Trends in Twentieth-Century U.S. Extreme Snowfall Seasons

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ABSTRACT

Temporal variability in the occurrence of the most extreme snowfall years, both those with abundant snowfall amounts and those lacking snowfall, was examined using a set of 440 quality-controlled, homogenous U.S. snowfall records. The frequencies with which winter-centered annual snowfall totals exceeded the 90th and 10th percentile thresholds at individual stations were calculated from 1900–01 to 2006–07 for the conterminous United States, and for 9 standard climate regions. The area-weighted conterminous U.S. results do not show a statistically significant trend in the occurrence of either high or low snowfall years for the 107-yr period, but there are regional trends. Large decreases in the frequency of low-extreme snowfall years in the west north-central and east north-central United States are balanced by large increases in the frequency of low-extreme snowfall years in the Northeast, Southeast, and Northwest. During the latter portion of the period, from 1950–51 to 2006–07, trends are much more consistent, with the United States as a whole and the central and northwest U.S. regions in particular showing significant declines in high-extreme snowfall years, and four regions showing significant increases in the frequency of low-extreme snowfall years (i.e., Northeast, Southeast, south, and Northwest).

In almost all regions of the United States, temperature during November–March is more highly correlated than precipitation to the occurrence of extreme snowfall years. El Niño events are strongly associated with an increase in low-extreme snowfall years over the United States as a whole, and in the northwest, northeast, and central regions. A reduction in low-extreme snowfall years in the Southwest is also associated with El Niño. The impacts of La Niña events are strongest in the south and Southeast, favoring fewer high-extreme snowfall years, and, in the case of the south, more low-extreme snowfall years occur. The Northwest also has

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a significant reduction in the chance of a low-extreme snowfall year during La Niña. A combination of trends in temperature in the United States and changes in the frequency of ENSO modes influences the frequency of extreme snowfall years in the United States.

1. Introduction

Snowfall is a uniquely sensitive climate variable resulting from the integration of temperature, precipitation, and other synoptic inputs at a variety of temporal and spatial scales. Although changes and variations in snow on the ground have been studied extensively because of their direct impacts on the earth's radiation budget (Dery and Brown 2007; Dyer and Mote 2007; Groisman et al. 1994) and regional hydrology (Dyer and Mote 2006; Barnett et al. 2005; Regonda et al. 2005; Stewart et al. 2005), snowfall itself has been subject to relatively less scrutiny (Kunkel et al. 2007). Small changes in observational practice, station surroundings, or station location can lead to large inhomogeneities in the time series of a sensitive variable such as snowfall (Doesken and Judson 1997; Robinson 1989). Kunkel et al. (2007) described many of these challenges. The authors recently completed a project to identify the most homogeneous long-term U.S. snowfall records for use in trend analyses. Distinct patterns of cold-season snowfall trends have been identified (Kunkel et al. 2009a), including steep twentieth-century declines along the West Coast, Mid-Atlantic coast, and the southern margins of the seasonal snowpack. Snowfall has been increasing in the lee of the Rocky Mountains, portions of the north-central United States, and in the Great Lakes–northern Ohio Valley.

Although trends in mean snowfall totals are an important indicator of changes in climate, it can be argued that the most influential snowfall years are those with extremely large or extremely small amounts of snowfall. High-extreme snowfall years are often accompanied by high-impact snowstorms that cause hazardous transportation conditions (Changnon and Changnon 2006). Also, the resulting snowpack can lead to flooding during the spring, especially if heavy rain accelerates melt (Todhunter 2001). Ski resorts and other winter recreation businesses can benefit in these years from deep and long-lasting snowpacks, and snowmelt can also fill downstream reservoirs. On the other hand, low-extreme snowfall years can lead to serious water shortages in regions dependent on deep snowpacks as a water reservoir (Mote et al. 2005); winter wheat can be vulnerable to winter frosts without a snow cover (Landau et al. 2000); and the winter frost wave may reach deeper into the soil in northern climates and damage tree roots without an insulating blanket of snow (Sutinen et al. 1999). Society benefits directly from a lack of snow by reductions in transportation hazards, roof and building damage, and snow-removal costs (Changnon et al. 2008). Extreme snowfall years have a large impact on the spatiotemporal distribution of the seasonal snowpack, greatly influencing the climate system (Dery and Brown 2007). The frequency of extreme snowfall years of either type can also be a sensitive indicator of climate change.

Low snowfall years and changes in the seasonal cycle of mountain snowpacks in the west during the late 1990s and early 2000s have been examined because of their impacts on water resources (Mote et al. 2005; Mote 2003; Regonda et al. 2005). High snowfall years such as those of the late 1970s in the north-central and northeastern United States have been studied extensively (Harnack 1980; Namias 1978). Likewise, the synoptic meteorological bases of many individual major snowstorms and their impacts have been closely examined (Kocin and Uccellini 2005a,b; Changnon and Changnon 2006). However, there has been no systematic examination of the temporal variability of high- or low-extreme snowfall years in the United States. Using a homogeneous subset of snowfall records, referenced to the same long base period, this study examined national and regional trends in extreme snowfall years, and the relationships of extreme snowfall years to temperature, precipitation, and El Niño and La Niña events.

2. Methods

The station snowfall data used in this study are from the National Weather Service Cooperative Observer Network (COOP). A substantial portion of the data prior to 1948 was keyed in the past decade as part of the Climate Database Modernization Program (Kunkel et al. 2005). There are a number of issues with these snowfall data that potentially affect any long-term analyses of extremes (Kunkel et al. 2007). Changes in station location, observer, and measurement practices over time can have a substantial effect on the homogeneity of individual time series. Therefore, a set of 440 long-term snowfall records specifically identified as sufficiently homogeneous for trends analysis were used for this study. The creation of this data subset will be described briefly; a more extensive discussion can be found in Kunkel et al. (2009a).

Initial screening of the COOP snowfall data yielded 1124 station time series that had fewer than 10% of the total number of days missing during the October–May snow seasons from 1930 to 2004, assuming that days left

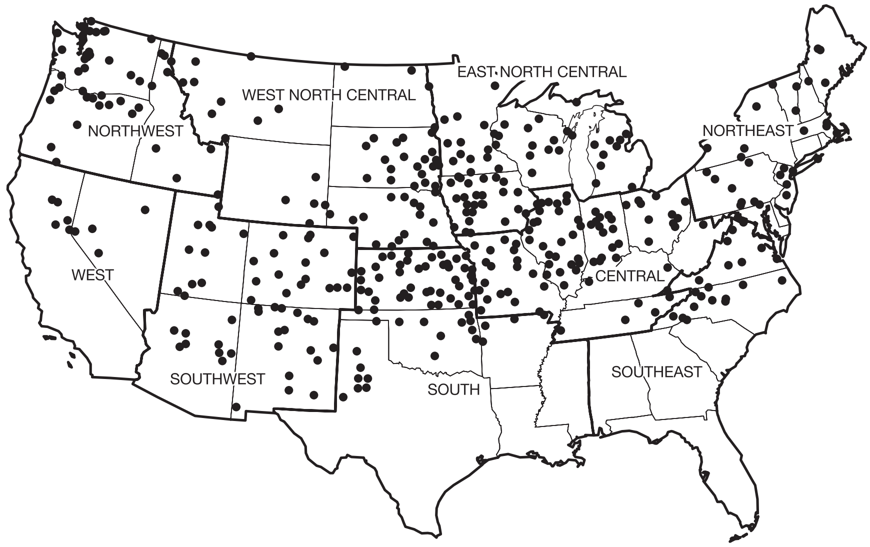

FIG. 1. Long-term homogenous snowfall stations in the conterminous United States that were identified by Kunkel et al. (2009a).

blank on the observer forms and listed as ''missing'' in the official records actually represented days with no snow if precipitation was recorded as zero. Winter-centered annual snowfall totals were calculated for snow seasons from 1900–01 to 2006–07. Winter-centered years were designated as missing if any of the following criteria were met: 1) there were 20 or more days with missing snowfall data during 1 December–28/29 February, 2) there were 40 or more days with missing snowfall data during 1 October–31 May, or 3) there were 5 or more days with potentially significant snowfall but missing snowfall data. A potentially significant snowfall day was defined as a day with a precipitation (liquid equivalent) total of >2.5 mm and a mean daily temperature of <0°C. Snowfall data for seasons with anomalies above 5.0 or below −5.0 standard deviations were checked manually for keying errors against observer forms or *Climatological Data* publications, and any such errors were corrected. Station time series were required to have at least five nonmissing winter-centered years in the last decade of the time series, so as to substantively represent any recent changes in snowfall extremes. Finally, the screening required that the 1971–2000 mean annual snowfall be greater than 12.5 cm, to focus on those areas where snowfall was a common seasonal occurrence. The 1124 stations were then examined by the authors manually for homogeneity, using techniques described in Kunkel et al. (2009a). A total of 440 were found by a plurality of the authors to be homogenous, and suitable for trend analyses. Of the selected stations, 314 contain 5 or more years of snowfall data in the 1920s, 260 have 5 or more years of data in the 1910s, and 194 have 5 or more years of data in the 1900s. The 440 stations (Fig. 1) are heavily concentrated in the central United States, with less dense coverage in the eastern and western United States, especially in the northern Great Plains. There was a higher density of long-term snow-observing stations in this area prior to selection for homogeneity. This high concentration may be a result of a number of factors such as (i) the relatively flat and homogeneous terrain made it easier to meet homogeneity requirements when a site needed to move, and (ii) the high interest in agricultural weather made it easier to find nearby replacement observers when necessary. In mountainous areas, particularly the western United States, cooperative observer network stations are systematically located at lower elevations where most observers reside. Thus, the results presented here do not necessarily reflect the possibility of valley behavior different from that of adjacent snow-dominated higher elevations.

Extreme snowfall years were defined as having snowfall greater than or equal to the 90th percentile (hereafter referred to as high-extreme snowfall) or snowfall equal to or less than the 10th percentile (hereafter referred to as low-extreme snowfall) of the station specific distribution for the period from 1937–38 to 2006–07. This 70-yr period was chosen to generate percentile thresholds for the longest period possible that all stations held in common, so that individual station counts of years exceeding the thresholds could be combined spatially without concern for their compatibility. Percentile thresholds were derived from the empirical distribution of the annual snowfall records of each station by ranking the time series to find the 10th and 90th percentile thresholds.

The average percentage of occurrences, or frequency, of threshold exceedances would be nominally 10%, but can deviate from this due to the thresholds being applied to years before 1937–38.

The record of extreme snowfall occurrences was examined using two approaches. First, winter-centered annual values for the percentage of the conterminous United States with high-extreme and low-extreme snowfall totals were calculated using an area-weighted approach. Within each 1° latitude by 1° longitude grid cell, the number of stations with snowfall exceeding an extreme threshold was counted and then a fraction was calculated based on the total number of stations with data in that grid cell. The gridcell fractions were then added together and divided by the number of grid cells with station snowfall data in that year in order to calculate the U.S. fraction, expressed as a percentage. For regional time series, a more direct approach was used since spatial variations in station density were not as great on a regional scale. The number of stations reporting an extreme snowfall amount for a given year and region was divided by the total number of stations with snowfall data for that year in that region. These time series were constructed for the nine standard regions established by the National Climatic Data Center (NCDC; Table 1). The use of the NCDC standard regions facilitates comparisons with regional temperature and precipitation time series already derived for these same regions from the time-of-observation bias-corrected climate division dataset (Karl et al. 1986). The nine NCDC regions are routinely used to summarize data in climate monitoring activities. Although not ideal in terms of a consistent climate across each region and not defined in terms of snowfall observations, they are sufficiently large to provide meaningful regional patterns in the continental United States, without resorting to a large number of smaller regions. These regions have been used in a number of recent studies documenting observed changes in climate including heavy precipitation (Karl and Knight 1998) and frost days (Easterling 2002). The regional analyses provide a spatially averaged view of the data that is complementary to the detailed station-by-station results, which reveal local detail. Statistical analysis of results is also more robust for regional time series than for station time series, an important consideration when analyzing extremes.

The national and regional time series were subjected to trend analysis. Although annual-to-decadal-scale variability are dominant features of these time series, as will be seen, the long-term trend is also of interest because of documented long-trends in temperature and precipitation in many regions. Given the obvious connection of snowfall to temperature and precipitation, it is of interest to examine whether any long-term snowfall extreme trends are consistent with observed trends in temperature and precipitation. Tests of the various regional time series indicated that in many cases the data distributions were not normal. Therefore, the nonparametric Kendall test was used to determine trend magnitude and statistical significance.

TABLE 1. The states within the nine NCDC climate regions. The states that are set italic have no long-term homogeneous snowfall records, either because there are no stations meeting the minimum average criteria of 12.5 cm or all long-term stations were judged to be of unsuitable quality for trend analysis.

Northeast: *CT*, *DE*, ME, *MD*, MA, NH, NJ, NY, PA, *RI*, VT
East north-central: IA, MI, MN, WI
Central: IL, IN, KY, MO, OH, TN, WV
Southeast: *AL*, *FL*, *GA*, NC, *SC*, VA
West north-central: MT, NE, ND, SD, WY
South: AR, KS, *LA*, *MS*, OK, TX
Southwest: AZ, CO, NM, UT
Northwest: ID, OR, WA
West: CA, NV

3. Results

a. Trends in high- and low-extreme snowfall years for the conterminous United States

The time series of the annual percentage of the United States with high-extreme snowfall (Fig. 2a) displays large interannual variability and visible decadal-scale variability. During the 1900–01 to 1920–21 and 1961–62 to 1984–85 periods, the area with high snowfall extremes averaged 12.6% and 13.9%, respectively, considerably higher than during 1921–22 to 1940–41 and 1985–86 to 2006–07, when the area averaged 8.2% and 7.3%, respectively. Given the juxtaposition of a relative maximum during the beginning decades of the record, and a relative minimum in recent decades, there is a downward trend [-1.7% (100 yr)$^{-1}$], but it is not statistically significant. The dominant characteristic of the time series is the pronounced multidecadal variability.

The time series of the annual percentage of the United States with low-extreme snowfall (Fig. 2b) also displays large interannual variability, but more subtle decadal-scale variability. Interestingly, the maximum U.S. coverage for low-extreme snowfall occurred during the 1980–81 season, only 2 yr after the maximum U.S. coverage for high-extreme snowfall in 1978–79. These years were well known for the 1980 drought (Karl and Quayle 1981) and the severe winter of 1978–79 (Harnack 1980). There is virtually no trend in the low-extreme snowfall coverage for the 107-yr record. An inverse relationship between the high and low snowfall extreme coverage time series is apparent; the annual values of the two time series are highly significantly correlated, with $r = -0.57$. However,

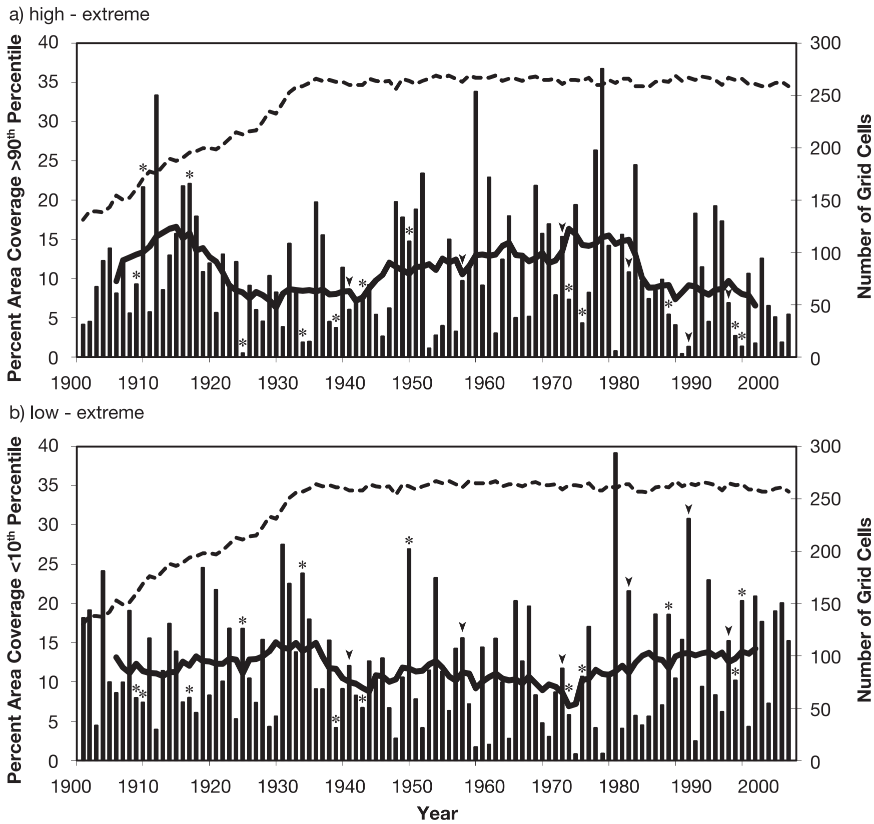

FIG. 2. (a) Area-weighted annual percentage of U.S. homogeneous snowfall stations exceeding the 90th percentile, 1900–01 to 2006–07. Reference period is 1937–38 to 2006–07. Values determined as described in text. Thick black line: 11-yr running mean of the percentages. (dashed line) Number of grid cells with active stations each year. Individual annual values plotted on the ending year of the winter season; 11-yr running mean plotted on the sixth year. (b) As in (a), but for the percentage of conterminous U.S. snowfall records below the 10th percentile. Arrows (asterisks) denote El Niño (La Niña) events with December–January–February average ONI $> +1.5$ (< -1.5).

two-thirds of the variance of these time series is not held in common, and there were periods when decadal tendencies in both extremes overlapped in time and space.

The period 1921–22 to 1940–41 displays some of the relationship complexity between high and low snowfall extreme occurrences. In the central United States, the frequency of high-extreme snowfall years was less than the 1937–38 to 2006–07 mean for most stations (Fig. 3a), while the frequency of low-extreme snowfall years was greater than the mean for most stations (Fig. 3b). However, in the eastern United States both types of extreme snowfall years occurred less frequently than normal, while in the far western United States, the few stations available indicated that both occurred more frequently than normal. These inconsistent relationships between the frequencies of high- and low-extreme snowfall years in some regions and time periods reflect the complex combination of temperature, precipitation, and atmospheric circulation factors causing extreme snowfall seasons. In this case, the west was cooler than normal, so even with less precipitation than normal, there was still an appreciable likelihood of high-extreme snowfall years as well as low-extreme snowfall years.

During 1961–62 to 1984–85, high-extreme snowfall years occurred much more frequently than the mean in most of the United States (Fig. 3c). This is a well-known period of colder temperatures, both in the United States and globally (Hansen et al. 2001). Interestingly, during this period a cluster of stations in the north-central United States displays greater frequency of low-extreme snowfall years (Fig. 3d). The likely explanation for this behavior is the increased frequency of highly meridional flow during this period (Palecki and Leathers 1993). Cold air outbreaks were frequent and traveled far to the south, limiting moisture availability for snowfall in the north-central United States during some of these seasons.

The most recent epoch, 1985–86 to 2006–07, was characterized by below-average frequency of high-extreme

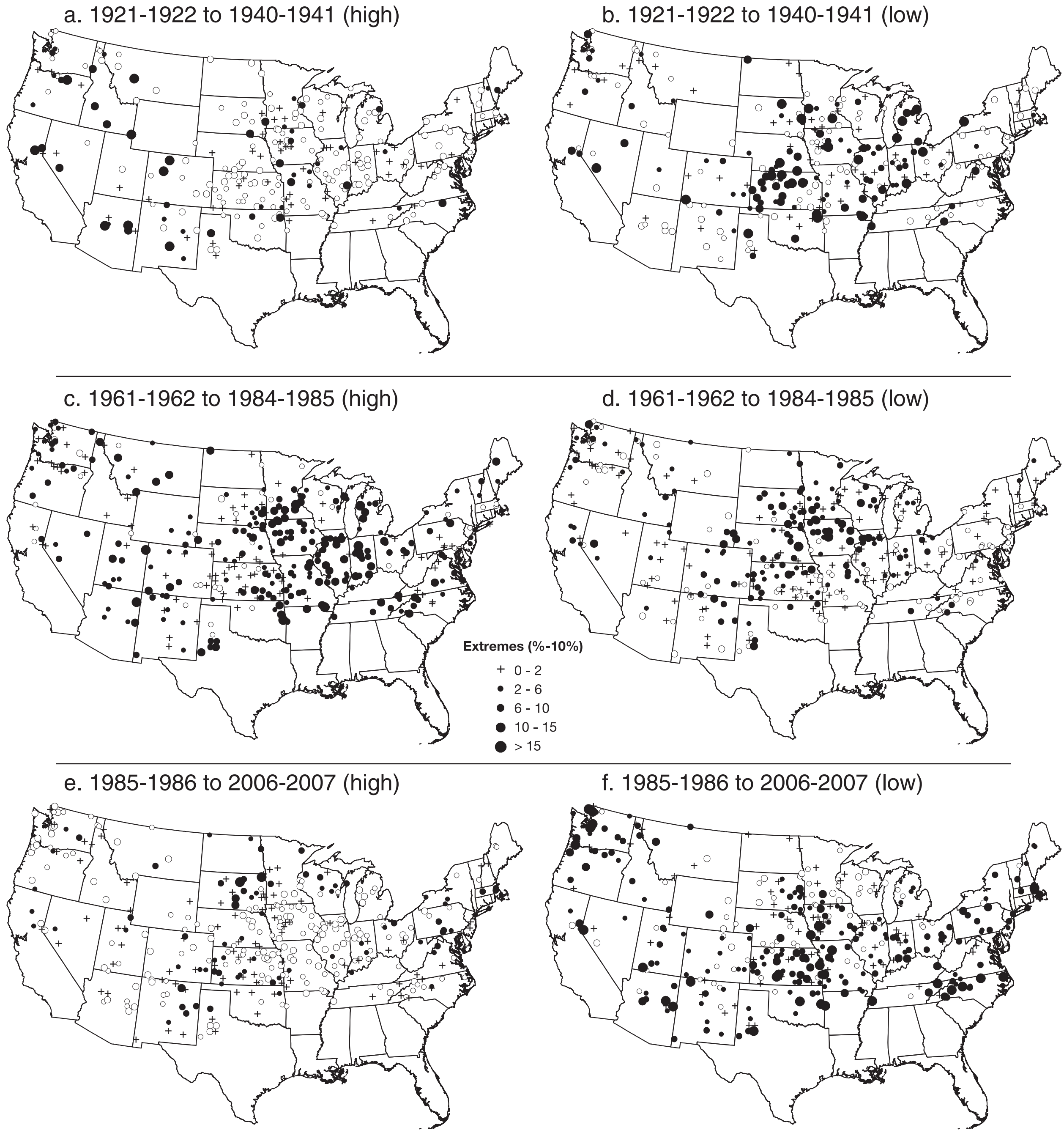

FIG. 3. The percentage deviations from the mean of the frequency of extreme snowfall years by station for (a) high-extreme years during 1921–22 to 1940–41, (b) low-extreme years during 1921–22 to 1940–41, (c) high-extreme years during 1961–62 to 1984–85, (d) low-extreme years during 1961–62 to 1984–85, (e) high-extreme years during 1985–86 to 2006–07, and (d) low-extreme years during 1985–86 to 2006–07. The nominal percentage of 10% was subtracted to calculate the deviation. Open circles indicate negative percentage deviations for the period (below mean), black circles indicate positive percentage deviations for the period (above mean), and the plus signs indicate very small positive and negative deviations.

snowfall over most of the United States (Fig. 3e), while low-extreme snow years were more frequent, especially along the western, southern, and eastern margins of the winter snowpack (Fig. 3f). These areas also experienced downward trends in annual snowfall totals (Kunkel et al. 2009a). At the same time, increases in temperature occurred. Stations from North and South Dakota to northern Michigan, and some stations in the lee of the Rocky

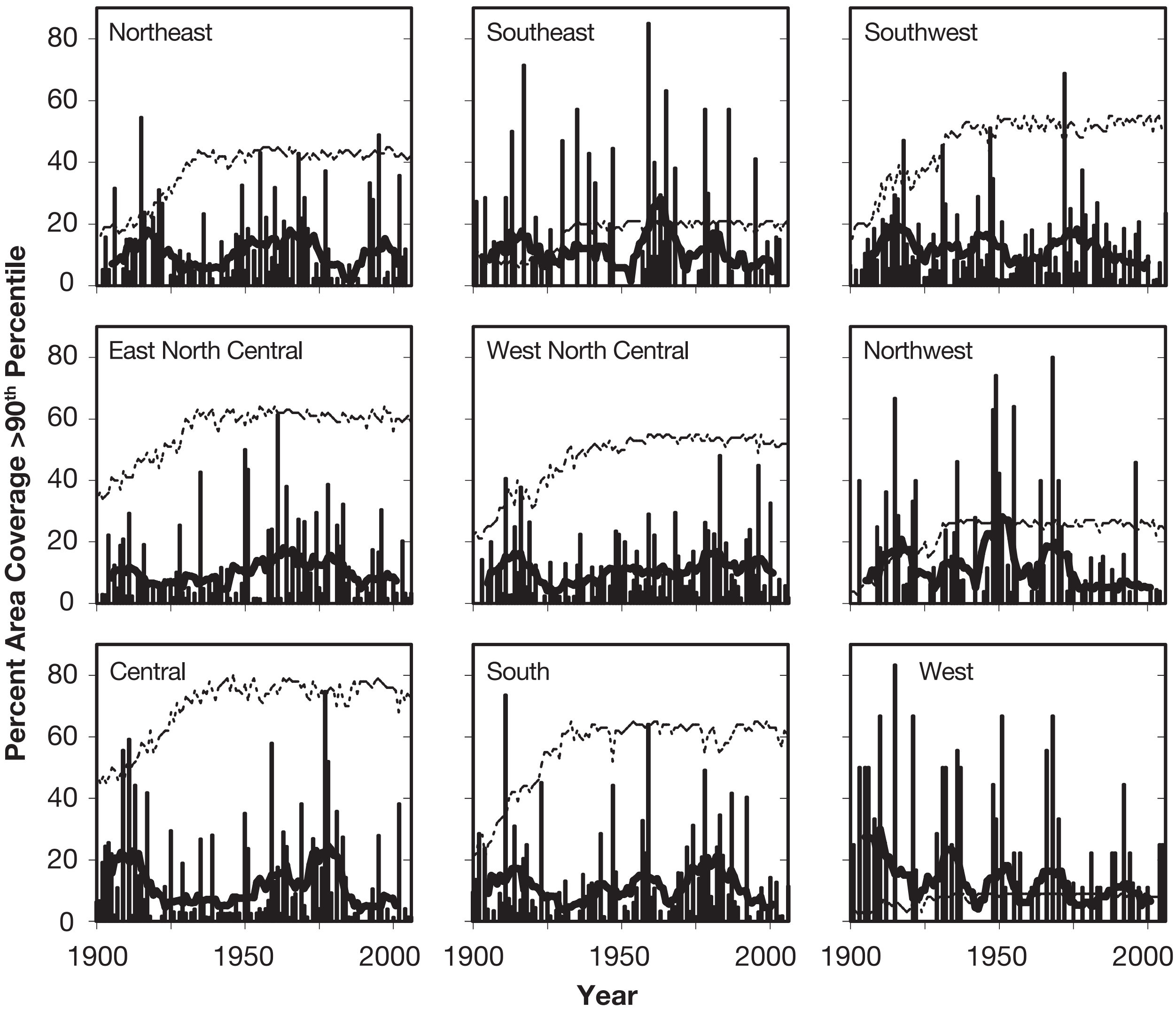

FIG. 4. Regional average annual percentages of homogeneous snowfall stations exceeding the 90th percentile, 1900–01 to 2006–07. The snowfall percentile threshold for each station was calculated using the base period of 1937–38 to 2006–07. The percentage of stations exceeding the threshold for each region is calculated by dividing the number of stations in the region exceeding the threshold by the number of active stations each year. The thick black line is an 11-yr running mean of the percentages, and the dashed line indicates the number of active stations each year.

Mountains, are the only coherent groups that showed frequencies of high-extreme snowfall years that are greater than the mean, and frequencies of low-extreme snowfall years that are less than the mean. These regions also experienced an increase in winter precipitation totals. Northern areas may experience an increase in temperatures while still being cold enough to snow; thus, an increase in precipitation is all that is needed to increase snowfall. In the central United States, this epoch is similar to 1921–22 to 1940–41, with widespread below-normal (above-normal) frequencies of high-extreme (low-extreme) snowfall years. However, these epochs are quite different in the western United States, particularly with widespread high (low) frequencies of high-extreme snowfall years in the earlier (later) epoch.

Some of the stations in the vicinity of the Great Lakes exhibit deviations considerably different than nearby areas (e.g., Figs. 3b,c,e). This may be due to lake-effect snowfall, a local phenomenon that may behave differently than large-scale synoptic forcing of snowfall events. Lake-effect snowfall has been studied separately and these results appear in Kunkel et al. (2009b).

Analyses of changes and variations in snowfall extremes compiled from the nine NCDC climate regions (Fig. 1, Table 1) provide additional regional detail. The nationally averaged low frequencies of high-extreme snowfall during the 1920s–40s period (Fig. 2) are apparent in most of the regional time series (Fig. 4). All six of the eastern and central U.S. regions displayed a lowered frequency of high-extreme snowfall years in the period from 1920 to the 1940s, while all U.S. regions indicated a relative maximum during 1900–20 that was often as high as or higher than during the 1960–80 era (Fig. 4). While all regions except for the east north-central and west north-central have nominal downward trends for high-extreme snowfall years, none of the 1900–01 to 2006–07 trends are statistically significant (Table 2).

The regional time series of low-extreme snowfall year frequency (Fig. 5) show a local peak in the occurrence of low-extreme snowfall years from 1980–81 to 2006–07 in several regions, notably the Northeast, Southeast, South, and the Northwest. By contrast, low-extreme snowfall frequencies are low during the period in the west north-central and east north-central regions. These latter two regions show statistically significant downward trends since 1900; the west, South, Southwest, and central regions do not exhibit statistically significant trends; and the remainder of the regions in the east and west display statistically significant positive trends (Table 2). In the Southwest, South, and central regions, the frequencies of low-extreme snowfall years were about as high in the early records as in the most recent period. Low-extreme snowfall years were also prevalent early in the record in the east north-central and west north-central United States, where a recent reduction in low-extreme snowfall years combined with the early maximum results in statistically significant negative trends from 1900–01 to 2006–07.

The modern half of the time domain from 1950–51 to 2006–07 displays trends that are much more uniform over the United States (Table 2). All regions show negative trends in high-extreme snowfall frequencies. Although these regional trends are significant only in the central and Northwest regions, their consistency results in a marginally significant downward trend in high-extreme snowfall frequencies for the continental United States as a whole at $p < 0.10$. Likewise, 7 of 9 regions display upward trends from 1950–51 to 2006–07 in low-extreme snowfall frequencies, with significant upward trends in the Northeast, Southeast, South, and Northwest. Two northern regions, west north-central and east north-central, show zero and slightly negative trends, respectively. The continental U.S. trend is not significant for this period, although it is upward in agreement with the majority of regional results for the period.

TABLE 2. Trends in extreme high and extreme low snowfall years for the periods 1900–01 to 2006–07 and 1950–51 to 2006–07 sorted by NCDC region. Trends are reported as the change in the percentage frequency $(100\ \mathrm{yr})^{-1}$ using Kendall's estimate of the regression slope. The average percentage frequency during the 1937–38 to 2006–07 climatological base period is 10% in each case. Trends significant at the $p < 0.10$ level are bold, and at $p < 0.05$ are bold and italic.

NCDC region	1900–2006 extremes' trends		1950–2006 extremes' trends	
	High	Low	High	Low
Northeast	−2.2	**12.7**	−15.3	***21.7***
East north-central	0.8	***−14.5***	−5.9	−5.2
Central	−8.4	6.7	***−19.4***	11.4
Southeast	−1.9	***14.9***	−5.8	**16.0**
West north-central	6.1	***−17.1***	−5.1	0.0
South	−2.5	3.7	−5.0	***18.8***
Southwest	−8.9	4.5	−3.5	13.1
Northwest	−5.7	***16.7***	**−18.1**	***21.8***
West	−6.5	9.1	−0.2	12.3
Conterminous United States	−6.7	−2.1	**−16.0**	13.4

b. Relationships of extreme snowfall years to climate factors

Although snowfall is a type of precipitation, the frequency of extreme snowfall years is more closely associated with November–March temperatures than November–March precipitation in most regions of the United States. In all U.S. regions, there is a highly significant ($p < 0.01$) negative (positive) correlation between temperature and high-extreme (low-extreme) snowfall years (Table 3). The amount of temperature-related variance explained fluctuated from only 5% to 25%, but this amount was still more than the variance explained by precipitation in all cases except for high-extreme snowfall year frequency in the west. Local correlations between temperature and extreme snowfall are stronger in the Northeast, Northwest, and west for low-extreme snowfall, and stronger in the other regions for the high-extreme snowfall year (Table 3).

Scatterplots for the Southwest (Figs. 6 and 7), generally representative of the other regions, show relatively high scatter and a somewhat nonlinear nature of the relationship between extreme frequencies and temperature and precipitation. This accounts for the relatively low amount of variance explained by regressions. Multiple regression analysis results in a significant improvement. A stepwise multiple regression relating temperature and precipitation with the Southwest high-extreme snowfall year percentages explains 53% of the variance. Temperature and precipitation together explain 39% of the variance of the Southwest low-extreme snowfall year percentages.

Some climate modes of variability are related to the occurrences of high- and low-extreme snowfall years. El Niño and La Niña events have already been shown to impact total winter snowfall in some U.S. regions

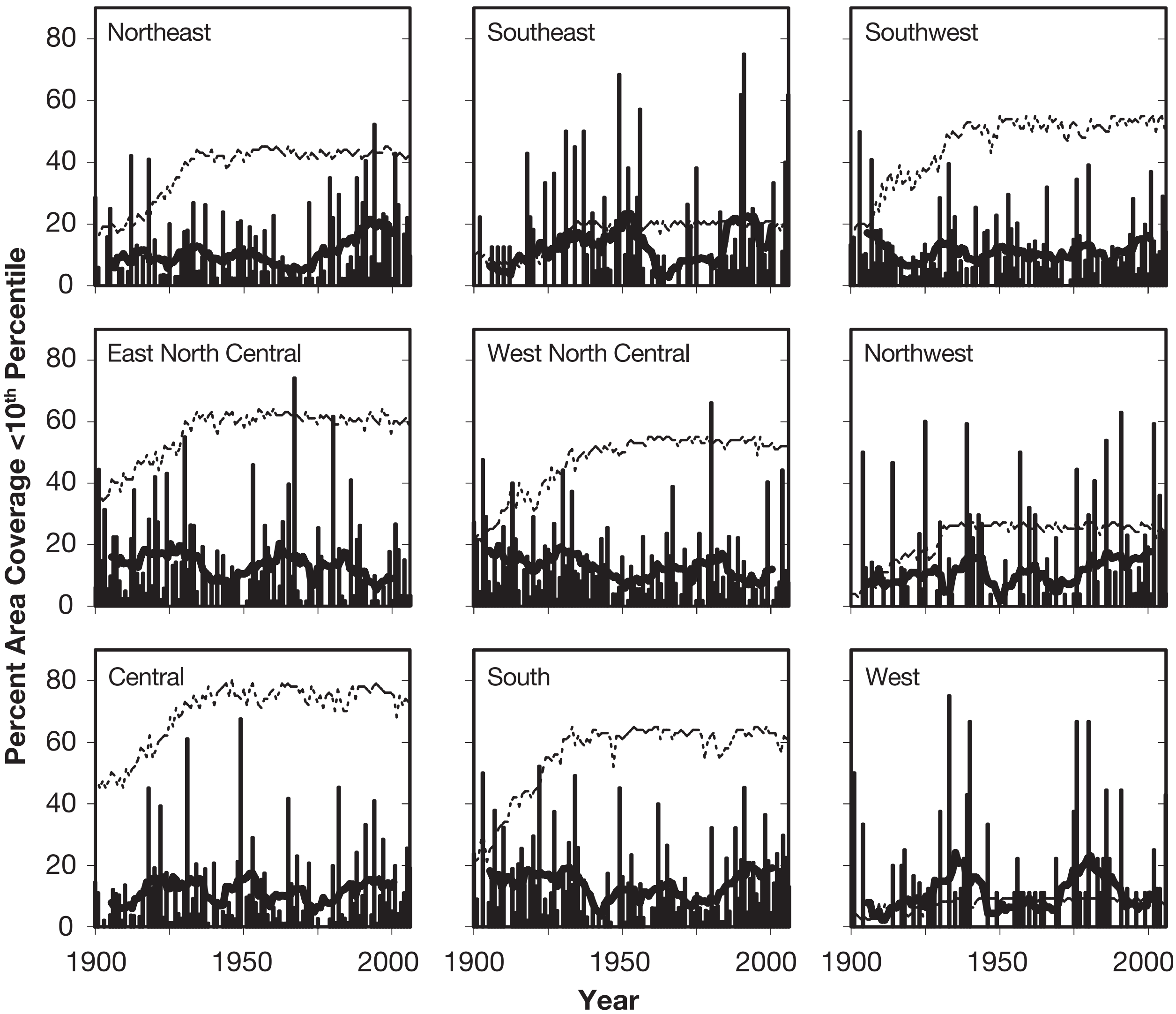

FIG. 5. As in Fig. 6, but the percentages of snowfall stations are below the 10th percentile, 1900–01 to 2006–07.

(Patten et al. 2003; Smith and O'Brien 2001; Kunkel and Angel 1999; Serreze et al. 1998; Redmond and Koch 1991). Based on version 3 of the Extended Reconstructed Sea Surface Temperature (ERSSTv.3; Smith and Reynolds 2004) for the Niño-3.4 region, 6 El Niño and 13 La Niña events have reached an oceanic Niño index (ONI) absolute magnitude of 1.5 or larger for December–January–February during 1900–2007. These years are marked in Fig. 2, and represent the strongest events during the study period. The U.S. and regional high- and low-extreme snowfall percentages were averaged for each type of event, and simple *t* tests were performed to see if the resulting averages were significantly different from the nominal 10% expected given the definition for extreme snowfall years (below the 10th percentile or above the 90th percentile).

Strong El Niño events are associated with increased percentages of stations with low-extreme snowfall years in several regions, and in the United States as a whole (Table 4). This is quite evident from a visual inspection of Fig. 2b where all 6 El Niño events show low-extreme percentages above 10%. The U.S. result is significant at $p < 0.05$, and three individual regions are significantly above normal in low-extreme years: the Northeast ($p < 0.10$), central ($p < 0.05$), and Northwest ($p < 0.05$) regions. Only in the Southwest is the low-frequency percentage well below normal, at a significance level of $p < 0.01$. The Northwest and central regions have far smaller high-extreme percentages during El Niño, significant at $p < 0.01$. These relationships are consistent with the observed pattern in El Niño years of generally warmer and drier-than-normal conditions over much of the northern

TABLE 3. Kendall correlations between high-extreme and low-extreme snowfall frequency time series and November–March temperature and precipitation anomalies in the same NCDC regions, 1900–01 to 2006–07. Correlations significant at the $p < 0.05$ level are bold, and at $p < 0.01$ are bold and italicized.

	Temperature vs snowfall extremes		Precipitation vs snowfall extremes	
NCDC region	High	Low	High	Low
Northeast	***−0.23***	***0.24***	**0.14**	−0.03
East north-central	***−0.35***	***0.32***	***0.28***	***−0.27***
Central	***−0.48***	***0.44***	−0.04	0.02
Southeast	***−0.36***	***0.35***	**0.18**	−0.10
West north-central	***−0.44***	***0.33***	***0.37***	***−0.24***
South	***−0.46***	***0.42***	***0.24***	***−0.19***
Southwest	***−0.49***	***0.39***	***0.34***	***−0.32***
Northwest	***−0.43***	***0.45***	***0.19***	***−0.20***
West	***−0.26***	***0.30***	***0.29***	***−0.18***

half of the United States and cooler and wetter-than-normal conditions over the southern half, although the small number and nonuniform coverage of stations in the west make it difficult to evaluate the consistency in that region.

Strong La Niña events did not have an overall impact on the national high and low snowfall extremes percentages, but some regions did have a strong response (Table 4). In the Northwest, low-extreme snowfall years were significantly ($p < 0.05$) less common than normal during La Niña events, and in the South, significantly more common ($p < 0.10$). The South and Southeast regions display statistically significant low percentages of high-extreme snowfall and the South also shows high percentages of low-extreme snowfall. The two southern regions with declines in high-extreme snowfall percentages and increases in low-extreme snowfall percentages all received significantly less precipitation than normal ($p < 0.01$) during La Niña events, and the South was also significantly warmer than normal.

Significant relationships between El Niño and La Niña and extreme snowfall events in some U.S. regions may explain some portion of the trends observed. There was an increase in the frequency of strong El Niño events relative to strong La Niña events between the first half of the twentieth century and the more recent epoch, with the ratio changing from 1/8 to 5/5. In addition, there were also many more weak-to-moderate La Niña winters during 1900–50 than during 1951–2006. Changes in the frequency of these major climate anomalies could be an important component of the total trends in the frequency of high- and low-extreme snowfall years, as these effects may add to or subtract from the effects of regional trends in temperature and precipitation that are being caused by other factors, including human-induced

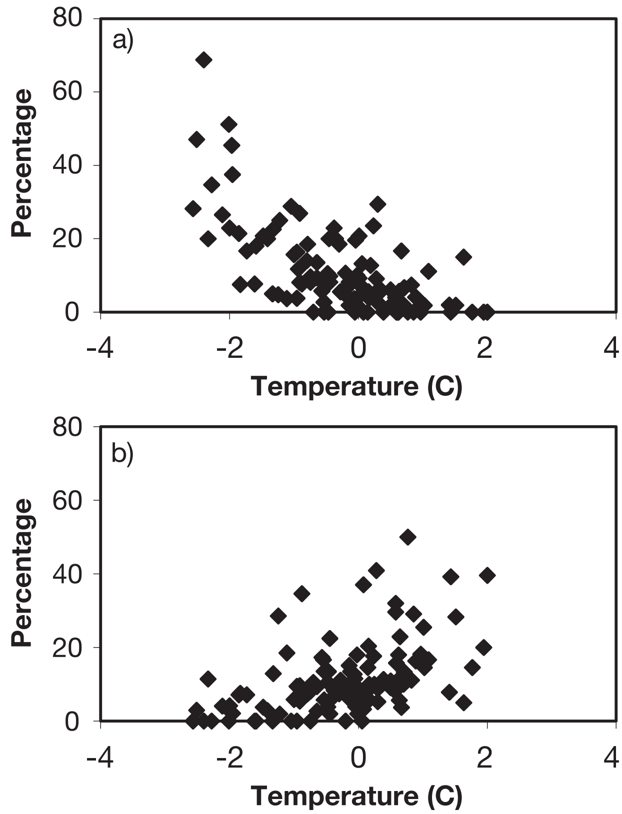

FIG. 6. (a) The annual high-extreme snowfall percentage for the Southwest is plotted against the November–March temperature anomaly for the same region. (b) The annual low-extreme snowfall percentage for the Southwest is plotted against the November–March temperature anomaly for the same region.

climate change. For example, there are upward trends in the frequency of low-extreme snowfall years in the Northwest and Northeast (Table 2), regions where there are statistically significant positive relationships between low-extreme snowfall and El Niño occurrence (Table 4).

Since the smoothed snowfall extreme time series show considerable decadal-scale variability, the question arises whether these are related to climate modes that vary on similar time scales. Two such modes are the Atlantic multidecadal oscillation (AMO) and the Pacific decadal oscillation (PDO). Relationships of extreme snowfall to the AMO and PDO were examined. [PDO data were obtained from the University of Washington (http://jisao.washington.edu/pdo/PDO.latest; Zhang et al. 1997; Mantua et al. 1997). AMO data were obtained from the NOAA Climate Diagnostic Center (http://www.cdc.noaa.gov/data/climateindices/List/; Enfield et al. 2001).] Since there is considerable year-to-year persistence in the AMO and PDO and in the smoothed snowfall extreme time series, the number of statistically independent samples

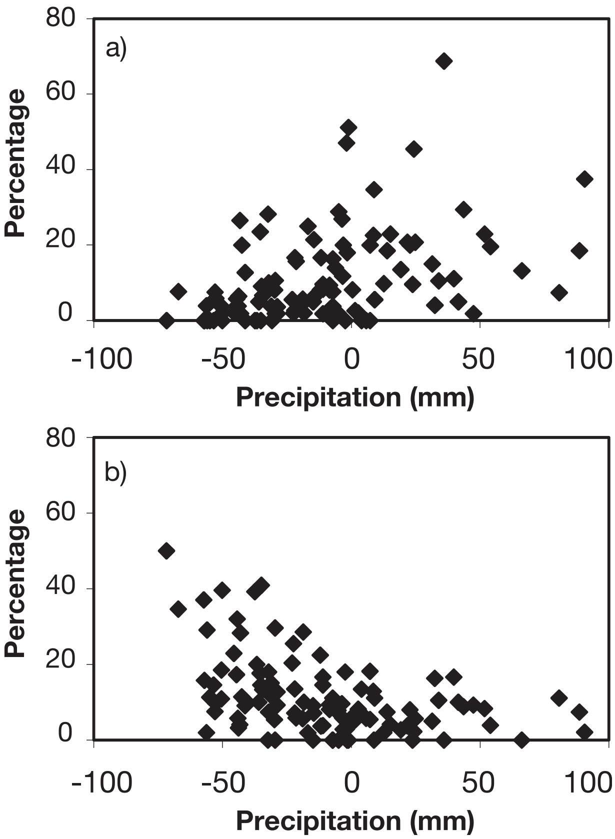

FIG. 7. (a) The annual high-extreme snowfall percentage for the Southwest is plotted against the November–March precipitation anomaly for the same region. (b) The annual low-extreme snowfall percentage for the Southwest is plotted against the November–March precipitation anomaly for the same region.

TABLE 4. U.S. and regional high- and low-extreme snowfall percentages for moderate to strong winter El Niño (ONI $> +1.5$) and La Niña (ONI < -1.5) events from 1900–01 to 2006–07. The average percentage during the 1937–38 to 2006–07 climatological base period is 10% in each case. U.S. and regional event percentages that are significantly different from 10% at the $p < 0.10$ level are bold, at $p < 0.05$ are bold and underlined, and at $p < 0.01$ are bold and italicized.

	El Niño and snowfall extremes		La Niña and snowfall extremes	
NCDC region	High	Low	High	Low
Northeast	4.1	**24.3**	7.7	11.5
East north-central	8.3	11.6	7.6	12.3
Central	***0.7***	***27.8***	8.4	13.6
Southeast	6.0	25.9	***2.1***	17.4
West north-central	6.6	14.3	9.1	12.9
South	17.4	12.9	***2.3***	**17.9**
Southwest	22.3	***3.5***	6.5	14.2
Northwest	***0.0***	**33.3**	14.5	**4.3**
West	7.6	20.4	10.0	12.1
Conterminous United States	8.3	**17.8**	7.8	12.9

is reduced. This reduction was accounted for in the statistical tests following Santer et al. (2008). A statistically significant inverse relationship ($p < 0.05$) was found between the AMO and the smoothed (11-yr moving average) time series of U.S. high-extreme snowfall ($r = -0.43$). A statistically significant relationship ($p < 0.01$) was also found between the PDO and low-extreme snowfall ($r = -0.35$) smoothed time series. Statistically significant relationships were not found between the AMO and low-extreme snowfall and the PDO and high-extreme snowfall.

4. Summary and conclusions

The 1900–01 to 2006–07 trends in the annual percentage of high- and low-extreme snowfall years for the entire United States are not statistically significant. This is also the case for regional trends in high-extreme snowfall years. However, several regions exhibited statistically significant trends in low-extreme snowfall years, including downward trends in the east north-central and west north-central regions and upward trends in the Southeast, Northeast, and Northwest. More recent trends from 1950–51 to 2006–07 display far more consistent tendencies toward reductions in high-extreme snowfall years (central and Northwest regions significantly decreasing) and increases in low-extreme snowfall years (Northeast, Southeast, South, and Northwest significantly increasing). The U.S. high-extreme snowfall frequency is trending downward at a $p < 0.10$ significance level.

In all nine U.S. regions, November–March temperatures were highly significantly correlated ($p < 0.01$) with both high-extreme and low-extreme snowfall annual percentages, negatively with high-extreme snowfall, and positively with low-extreme snowfall. While regional November–March precipitation was also highly significantly correlated with extreme snowfall annual percentages in many cases, only in the western region did precipitation explain more variance than temperature, and only for the high-extreme snowfall annual percentage. It is apparent that air temperature is the key to the occurrence frequency of both types of extreme snowfall seasons, and that precipitation anomalies contribute more to the explanation of high-extreme snowfall seasons than to low-extreme snowfall seasons. In other words, high-extreme snowfall seasons are favored when it is both cold and wet, while low-extreme snowfall seasons can be either wet or dry, as long as it is warmer than normal in the wet case.

The regression analysis of high- and low-extreme snowfall percentages also reveals that other synoptic factors explain a proportion of the variance. Recent findings indicate that El Niño and La Niña events can increase the probability of high- and low-percentile snowfall totals in various regions (Schubert et al. 2008; Smith and O'Brien 2001). The Northeast, central, west north-central, and Northwest regions, and the United States as a whole displayed a statistically significant better-than-normal chance for low-extreme snowfall totals during El Niño. This is probably associated with the nearly ubiquitous warming that often accompanies El Niño over much of the snowier areas of the United States. High-snowfall extremes are significantly less likely to occur in the Northwest and central United States during El Niño. La Niña influences on snowfall extremes were somewhat weaker, with no nationally significant signal. The Southeast and South had significantly below-normal occurrences of high snowfall extremes during La Niña, while the South alone had an increased chance of low snowfall extremes, and the Northwest had a decreased chance of low snowfall extremes. Changes in the relative frequencies of El Niño and La Niña events could have had an important influence on the trends in high- and low-extreme snowfall percentages seen in some regions.

Given the sensitivity of extreme snowfall seasons to temperature, and the signs of recent trends observed since 1950, it is likely that the increasing frequency of low-extreme snowfall years and decreasing frequency of high-extreme snowfall years are at least partially a consequence of the general warming that has occurred over that time period.

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