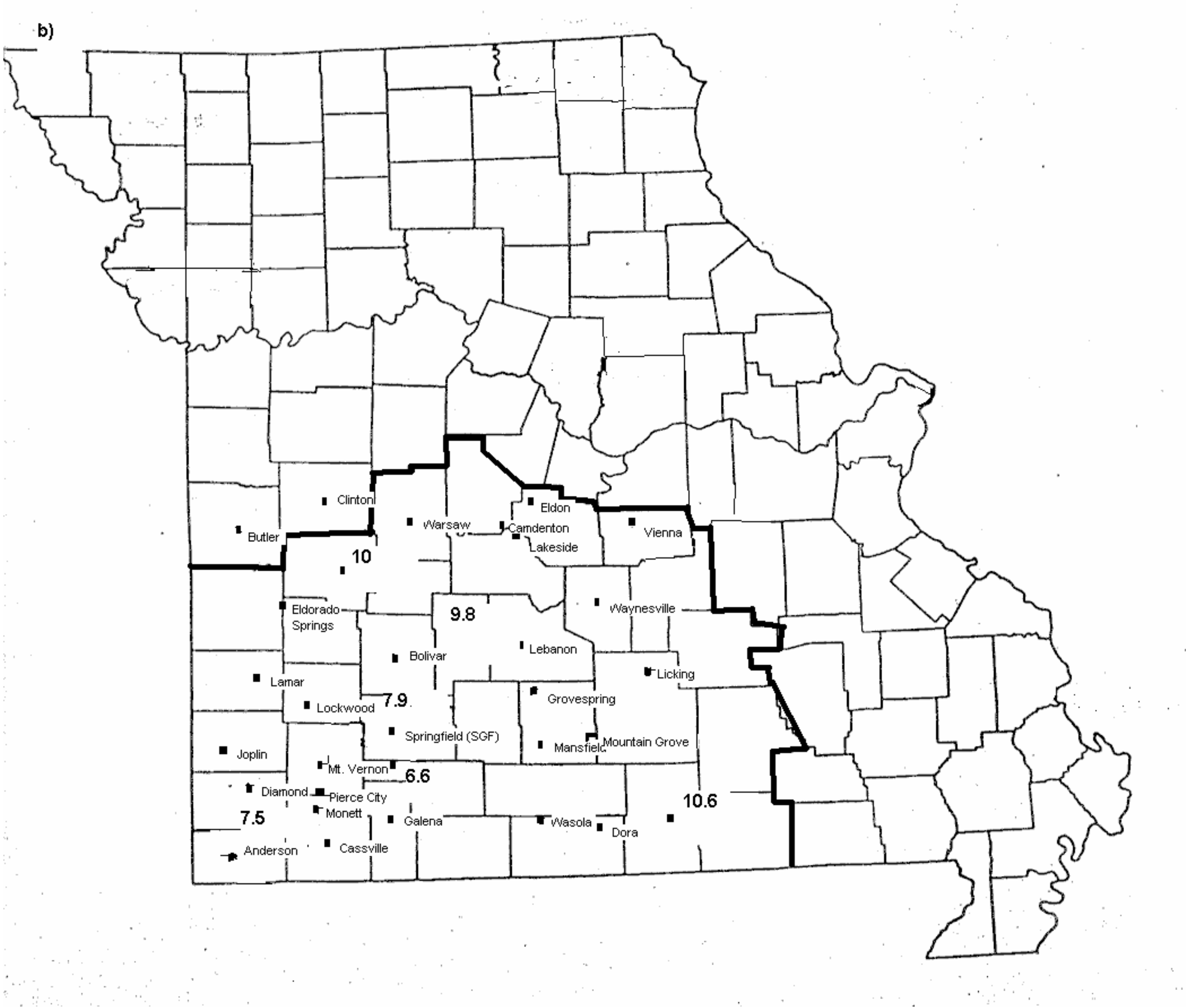
Cassville

2b)



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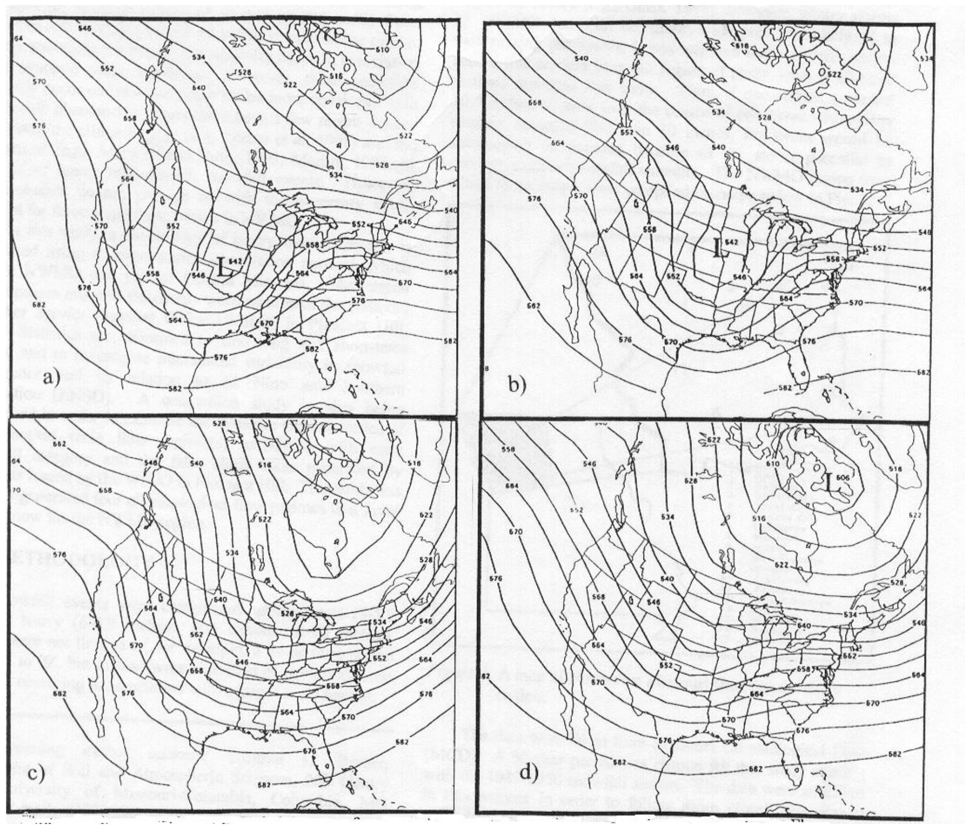

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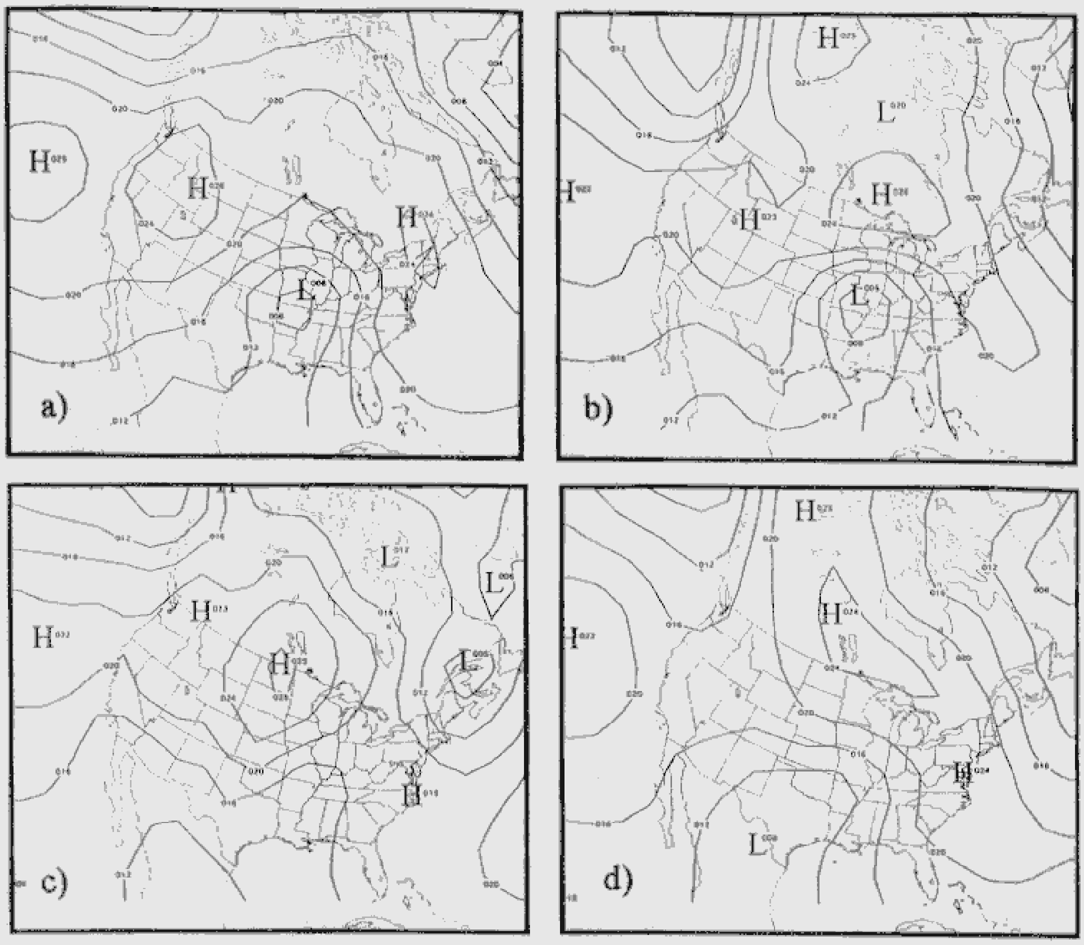

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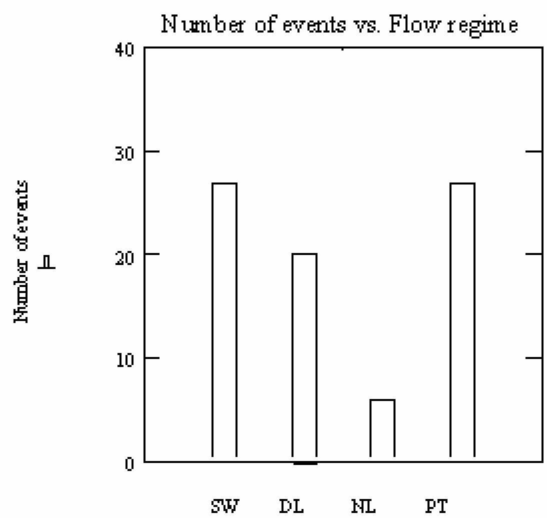

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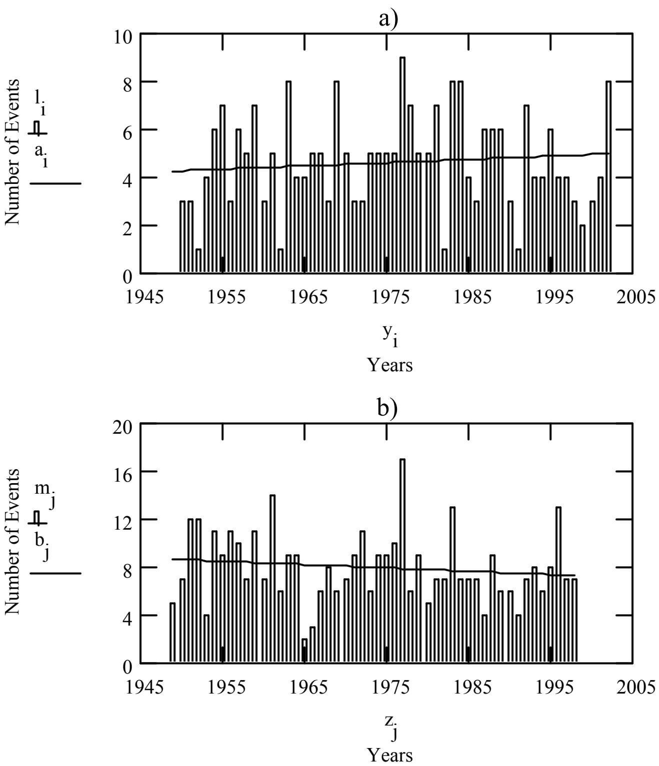

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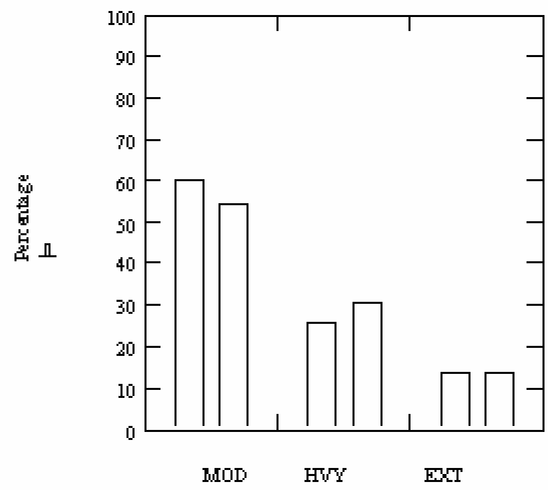

Figure 7. The total percentage of snowfall events in Southwest Missouri (left bar) and for the Springfield, MO, WFO (right bar) classified as moderate, heavy, or extreme.

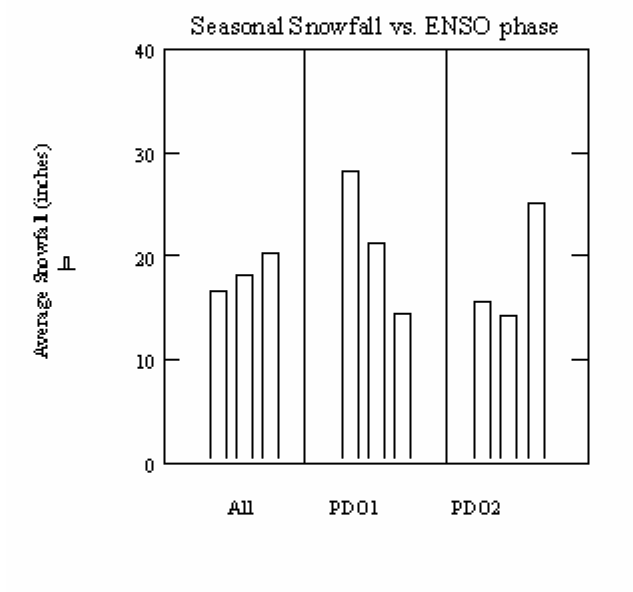

Figure 8. The average seasonal snowfall (inches, October – May) for the SGF WFO for the entire 51-year period (All) by El Nino / La Nina phase, and the PDO2 (1949-1976, 1999-) and PDO1 (1977 - 1998) periods. The left, middle, and right bars represent La Nina, Neutral, and El Nino snowfall seasons.