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16.9 INTERANNUAL VARIABILITY OF SNOWFALL EVENTS AND SNOWFALL-TO-LIQUID WATER AMOUNTS IN SOUTHWEST MISSOURI

Anthony R. Lupo,*[1] Drew Albert,[2] Ronald Hearst,[3] Cyndi L. Allmeyer,[1] and Patrick S. Market[1]

[1]Department of Soil and Atmospheric Sciences
116 Gentry Hall
University of Missouri-Columbia
Columbia, MO 65211

[2]National Weather Service Forecast Office
5805 West Highway EE
Springfield, MO 65802-8400

[3]KYTV - 3
999 W. Sunshine Rd.
Springfield, MO 65807

1. INTRODUCTION

A difficult forecasting challenge in Southwest Missouri (SWMO) is determining the arrival and amount of heavy snowfall, as was evidenced by the 13-14 March 1999 snowfall event (Market and Cissell, 2001). Heavy snowfalls occur frequently during the cold season and generally occur in association with synoptic-scale transients. However, heavy snowfalls occur on time and space scales more consistent with mesoscale phenomena, and may be forced by processes on that scale. There have been recent studies that detail the climatological aspects (e.g. Berger et al., 2001) and the dynamic aspects (e.g., Martin, 1998, Market and Cissell, 2001) of such events.

These snowfalls are a particular challenge for forecasters at the National Weather Service (NWS) Weather Forecast Office (WFO) in Springfield, MO (SGF). The onset of the 13-14 March snowfall was well forecast by the SGF WFO, but snowfall amounts were not. It is well known that there is a relationship between the liquid-to-snow (LS) ratio and the synoptic and/or large-scale environment of the embedded storm (e.g., Harms, 1970; Schofield and Spayd, 1984; Mote, 1991). There are several flow regime types which are responsible for heavy snowfall across Missouri (e.g. Berger et al., 2001), and each may produce varying LS ratios depending on surface, horizontal, or vertical temperature distributions.

Thus it is proposed here that the climatological aspects of heavy snowfalls and their LS ratios be examined in order to thoroughly examine the character of snow events impacting the SWMO region. In examining LS ratios, the data will be stratified by season, but also by flow regime character.

2. DATA AND METHODOLOGIES

a. Data

The data used for this study was acquired from the Missouri Climate Center and the SGF WFO. Several sources were used including cooperative and first order observation station records, the daily weather map series (published by the National Center for Environmental Prediction (NCEP), and hourly observations archived at the SGF WFO. A 50-year period was chosen for this study starting with the 1949-1950 snowfall season.

Corresponding author address: Anthony R. Lupo, Department of Soil and Atmospheric Sciences, 109 Gentry Hall, University of Missouri-Columbia, Columbia, MO 65211. E-mail: LupoA@missouri.edu.

b. Methodologies

In this study, snowfall events were categorized as moderate (3-5.9 inches), heavy (6-9.9 inches), and extreme (>10 inches). Four flow regimes were identified as being responsible for these snowfalls in Northwest Missouri (NWMO), and these basically describe SWMO snowfalls as well. Berger et al. (2001) describes the rationale for these snowfall categorizations in detail. A climatology of all SWMO snowfalls was compiled following the Berger et al. (2001) study. Then the climatology was re-derived using only data from the SGF WFO location in order to determine whether this one station adequately represents SWMO. Then the SGF snowfalls were stratified by LS ratio since this station was the only reporting station in SWMO that provided reliable liquid equivalents of snowfall. The LS ratio categorizations used here are as follows; a) 1 inch liquid to 8 inches of snow or solid precipitation or less (1:8 or less), b) 1:8 - 1:12, c) 1:12 - 1:18, and d) 1:18 or greater inches.

3. TRENDS AND VARIATIONS IN LS RATIO

A total of 235 snowfall events of 3 inches or more occurred within the SWMO region over the 50-year period. This represents an average of about 4.7 events per year. Most of these events were of moderate intensity (142) and occurred in the winter (172). As in NWMO, there were more spring events than there were fall events in SWMO. There was no apparent long-term trend in SGF snowfalls (not shown), as the confidence intervals calculated for the total sample, and each category, were large (95% confidence band was +/- 4.32 snowfall events, see e.g., Neter et al., 1988).

In order to determine whether or not SGF was representative of SWMO, we examined only the 73 snowfall events that were recorded at the WFO. The distribution of SGF WFO snowfalls by percentage across each category was very similar to that of all SWMO snowfalls (Table 1). Since the SGF subset was distributed in a similar manner to SWMO snowfalls, it is reasonable to assume SGF LS ratios would adequately represent all of SWMO. SGF liquid equivalent precipitation amounts were the only reliable values available for this study.

Table 2 demonstrates, as expected, that most (63%) snowfall events produce an LS ratio of 1 inch of liquid to 12 inches of snow (1:12) or less, and 56% of the total number of storms produced LS ratios in the 1:8 - 1:12 category. Winter snowfall events were more evenly distributed across the four LS ratio categories as 60% of events had LS ratios of 1:12 or less. Spring and fall events were skewed more heavily toward smaller LS ratios, with 70% of these snow events producing 1:12 inches of snow or less. An examination of the total sample by decade (not shown) reveals there was no statistically significant trend toward "wetter" (low LS ratio events) or "drier" (high LS ratio) snowfall events.

Table 1. The total number of seasonal and overall snowfall events for the Springfield, Missouri Weather Forecast Office. The second and third numbers represent the percentage of total snowfalls for the SGF WFO only and SWMO region, respectively.

	Fall	Winter	Spring	All
Moderate	4 /5.5/2.5	33 /45/47	4 /5.5/11	41 /56/60
Heavy	3 /4/2.5	15 /21/18	5 /7/6	23 /31/27
Extreme	0 /0/1	5 /7/8	4 /5.5/4	9 /13/13
Total	7 /9.5/6	53 /74/73	13 /17/21	73

Table 2. The total number of seasonal and overall snowfall events for the Springfield, Missouri Weather Forecast Office categorized by LS ratio.

(inches)	Fall	Winter	Spring	All
< 1:8	0	3	2	5
1:8-1:12	5	29	7	41
1:12-1:18	1	21	4	26
> 1:18	1	0	0	1
Total	7	53	13	73

4. INTERANNUAL VARIABILITY

Snowfall data were then stratified into El Nino, neutral and La Nina phases (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. (2001).

Examining Table 3 reveals that there is only weak variability associated with ENSO in SWMO snowfalls, and none of these were statistically significant. However, the interannual variability SWMO snowfall events were different than that found for NWMO snowfalls. In SWMO, there were 15% fewer events during La Nina and El Nino years than there were during neutral years (all accounted for in the moderate snowfall category). There were more snowfalls in La Nina and neutral years in NWMO. As was shown for NWMO snowfalls, however, examining 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, presumably due to interactions with longer term variations such as the PDO. When this analysis is performed (Table 3), it can be shown that during the earlier half of the 50-year time period (PDO2), El Nino years experienced 20% more snowfall events. During the latter portion of our study period (PDO1) there were more snowfalls in La Nina and neutral years (significant at the 90% confidence level). The PDO1 snowfall seasons in SWMO experienced ENSO variability similar to that of NWMO, while during the earlier period, the statistical character of SWMO winters was different from those in NWMO.

Table 3. The total number and average occurrence of snowfalls versus El Nino / La Nina phase for the a) total sample, b) PDO2 (1949-1976), and c) PDO1 (1977 - 1999) period.

a.	All	Moderate	Heavy	Extreme
Cold	51 / 4.2	28 / 2.3	15 / 1.2	8 / 0.7
Neutral	129 / 5.0	81 / 3.1	34 / 1.3	14 / 0.6
Warm	55 / 4.2	33 / 2.5	15 / 1.2	7 / 0.5
Total	235 / 4.7	142 / 2.8	64 / 1.3	30 / 0.6

b.	All	Moderate	Heavy	Extreme
Cold	45 / 4.1	26 / 2.4	12 / 1.1	7 / 0.6
Neutral	42 / 4.2	25 / 2.5	12 / 1.2	5 / 0.5
Warm	32 / 5.3	17 / 2.8	11 / 1.8	4 / 0.7
Total	119 / 4.4	74 / 2.5	35 / 1.3	16 / 0.6

c.	All	Moderate	Heavy	Extreme
Cold	6 / 6	2 / 2	3 / 3	1 / 1
Neutral	87 / 5.4	56 / 3.5	22 / 1.4	9 / 0.6
Warm	23 / 3.3	16 / 2.3	4 / 0.6	3 / 0.4
Total	116 / 4.8	74 / 3.1	29 / 1.2	13 / 0.5

The interannual variability of SGF WFO snowfalls only were examined in order to determine if this station was representative of SWMO variability. As was the case for the general statistical character of SGF winters (Section 3), the observations from the SGF WFO showed variability that was remarkably similar to that of SWMO (not shown). Thus, we will use the LS ratio data from SGF to examine the interannual variability of this characteristic as well.

When LS ratio data were stratified by ENSO year (Table 4), a majority of La Nina and neutral year snowfalls were associated with lower LS ratios (58% with LS ratios less than 1:12). This distribution is not significantly different from the distribution of the total set of the SGF WFO LS ratios. However, during El Nino years, 78% of the snowfall events were associated with LS ratios of less than 1:12, which is significantly different from the other years. When stratifying the data by PDO phase and then ENSO phase, there was no difference in the LS ratio distributions between PDO1 and PDO2 years, and the ENSO distributions within each were the same as the ENSO distribution of the total SGF snowfall set.

This suggests that, during El Nino years, there may be less cold air available for these events (and associated with more mixed or liquid precipitation at some point during the storm). Berger (1999) shows that there are four basic flow regimes that are associated with NWMO snowfalls. She also found that during El Nino years, there were more storms originating over the southwest US, which tend to bring warmer air into the SWMO region at least initially. SWMO snowfalls are also being categorized in order to determine if the hypothesis discussed here adequately explains the difference in snowfall distributions between El Nino and La Nina + neutral years.

Table 4. The total number and average occurrence of snowfalls versus El Nino / La Nina phase.

	All	< 1:8	1:8-1:12	1:12-1:18	> 1:18
Cold	14	2	6	6	0
Neutral	41	1	23	16	1
Warm	18	2	12	4	0
Total	73	5	41	26	1

5. SUMMARY AND CONCLUSIONS

The climatological character of SWMO snowfalls were examined and compared to that of NWMO. This examination included the study of LS ratios, providing even more detail about the character of SWMO snowfall events for WFO personnel. The methodologies used here were similar to those of Berger et al. (2001), and the interannual variability of snowfall events as associated with ENSO and PDO were characterized.

Initial results demonstrate that, as expected, there were fewer snowfall events per year in SWMO than in NWMO. The intraseasonal distribution of these snowfall events, however, was similar to that of NWMO. An examination of the interannual variability of SWMO snowfalls reveal that ENSO-neutral winters produced more snowfall than the El Nino or La Nina snowfall seasons. When winter seasons were further stratified by phase of the PDO, the interannual variability of snowfall events associated with ENSO changed somewhat. During the PDO2 period (1949-1976), El Nino winters produced more snowfalls. La Nina and neutral winters produced more snowfalls during the later period (PDO1 - 1977-1999), and this result is similar to that of NWMO. Then, the climatological character of snowfalls using data from the SGF WFO only demonstrated that this one station represented the climatological character of the SWMO region very well, and this included the interannual variability of SGF snowfall events. Thus, the SGF LS ratio climatology would be representative of the SWMO region.

An examination of the SGF WFO LS ratios showed that most snowfall events were associated with a lower (< 1:12) LS snowfall ratio. Winter season snowfalls were more evenly distributed between lower and higher LS ratios than were spring or fall season events, since presumably winter season synoptic event would be associated with colder air. An examination of the interannual variability of SGF snowfall LS ratios reveals that there was significant 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 significantly higher distribution of low LS ratio snowfall events during El Nino years than during non-El Nino years. Further research is underway to determine whether the same basic flow regimes that produce snowfall in NWMO produce snowfalls in SWMO as well. Then a determination will be made as to whether snowfall events during El Nino years are associated with synoptic conditions that favor a warmer environment, and thus, more mixed precipitation (and presumably lower LS ratio) events.

6. ACKNOWLEDGEMENTS

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