8.1 CHANGES IN CHARACTERISTICS OF UNITED STATES SNOWFALL OVER THE LAST HALF OF THE TWENTIETH CENTURY

Daria Scott
Dept. of Earth and Atmospheric Sciences
St. Could State University, St. Cloud, MN

Dale Kaiser*
Carbon Dioxide Information Analysis Center
Oak Ridge National Laboratory, Oak Ridge, TN

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). In regions of the United States experiencing increased precipitation there has also been an increase in the number of “extreme” precipitation events, defined as daily amounts greater then 50.8 mm (2 inches) of liquid precipitation (Karl et al., 1998). Interestingly, along with these significant changes, recent research has found that Northern Hemisphere annual snow-cover extent (SCE) has decreased by about 10% since 1966 (IPCC, 2001), mainly resulting from spring and summer decreases since the mid-1980s over Eurasia and North America (Robinson, 1997, 1999), with winter and summer SCE showing no statistically significant change. Add to all this the most well-known evidence of recent climate change—a global average warming of near-surface air temperature of about 0.6°C since the late 19th century (IPCC, 2001)—and we have an interesting climate picture indeed, involving extremely complex interactions between the various components of the global climate system.

Given the plethora of interesting and important climate questions being currently studied, we sought in this paper to examine a climate variable related to all those referred to above that has been studied relatively little by comparison: that of trends in snowfall.

IPCC (2001) points out that relatively few studies of snowfall trends across the globe have been undertaken. We decided to focus our study on the United States snowfall record at this point, as we had ready access to high-quality data that will be described in the next section.

There have of course been some studies of U.S. snowfall conducted in recent years. Some of the main findings include: an increase in inter-annual variability in nationally averaged snowfall over the 1970s and 1980s (Karl et al., 1993); increases in snowfall in the central United States over the 20th century (Hughes and Robinson, 1996); and, in recent decades, heavier snowfall to the lee of the Great Lakes than earlier in the 20th century (Leathers and Ellis, 1996). Here we seek to expand on these earlier findings by examining some additional snowfall variables and using the latest snowfall data available.

2. DATA

The data used in this analysis were obtained from Easterling et al. (1999), which contains daily data from stations in the United States Historical Climatology Network (USHCN) covering the period 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

---

*Corresponding author address: Dale Kaiser, CDIAC, Oak Ridge Nat. Lab., Oak Ridge, TN 37831-6335; e-mail: kaiserdp@ornl.gov.

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 had to be made that weighed 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, that 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. At this point in our work we chose to examine the following variables: (1) the number of days with measurable snow [exceeding a trace (0.1")], hereafter referred to as "snow days"; (2) snowfall; and, (3) the percentage of annual precipitation resulting from the liquid water content of snowfall. For this third variable, we actually used entire calendar years from 1948–2001. Calculating this percentage value was made possible by also extracting daily total precipitation values (total liquid equivalent, i.e., rainfall plus liquid from any melted snowfall) from the database. Trends in all variables were calculated over the period of record for each station, with significance being specified by the 95% confidence level.

4. RESULTS AND CONCLUSIONS

Figure 1 depicts trends in snow days over the 53 winters from 1948/49 to 2000/2001. 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. Perhaps the most obvious evidence of change 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. Trends of −3 to −4 snow days per decade are quite common in this region, which would imply a decrease in the number of snow days per winter of approximately 15 to 20 over roughly the last 50 years. Trends over the rest of the country show a more mixed signal, but a few observations worth noting are: (1) more snow days at stations in a swath extending from roughly Colorado northeastward to Minnesota; (2) generally fewer snow days over an area from roughly Kansas eastward through New Jersey; and, (3) more snow days observed in the lee of Lake Ontario in northern New York, extending into northern Vermont.

Figure 2 shows trends in snowfall over the period of record. Similar to the decrease in snow days indicated for PNW in Fig. 1, we see generally decreasing trends in snowfall amount for this region. Typical trend values range from –3 to –9 in. per decade or about –15 to –45 in. over the full period of record. The rest of the country shows less evidence of any 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 evidence of increased snowfall in the lee of Lake Ontario (similar to the increasing snow day trends seen there in Fig. 1). This small area of increasing snowfall is consistent with the findings of Leathers and Ellis (1996).

Trends in the percentage of annual precipitation resulting from the liquid water content of snowfall are shown in Fig. 3. Given our findings for trends in snow days and snowfall, the trends picture that is evident in the PNW is not surprising. A contiguous area of trends on the order of –2 to −3% per decade is observed (roughly –10 to –15 % over the entire period of record). Given the decreasing snowfall observed in this region, a lower (higher) fraction of annual precipitation is resulting from frozen (liquid) precipitation. This finding is consistent with an interesting phenomenon recently described by Easterling (2002). He found that the annual number of frost days (defined as a day when the temperature dropped below 0°C) decreased by 2.6 days per decade (the trend is significant at the 99% confidence level) from 1948–1999 over the WOI region, and that the change in the frost-free portion of the year has increased by 4.1 days per decade (an increase of about 20 days in 50 years) over this same region. These changes would imply fewer days with temperatures cold enough to support snow and thus conditions that would favor more liquid precipitation events.

Figure 3 shows two smaller and less well-defined areas of the country where the liquid from snowfall is making up a significantly smaller percentage of annual precipitation: parts of the central Great Plains states and portions of the southern Great Lakes states. The trends in Fig. 3 indicate that in no area of the country is there a significant increase in the amount of annual precipitation resulting from snowfall.

Since the major area of significant change in the snowfall variables we have examined lies in the PNW, we constructed time series (in terms of departures from the mean of each variable) for snow days (Fig. 4), snowfall (Fig. 5.), and percentage of annual precipitation resulting from the liquid water content of snowfall (Fig. 6) over the WOI region. The trends in the average number of snow days each winter (Fig. 4) and snowfall each winter (Fig. 5) over the WOI region from 1948/99–2000/01 are approximately –9 days, and −35 in., respectively. The proportion of total annual precipitation derived from snowfall over the WOI region has decreased by about 7% from 1948 to 2001, as seen in Fig. 6. The trends in the time series of all three snowfall variables depicted in Figs. 4–6 are significant at the 99% level.

5. FUTURE RESEARCH

Additional research we are planning will include obtaining many more records of U.S. cooperative observing stations from NCDC. This will provide much more dense data coverage, and it will be interesting to see if the general pattern and magnitude of the trends shown here will significantly change upon inclusion of more stations. We will also incorporate analysis of daily maximum and minimum temperatures at each station to further investigate the possible link between regional temperature change and the various changes in the snowfall regime we have begun to observe.

Acknowledgments: We thank Bob Cushman for comments and suggestions to improve this manuscript. This research is sponsored by the U.S. Department of Energy's Office of Science Biological and Environmental Research Program and was performed at Oak Ridge National Laboratory (ORNL). ORNL is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725.

REFERENCES

Easterling, D. R., 2002: Recent changes in frost days and the frost-free season in the United States. *Bull. Amer. Meteor. Soc.*, **83**, 1327–1332.

Easterling, D. R., T. R. Karl, J. H. Lawrimore, and S. A. Del Greco, 1999: *United States Historical Climatology Network Daily Temperature, Precipitation, and Snow Data for 1871–1997*. ORNL/CDIAC-118, NDP-070. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee. 82 pp.

Groisman, P.Ya, and D. R. Easterling, 1993: Variability and trends of total precipitation and snowfall over the United States and Canada. *J. of Climate*, **7**, 184–205.

Hughes, M. G., and Robinson, D. A., 1996: Historical snow cover variability in the great plains region of the USA: 1910 through to 1993. *Int. J. Climatol.*, **16**, 1005–1018.

IPCC, 2001: *Climate Change 2001: The Scientific Basis.* Cambridge University Press, Cambridge, United Kingdom.

Karl, T. R., P. Ya. Groisman, R. W. Knight, and R. R. Heim, 1993: Recent variations of snow cover and snowfall in North America and their relation to precipitation and temperature variations. *J. Climate,* **6,** 1327–1344.

Karl, T.R., and R. W. Knight, 1998: Secular trends of precipitation amount, frequency, and intensity in the United States. *Bull. Amer. Met. Soc.*, **79**, 231–241.

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.

Robinson, D. A., 1997: Hemispheric snow cover and surface albedo for model validation. *Ann. Glaciol.*, **25**, 241–245.

Robinson, D. A., 1999: Northern Hemisphere snow cover during the satellite era. *Proc. 5th Conf. Polar Met. And Ocean.*, Dallas, TX, American Meteorological Society, Boston, MA, pp. 255–260.

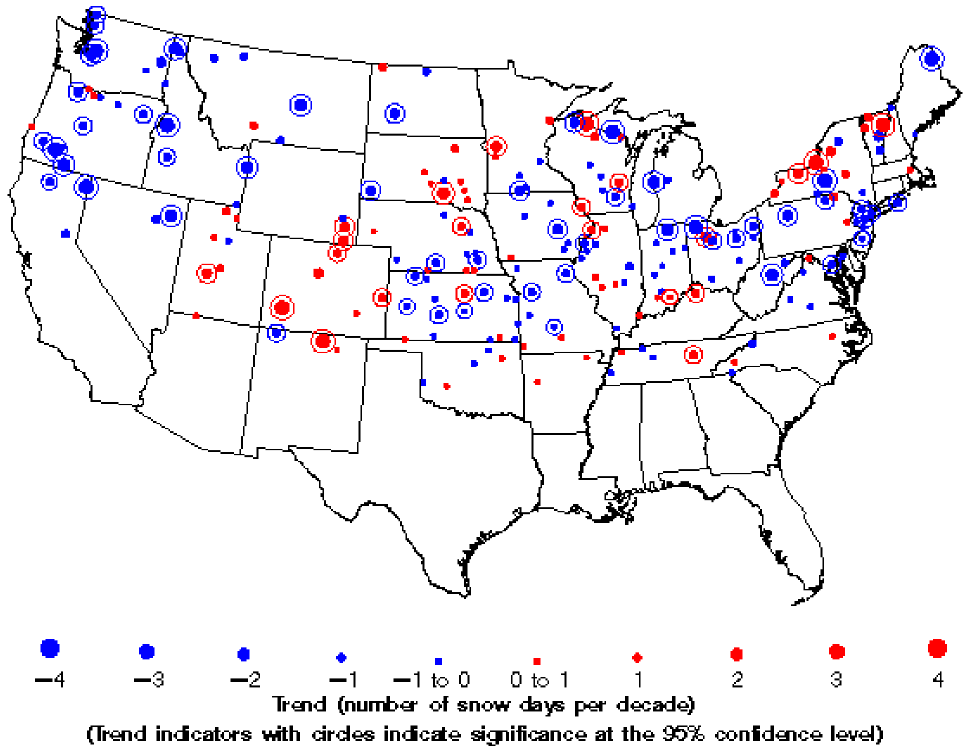

Figure 1. Trends in the number of October–May snow days, 1948/49–2000/01.

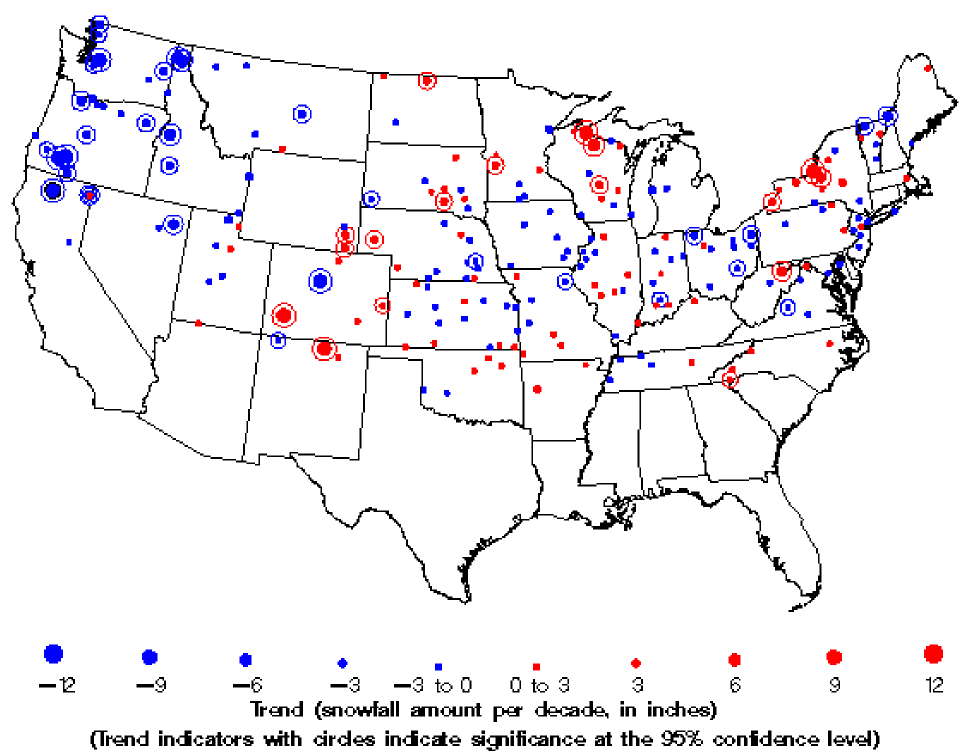

Figure 2. Trends in October–May snowfall (inches), 1948/49–2000/01.

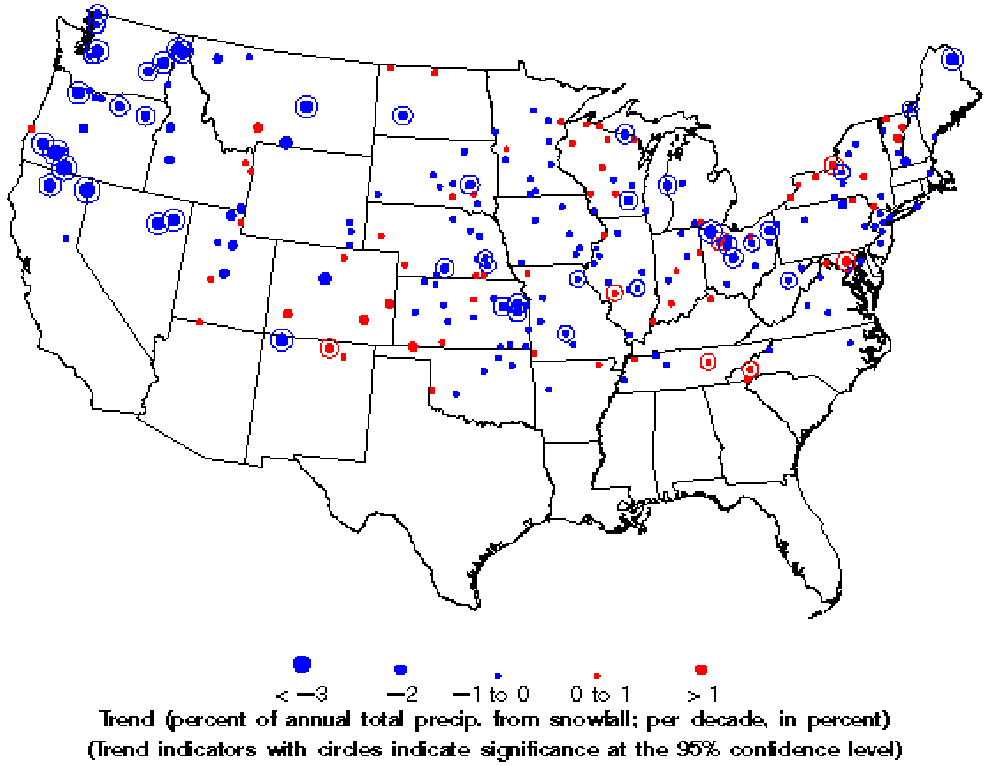

Figure 3. Trends in the percentage of annual precipitation resulting from the liquid water content of snowfall, 1948–2001.

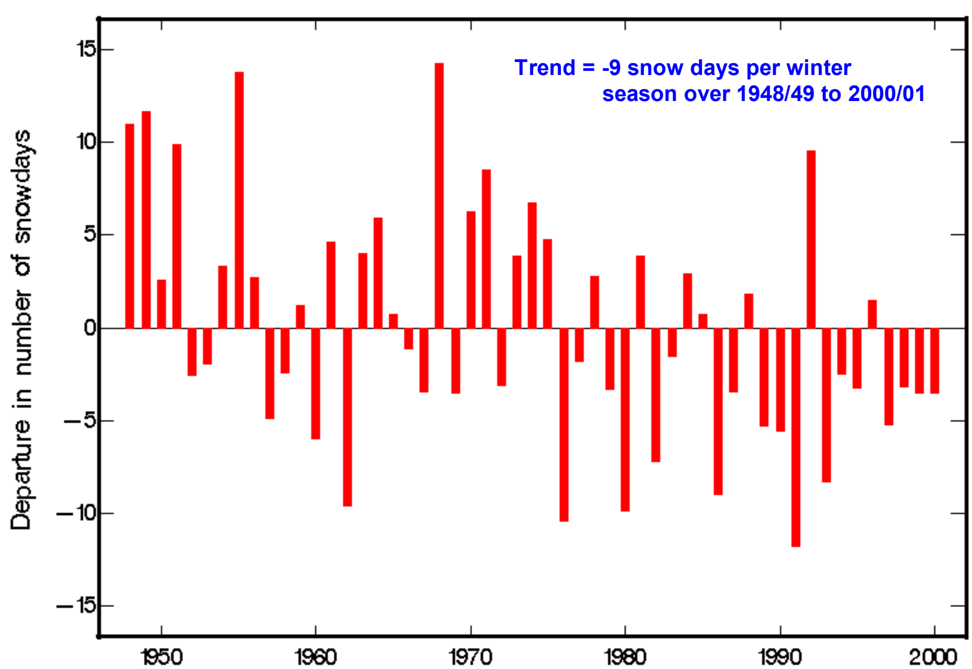

Figure 4. Time series of departures in winter season snow days over Washington, Oregon, and Idaho, 1948/49–2000/01.

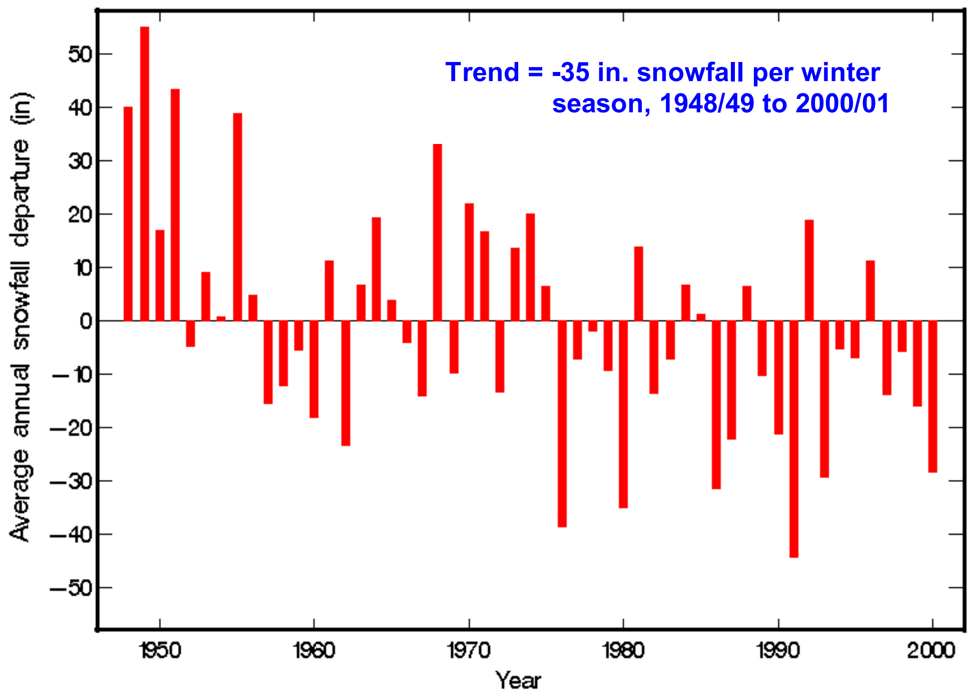

Figure 5. Time series of departures in snowfall (inches) over Washington, Oregon, and Idaho, 1948/49–2000/01.

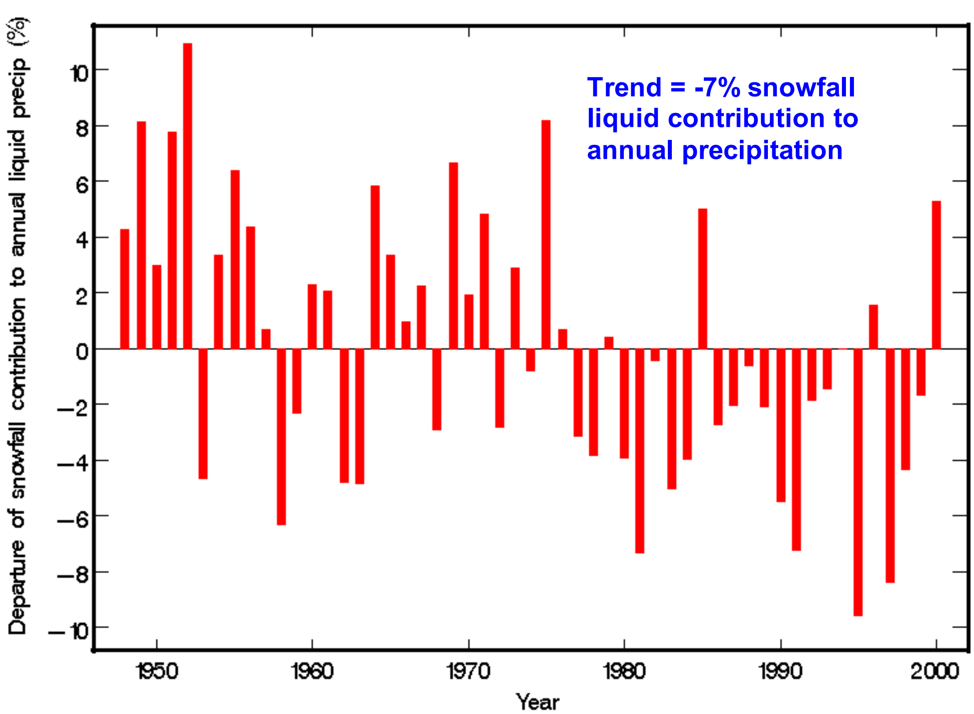

Figure 6. Time series of departures in percentage of annual precipitation resulting from the liquid water content of snowfall over Washington, Oregon, and Idaho, 1948–2001.