5.2 VARIABILITY AND TRENDS IN UNITED STATES SNOWFALL OVER THE LAST HALF CENTURY

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1. INTRODUCTION

Several recent studies have reported that large portions of the mid- and high-latitude land areas of the Northern Hemisphere (including much of the United States) have experienced increasing precipitation over the last half of the 20th century (e.g., Karl et al., 1993, 1998; Groisman et al. 1993). However, while global and regional changes in overall precipitation have received much attention, IPCC (2001) points out that relatively few studies of snowfall trends across the globe have been undertaken. Scott and Kaiser (2003) conducted a study of snowfall trends across the forty-eight contiguous United States for roughly the last half of the 20th century. Using daily data from the U.S. Historical Climatology Network (USHCN; Easterling et al., 1999), they found decreases in snow days and snowfall over several regions of the country (Figs. 1 and 2), with the largest decreases over the Pacific Northwest (PNW)—mainly over the Washington, Oregon, and Idaho (WOI) area. Coincident with these changes, a significantly smaller percentage of total precipitation over the WOI area has been due to snowfall events. These changes are consistent with a recent analysis by Mote (2003) which showed large declines in snow water equivalent (SWE) over the PNW, especially at locations below 1800 m, where both total precipitation and temperature have increased.

Kaiser and Scott (2003) also found fewer snow days over an area from roughly Kansas eastward through New Jersey, but more snow days at stations in a swath extending from roughly Colorado northeastward to Minnesota, and also to the lee of Lake Ontario (Fig. 1).

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Changes in snowfall (Fig. 2) were not always consistent with changes in the number of snow days over these areas, although an area centered roughly over Ohio shows decreases in both variables and an area to the lee of Lake Ontario shows increases in both. The changes downwind of Lake Ontario are consistent with the findings of Leathers and Ellis (1996) and the recent work of Burnett et al. (2003) which showed large century-scale increases in snowfall at "lake-effect" stations east of Lake Ontario, but no significant changes at close-by "non-lake-effect" sites.

In this paper we will continue our examination of snowfall trends over the "lower forty-eight" by analyzing additional variables such as average first and last day of snowfall, average length of entire snow season, temperature throughout the snow season, and number of snow days occurring within specific snowfall event size percentiles.

2. DATA

As in Scott and Kaiser (2003), the data used in this analysis were the USHCN data from Easterling et al. (1999), which contains daily data from 1871–1997. We extended these records through 2001 via personal communication with colleagues at the National Climatic Data Center (NCDC). This database includes daily observations of maximum/minimum temperature, precipitation amount, snowfall amount, and snow depth from 1062 sites that are mainly NOAA cooperative observer stations.

3. ANALYSIS PROCEDURE

USHCN stations used in this analysis were chosen based on their location and quality of record. Since we were analyzing snowfall events, we only chose stations that could be expected to have a good chance of receiving *some* snowfall in most winters and thus only examined stations north of 35°N latitude. [We realize that south of 35°N in the Southwestern United States there are many regions that receive large winter snowfalls, but we chose to keep the analysis region simply defined.] A large percentage of the stations in the USHCN only have digitized records since 1948; thus, to maximize the number of potentially usable stations we only examined stations' completeness of record from 1948–2001. Examining these 54 years of data led to decisions that were based on weighing the total number of stations available (maximum geographical coverage) versus the completeness of each station's snowfall record. We arrived at a compromise that required stations to have no more than 4 years with any missing snowfall observations, which in turn led to 217 stations being retained for analysis. If a station did have any missing observations for up to the maximum of four years, any years with missing data were left out of the analysis completely. Since we planned on looking at trends over the period 1948–2001, we preferred to get rid of partial years, so as to minimize bias from individual years with missing data and still retain the vast majority of the record.

For most of the snowfall parameters we chose to examine at this point in our research, it was appropriate to choose a "snowfall season" rather than draw from an entire calendar year of observations. This snow season ideally should encompass any months that would have some chance of snow based on climatology. We eventually chose the months October–May. While low-latitude, low-elevation stations would not be expected to see snow near the beginning or end of this season, more northerly, or high-elevation stations certainly often do (e.g., the significant snowfall events across the northern Rocky Mountain and Northern Plains states in May of 2002). Our choice of snow season resulted in our period of study extending from the "winters" of 1948/49 to 2000/2001, or 53 seasons.

4. RESULTS AND CONCLUSIONS

Figure 1 depicts trends in snow days [defined as a day with at least a trace (0.1") of snow] over the 53 winters from 1948/49 to 2000/2001 (days per decade). This figure was already presented in Scott and Kaiser (2003), but is shown here to provide background information. As in all similar maps we will show, blue station symbols indicate decreasing trends and red symbols indicate increasing trends. Significance at the 95% confidence level is indicated by a circle around a station symbol. Again, one of the most obvious changes depicted in this figure is the decreasing number of snow days observed in the Pacific Northwest (PNW)—mainly over the Washington, Oregon, and Idaho (WOI) area. Figure 2 shows trends in snowfall for 1948/49–2000/2001, expressed as a percent of "normal" (average) snowfall over the entire period of record. A similar depiction of snowfall trends was shown in Scott and Kaiser (2003), which expressed trends in inches of snowfall; we have changed the units to percent of normal in Fig. 2 so we may better compare the nature of changes over the entire country, since different stations will often have greatly different mean snowfall, even in the case of stations that are close to one another (e.g., due to elevation differences and location with respect to the Great Lakes). Similar to the decrease in snow days indicated for the PNW in Fig. 1, we see in Fig. 2 generally decreasing trends in snowfall amount for this region. The changes are quite large, in many cases exceeding a 60% decrease over the period of record.

The remainder of the country shows less evidence of cohesive regional trends; although, like the snow day trends seen in Fig. 1, a narrow swath of increased snowfall may have occurred from roughly Colorado northeastward to Minnesota, and for this variable actually farther eastward into Wisconsin. There is also evidence of increased snowfall in the lee of Lakes Ontario and Erie [as found in Leathers and Ellis (1996) and Burnett et al. (2003)]. A dense pocket of stations over Ohio shows decreasing snowfall trends; this same area has experienced fewer snow days (Fig. 1).

Figure 3 shows many U.S. stations with significant trends in the average date of the first snowfall of the season. For the PNW, unlike the other variables already examined for this region, there is not a homogeneous signal. However, for much of the region extending from the northern Rockies, across the northern plains, to the upper Midwest, there is evidence of the first snowfall arriving earlier, for some stations on the order of four days per decade (about 20 days earlier over the period of record). For a region extending from the mid-Mississippi Valley eastward—essentially the entire northeastern corner of the country—the trend is just the opposite: the first snowfall is arriving later at many stations; in some cases about four days later per decade.

As for trends in the average date of the last snowfall, Fig. 4 shows that earlier last snowfalls are quite common; mainly over the PNW and from the mid-Mississippi Valley eastward across the Ohio Valley. For the latter region, trends in the average date, while significant, are not as great, typically being earlier by three days or less per decade.

Given the results shown in Figs. 3 and 4, trends in the length of the snowfall season (the number of days between the first and last snow), as depicted in Fig. 5, are not surprising.

The PNW snowfall season has become shorter (for several stations at the rate of six days per decade), as has the snowfall season for a large region stretching from eastern Kansas, across the Ohio Valley, and into the northeastern states. For parts of the Rockies and the northern plains, however, the snow season has lengthened, at many seasons on the order of four to six days per decade. Additionally, it is interesting to note that there is evidence for a longer snowfall season in the lee of Lake Ontario, presumably caused by a longer lake effect snow season (consistent with Burnett et al., 2003).

We also examined mean temperature at our snowfall stations. Figure 6 shows quite a defined warming/cooling pattern for the October–May snow season. Significant warming has been observed from the PNW all the way to the northern and central plains, and into parts of the upper Midwest. While this change is consistent with less snowfall and fewer snow days in the PNW, the snowfall/temperature regime over parts of the Rockies and northern plains states looks to be more complicated, as Figs. 1 and 2 show more frequent and greater snowfall for many stations across this area. Parts of the mid-Mississippi and Ohio Valley have cooled for the October–May timeframe, but again, the snowfall season in this area has become shorter (Fig. 5).

Since the PNW is the area that shows the strongest trends (decreasing) in snow days and snowfall, we decided to start to explore how these changes may relate to the intensity of snowfall events. Figure 7 shows trends in the number of snow days within ten-percentile snowfall event size bins for the WOI region. It's very evident that the period of record has seen decreasing trends in the number of heavier snowfall events per snowfall season (greatest decrease for events above the 90th percentile).

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Leathers, D. J., and A. W. Ellis, 1996: Synoptic mechanisms associated with snowfall increases to the lee of Lakes Erie and Ontario. *Int. J. Climatol*., **16**, 1117–1135.

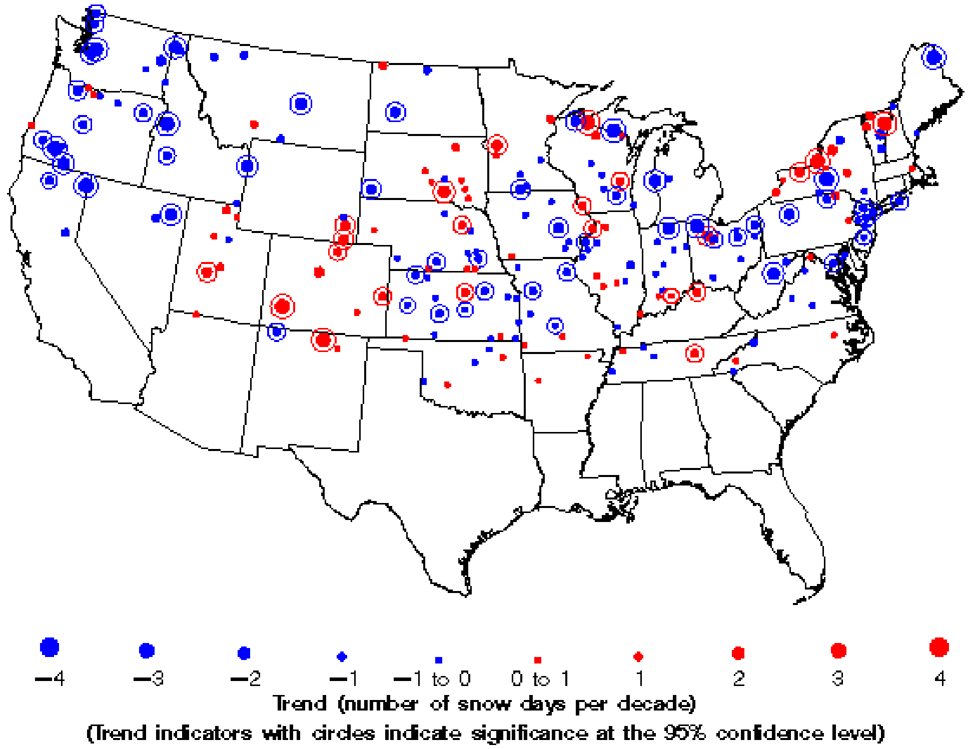

Figure 1. Trends in the number of October–May snow days, 1948/49–2000/01.

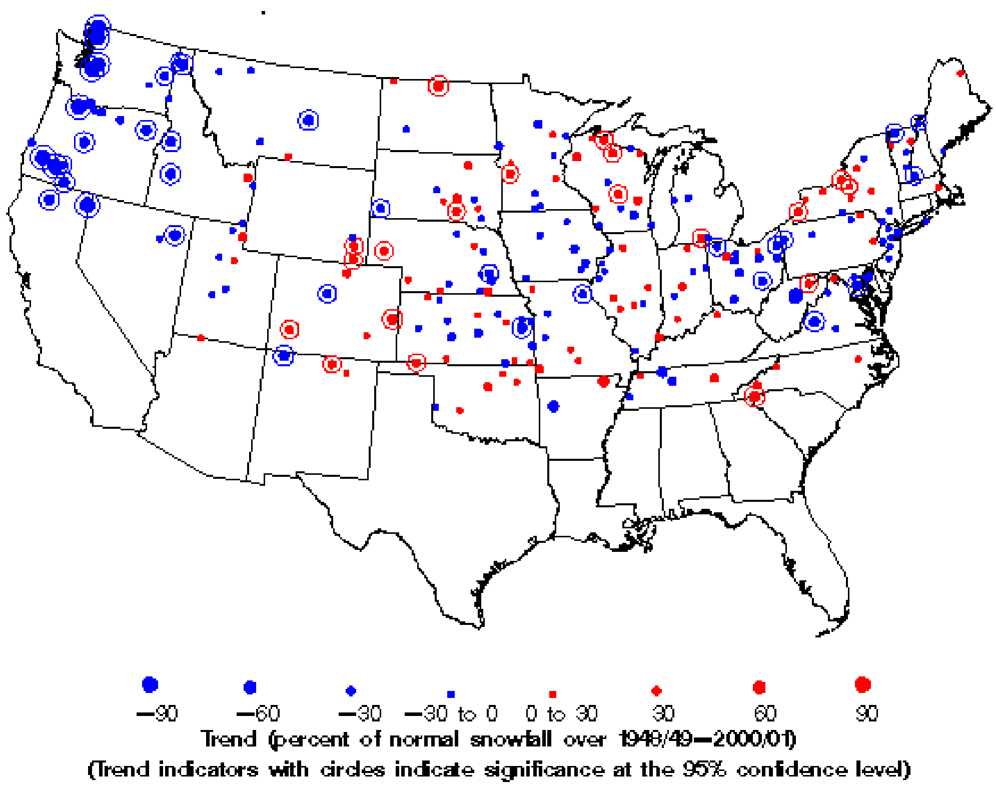

Figure 2. Trends in October–May snowfall (percent of normal), 1948/49–2000/01.

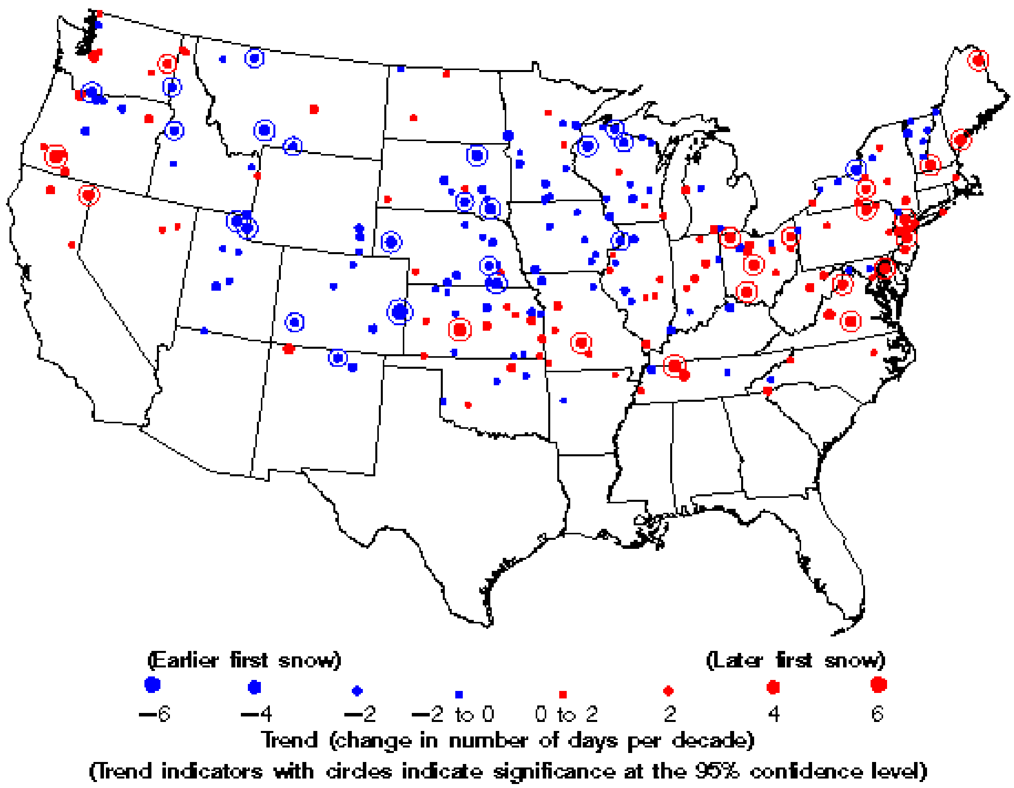

Figure 3. **Trends in the first day of the snowfall season (Oct–May), in days per decade 1948–2001.**

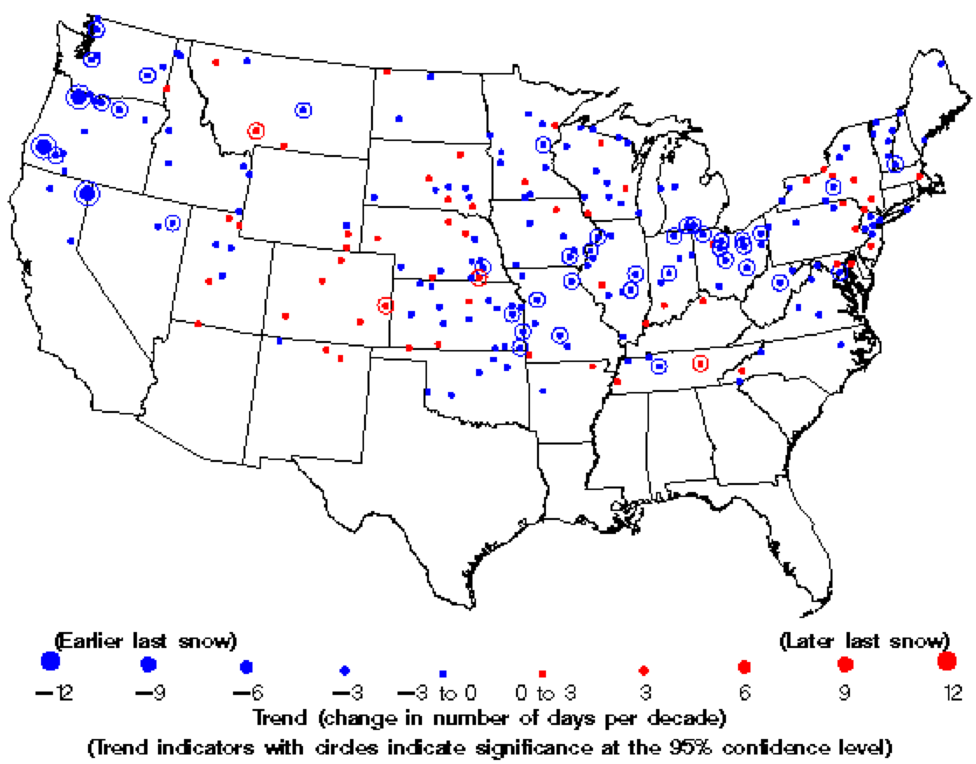

Figure 4. **Trends in the last day of the snowfall season (Oct–May), in days per decade, 1948/49–2000/01.**

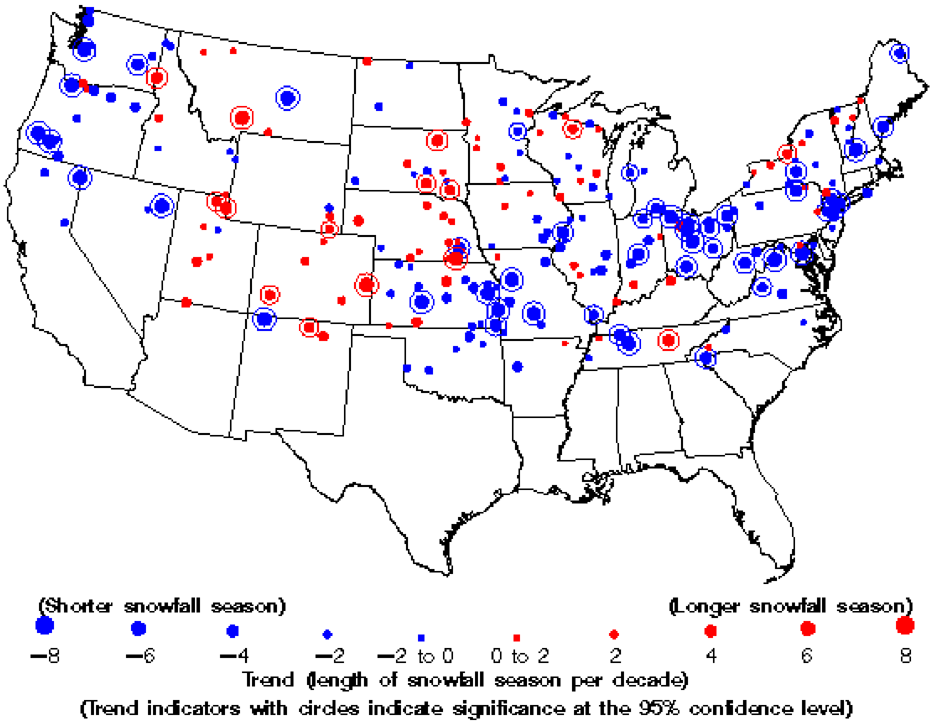

Figure 5. Trends in the length of the snowfall season (Oct–May), in days per decade, 1948/49–2000/01.

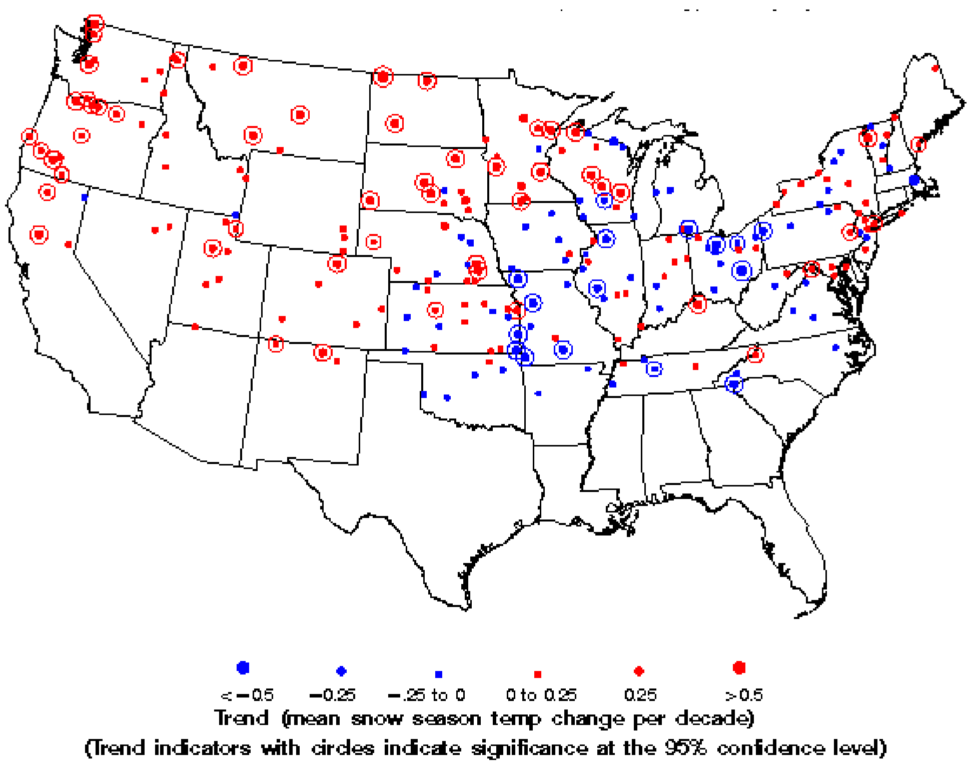

Figure 6. Trends in the mean temperature of the snowfall season (Oct–May), in °C per decade, 1948/49–2000/01.

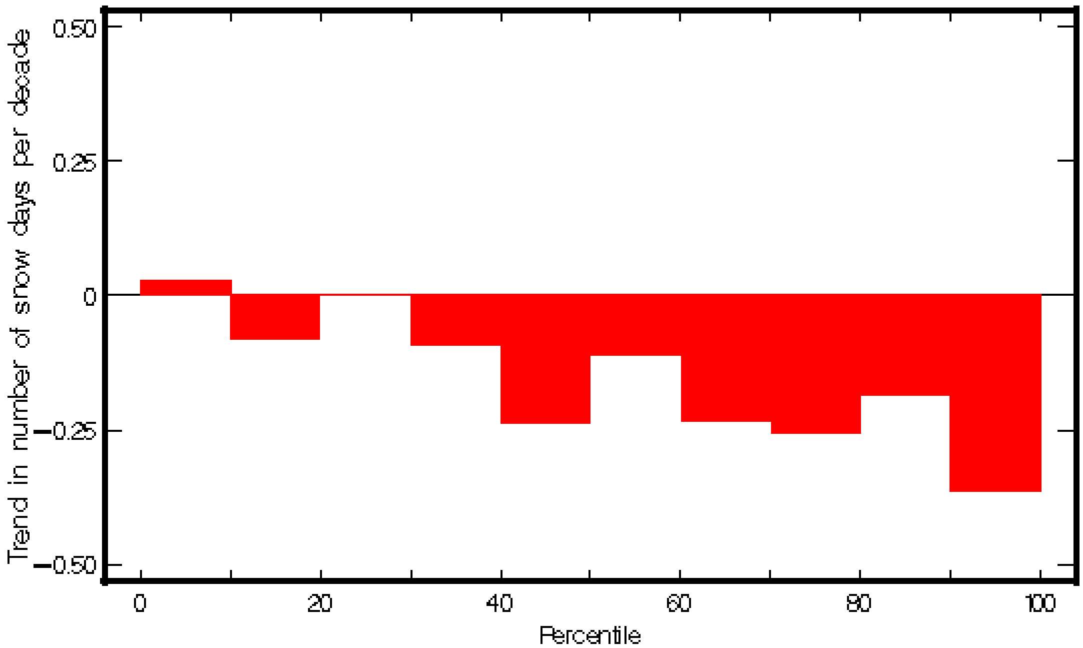

Figure 7. Trends in the number of snow days per decade within ten-percentile event size bins for the Washington, Oregon, and Idaho region, 1948/49–2000/01.