ISSUES WITH IDENTIFICATION OF TRENDS IN 20th CENTURY U.S. SNOWFALL

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ABSTRACT

Daily data from the National Weather Service cooperative observer network taken prior to 1948 was recently put into digital form, opening the door to analyses spanning the entire 20th Century. An examination of the U.S. daily snowfall records for the 20th Century revealed numerous apparent inconsistencies. For example, in many cases long-term snowfall variations and trends among neighboring stations differ greatly. Given the close proximity, such differences most likely are not the result of atmospheric processes, but instead probably reflect inhomogeneities in the snowfall records. Internal inconsistencies in the snow records of some of these stations also point to inhomogeneities. For example, the frequency of daily observations with a 10:1 snowfall to liquid equivalent ratio declined nationwide from 30% in the 1930s to a current value of around 10%, a change that is clearly due to observational practice. Since the change in the ratio of snowfall to liquid equivalent is due to observational practices, there must be biases in cold season liquid equivalent precipitation, or snowfall, or both. An empirical adjustment of snow-event, liquid-equivalent precipitation indicates that the potential biases can be statistically significant.

INTRODUCTION

Snow plays a critical role in the climate system through its effect on surface albedo and emissivity. It is likely to be a sensitive indicator of climate change in the cold season. Temporal variability in snow properties reflects fluctuations in both precipitation and temperature, sometimes with great sensitivity, and thus can add interpretive information about those elements. Snow on the ground and snowfall have a variety of significant socio-economic positive and negative effects. Snow is an important component of annual runoff, recharge, and water supplies, and greatly affects water management in the northern and western United States. Rapid melt of snowpack is a major cause of floods in the northern U.S. Recent studies have examined historical variability in snow cover (Hughes and Robinson 1996; Frei et al. 1999). However, studies of trends in other aspects of snow climatology, such as snowfall and snow depth, have generally examined records from the latter half of the 20th Century because digital data prior to that point has heretofore been sparse. Burnett et al. (2003) studied snowfall trends at several stations in the lake-effect snowbelts in the Great Lakes basin and found upward trends since 1951. Norton and Bolsenga (1993) identified an upward trend in lake-effect snowfall for the period 1951-1980. Groisman et al (2004) found a decreasing trend in spring season snowfall and a general shortening of the snow season, and stated that this was likely associated with recent spring season warming. A variety of recent studies pointed to significant and potentially serious declines in spring snowpack in the western United States (Mote 2003; Mote et al. 2004; Hamlet et al. 2004; Regonda et al. 2004; Stewart et al. 2004) and a trend toward more precipitation falling as rain than snow (Knowles et al. 2006).

During the first half of the 20th Century, there were significant climate trends and fluctuations that may have affected and/or been affected by the snowfall climatology. Most notably, there was substantial warming during the first 40 or so years of the century. Studies of snow (amount of fall and depth) variability and trends should provide further insights into the changes that occurred during that period.

For the past several years, the U.S. Congress has funded the Climate Database Modernization Project (CDMP), largely focused on digitizing climate data archived on hard copy forms and microfilm images. One of

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the most important early achievements of the CDMP was the completion of the keying of United States Cooperative Observer Network (COOP) daily data for the period 1892-1948. These new COOP daily data have greatly increased the spatial density of digital data for the 1892-1948 period across the United States. An initial examination of trends in snowfall revealed inconsistencies that complicate interpretation of results. The purpose of this paper is to document certain aspects of the snow data that must be considered in any analysis. The issues identified here are consequential, but it is not yet clear whether the problems are tractable.

DATA AND METHODS

The snowfall (depth of snow that accumulated since the previous observation) and snow depth (total depth of snow on ground) data were combined from two data sets, all derived from COOP observations. These were the routinely digitized COOP data, denoted as DSI-3200 by the National Climatic Data Center (NCDC), and the newly digitized pre-1948 COOP data produced by CDMP, denoted as DSI-3206 (Kunkel et al. 2005). The period of 1930-2000 was used to identify the station set used in this study. This set consisted of 1124 stations with less than 10% missing snowfall data for the 1930-2000 period and an annual average snowfall total > 5 in. Some analysis products extend back to 1900 but, as will be shown, the number of stations with data is substantially smaller in the early part of the 20th Century.

Annual total snowfall, annual maximum snow depth, and precipitation reported on days with snowfall were computed for each station for each year (July 1-June 30) with less than 20% missing data (both snowfall and precipitation) during October 1-May 31. For national average time series, station values were first converted to standardized anomalies. Then, the standardized anomalies were arithmetically averaged for all stations in a climate division. Finally, national values were obtained by areal weighting of the divisional averages.

RESULTS

Time series of U.S. annual snowfall were calculated for 1930-2000 using the full complement of 1124 stations and a subset of 326 stations with less than 10% missing data for 1900-2000. These time series (Figure 1) exhibit substantial interannual variability. There are some noticeable multi-decadal features. Above average values were common in the 1960s-1970s. Below average values were frequent in the 1920s-1930s and 1980s-1990s. The.

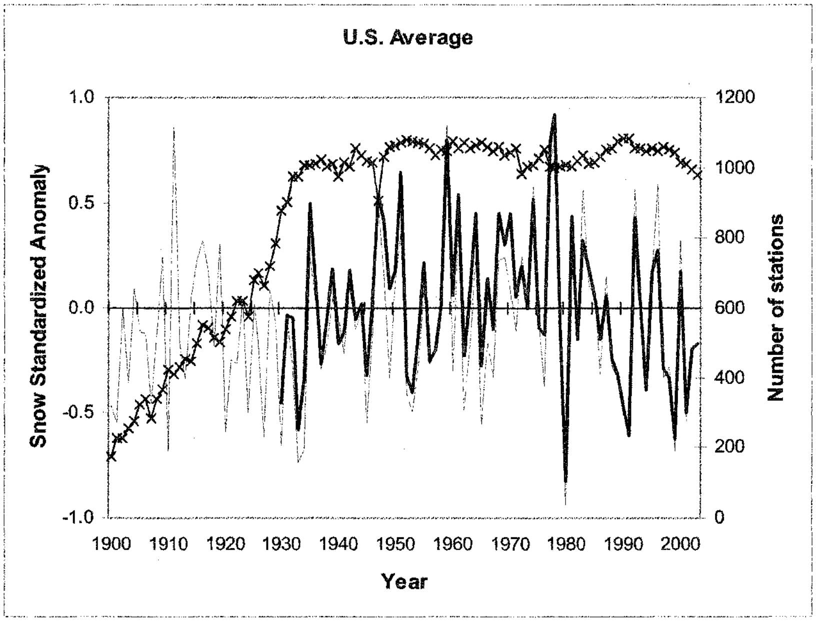

Figure 1. U.S. average time series of snowfall (expressed as standardized anomalies) for long-term stations with an annual average of at least 5 in. and less than 10% missing data for 1930-2000 (solid thick line). Also shown is time series for the subset of stations with less than 10% missing data for 1900-2000 (solid thin line). A time series of the number of available stations is shown by the line marked by "x".

1910s were snowier than either the 1900s or 1920s-1930s. During the overlapping period of 1930-2000, variations are generally similar between the two time series. Note that the number of available stations is substantially smaller before 1930, which is the motivation for the choice of 1930 as the breakpoint between the two analyses. For the 326 station subset, the spatial coverage is less than ideal, with substantial areas unsampled, particularly in the western U.S., increasing the uncertainty of the estimates in the early part of the time series. Although there is no obvious overall trend, the generally low values in the latter 20+ years of the time series could be interpreted as a response to anthropogenically-forced changes in the climate system. However, as will be shown, a number of inconsistencies are present in the data set and this simple interpretation of the time series must be tempered by uncertainties arising from the inconsistencies.

Doesken and Judson (1997) provided examples of inhomogeneities in individual station snow time series caused by a number of factors, including changes in observer, location, and observational practices. Although inhomogeneities are present in all large climate data sets, the interpretation of time series, such as in Figure 1, generally assumes that the timings and the signs of any biases in individual stations are random such that the net effect is negligible when averaging a large number of stations. Thus, of central importance is the identification of any inhomogeneities that are not random.

Station Example

The time series of total annual snowfall at Red Lodge, MT (Figure 2) exhibits a few key multi-decadal features. From the early part of the 20th Century into the 1960s, there is relatively little change with annual totals varying about 100 inches. However, in the 1970s and 1980s totals increase to the 150-250 inch range followed by a rapid decrease to around 50 inches during the early part of the 21st Century.

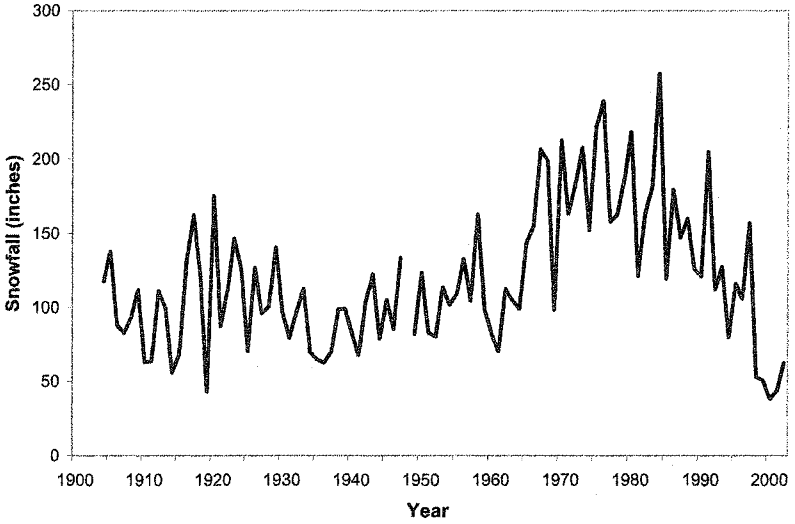

Figure 2. Time series of annual snowfall totals (inches) at Red Lodge, Montana.

The variations in the last 40 years are dramatic but are they real? One way to explore this is to look for corroboration at surrounding stations. Fourteen nearby stations were identified and analyzed. Annual snowfall totals at a particular station were expressed as anomalies from that station's period-of-record average. Then, the station anomalies were subtracted from the Red Lodge anomalies. If the time series for a neighboring station behaves in a similar manner to that of Red Lodge, then the anomaly differences should be small and fluctuate around zero. A comparison of the resulting time series for all 14 stations (Figure 3) indicates systematic behavior for all stations. The anomaly differences are large and positive for all stations in the 1970s and 1980s and then become negative in the late 1990s and 2000s. Thus, none of the neighboring stations exhibits features similar to those of Red Lodge, indicating a high likelihood that the Red Lodge data are inhomogeneous. Indeed, the changes in Figure 3 appear to generally coincide with station moves at Red Lodge, which suggests that the notable fluctuations in the Red Lodge time series (Figure 2) are caused by these moves and not by changes in climate.

Other Sources of Inhomogeneities

Other changes that can affect snowfall records include observer instructions, adherence to instructions, time of observation, observer changes, and the use of snow boards. At present, observers have the option of taking measurements at 6-hour intervals, clearing the snowboard after each measurement. This practice is known to inflate snowfall totals relative to daily measurements. There is no indication in the published instructions that this was an option in the earlier part of the record. Optional instructions such as this present special problems because there is no documentation whether such an option was used. One can imagine that for the typical observer the measurement of snowfall at sub-daily intervals, if practiced at all, might not be done all of the time, depending on the observer's schedule or circumstances during a particular event. The present instructions also indicate that the snowfall measurement should be taken as soon as possible after the end of an event, rather than waiting until the standard time of observation. Earlier instructions do not include this practice. Again, this would inflate snowfall totals relative to measurements at the time of observation by shortening the time available for compaction. Adherence to this modern instruction might also depend on the observer's schedule or circumstances during a particular event. For measurements taken at the standard time of observation, a change in observation time from late afternoon to early morning (the relative proportion of morning observers increased during the 20th Century) can induce an artificial increase in snowfall because snowfall events ending several hours before observation time will experience cooler temperatures and less frequent melting for morning observers than for afternoon observers. A change in observer not involving a station move can also introduce artificial changes if the new observer makes different choices about where to make measurements after wind-blown events or whether to follow an optional practice such as sub-daily measurements. The use of snow boards is not universal at the present time and early instructions do not mention their use, indicating that many or most long-term records will not reflect continuous use. The lack of a board most likely would lead to inflated snowfall totals if the observer measured over grass (first snow on the grass or the grass had been cleared), or reduced totals when snow previously was on the ground and the observer simply subtracted yesterday's snow depth from today's to get "snowfall". The importance of most of the above issues cannot be determined from documentation. As noted previously, an implicit assumption in analysis is that these effects are random and largely canceling when considering a large number of stations. However, some of these (e.g. the shift from mostly afternoon to mostly morning observers, the practice of sub-daily measurements) may introduce biases that should not be ignored in trend analysis.

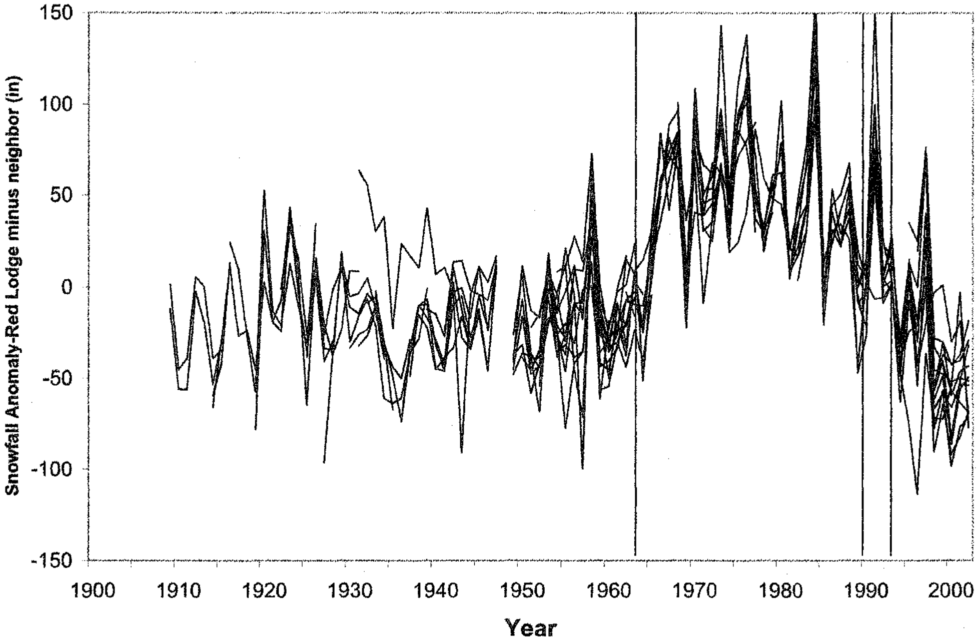

Figure 3. Time series of the annual snowfall anomaly at Red Lodge minus the snowfall anomaly at a nearby station. Time series for 14 nearby stations are shown. The vertical lines indicate times of station moves at Red Lodge.

An example of a potentially important shift in observational practice is the use of "rules of thumb" for estimation. A time series of the annual median ratio of snowfall to reported liquid-equivalent precipitation is shown in Figure 4; this annual median is derived from a single cumulative frequency distribution that in turn is constructed from all daily-ratio values for days with snowfall in excess of 2 in. during a year for the 1124 long-term stations. The median ratio exhibits an increase from about 10 in the early part of the record to 13-14 in the 1990s. Baxter et al. (2005) developed a climatology of the snowfall to liquid-equivalent ratio using data for 1971-2000, finding an average value of 13 for the latter part of the 20th Century. An examination of some individual stations revealed that the early part of the record has a high number of days with a 10:1 ratio. A time series of the frequency of exactly 10:1 ratios, first computed for each long-term station and then averaged for all of the long-term stations (Figure 5), shows a decrease from around 30% in the 1930s to about 10% in the 1990s. Instructions to observers in the early-mid 20th Century provided as an option the measurement of snowfall and then estimation of liquid equivalent using a 10:1 ratio. In *Instructions for Cooperative Observers* (U.S. Department of Agriculture Weather Bureau, 1935), the following instruction is given: "When [rainfall] cannot be measured accurately by melting, it is customary to take one-tenth the measured depth of the snowfall on a level, open place as the water equivalent of the snowfall" (p. 20). Similar instructions appear in earlier publications (e.g. USDA WB, 1922). However, a later publication (USDC WB, 1962) no longer explicitly included this option. Although this was an option in the early part of the record, an interesting and somewhat surprising feature is that there are spatial differences in the apparent application of this practice. The differences in the frequency of 10:1 ratios between 1930-1950 and 1980-2000 were computed for each station and then averaged for each state (Figure 6). In the central and eastern U.S., there are many stations with large positive (filled-in circles) differences between these two periods (indicating higher frequencies in the 1930-1950 period), consistent with Figure 5. Although there are some stations with opposite behavior, the state-wide averages are positive throughout the eastern U.S. However, in the west, the differences are very small and the frequency of 10:1 ratios is relatively low in the early part of the record as well as the latter part. Thus, there appear to be periods of time in the past when operational approaches to snowfall and winter precipitation measurement differed by region, perhaps due to regional exposure issues such as susceptibility to undercatchment in the Great Plains. Instructions to observers, and implementation and adherence to guidance, could very well have varied between different administrative units, and any of these could have changed through time.

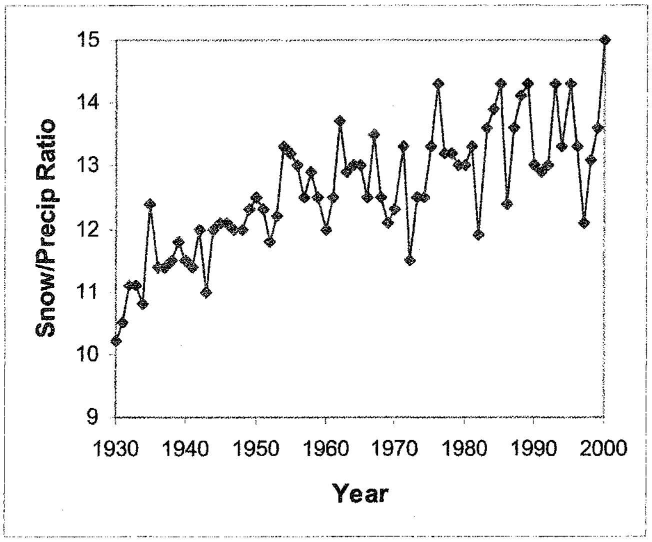

Figure 4. Annual median value of the ratio of snowfall to liquid equivalent for all long-term U.S. snowfall stations used in this study for all days with snowfall > 2 in.

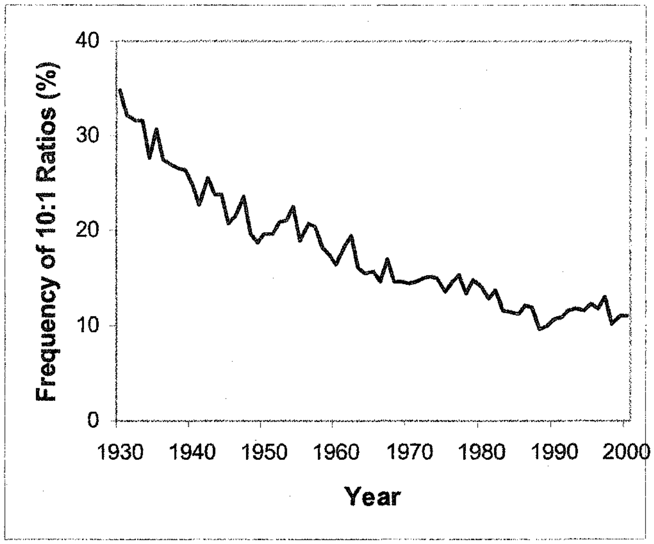

Figure 5. Time series of the frequency of daily values of 10:1 for the snowfall to liquid equivalent ratio based on all long-term U.S. snowfall stations.

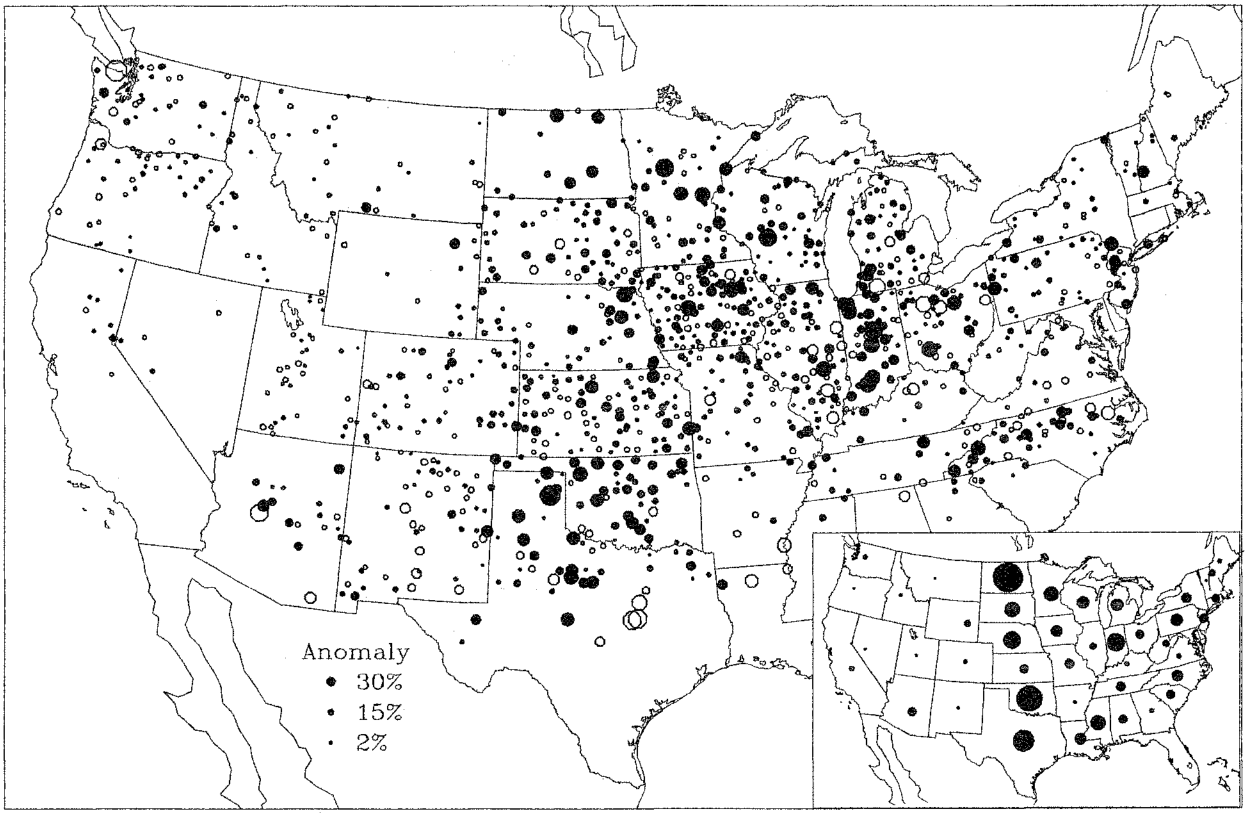

Figure 6. Difference of the percent of snowfall:precipitation ratios equal to 10 between 1930-1950 and 1980-2000 for each long-term snowfall station. Filled (open) circles indicate positive (negative) differences. The map insert shows state-averaged values.

The instructions to observers (USDA Weather Bureau, 1935) state that it is the snowfall that is measured and the liquid equivalent that is estimated when both are not done simultaneously. This suggests that the snowfall records could be homogeneous, but cold season liquid equivalent precipitation in snowy climates could be problematic. An estimate of the potential magnitude of such an effect was explored by developing an adjusted precipitation time series. Using a subset consisting only of 48 of the snowier stations (mean annual snowfall > 40 in) with 10% missing data for 1900-2000, daily snowfall and precipitation values with ratios different than 10:1 (and thus presumably reflecting independent measurement of these two variables) were used to develop an empirical relationship between temperature and the snowfall:precipitation ratio (note that this relationship is only an approximation since its calculation excludes all values with ratios exactly equal to 10:1 even though some small percentage of such values will be real). Then, for each day when the ratio was exactly 10:1, this relationship was used to calculate an adjusted precipitation value P_a from the observed value P as

$$P_a = P\,[10/R(T)] \qquad (1)$$

where R(T) is the empirically-determined ratio as a function of the daily mean (average of maximum and minimum) temperature T. Note that R(T) is station-specific. A time series of observed and adjusted total precipitation from snowfall (Figure 7) shows that the adjusted values are noticeably lower early in the record. This has a substantial effect on the trend. The trend for observed precipitation is not significantly different from zero, while the trend for adjusted precipitation is upward and statistically significant at the 95% level of confidence. Research involving snow liquid equivalent is ongoing; for example, Knowles et al. (2006) examined trends in the ratio of snow liquid equivalent to total precipitation in the western U.S. and primarily for the period after 1949. In that case, the focus on the latter half of the 20th Century and the western U.S. where there are minimal trends in the frequency of 10:1 ratio observations (Figures 5 and 6) minimize the impact of this effect. However, studies examining the entire COOP period of record and the entire U.S. will need to carefully consider the potential impacts of this non-climatic effect.

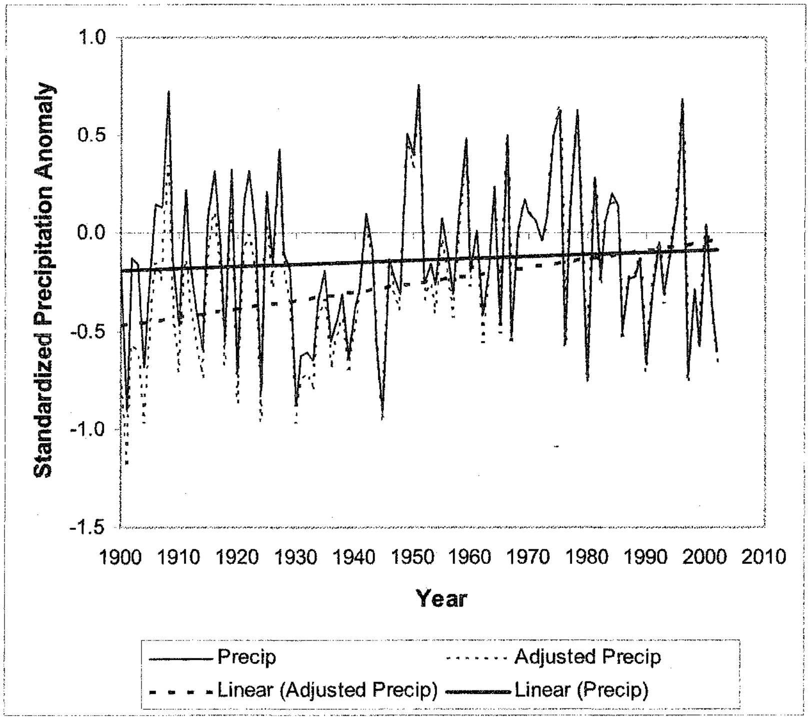

Figure 7. Time series of precipitation from snowfall events averaged for 48 stations with mean annual snowfall > 40 in and less than 10% missing data for 1900-2000. Observed and linear best fit (adjusted) values are shown by the solid (dashed) lines.

CONCLUSIONS

The issues raised here indicate that care must be taken in interpreting temporal variations and trends in the COOP snow data and associated liquid equivalent precipitation. In the early part of the record, the number of observers not making independent observations of snowfall and snowfall liquid equivalent was quite high and much higher than in the latter part of the record. Observer instructions suggest that snowfall is likely the measured quantity and liquid equivalent the estimated quantity, meaning that snowfall variations in the data may be real.

However, it is also clear that the snowfall time series are not homogeneous in some cases because of spatial variations on small scales that are highly unlikely to be real. Careful (and time-consuming) inspection of the data and histories of individual stations appears necessary to identify quality snow stations suitable for trend analysis.

On a larger scale, there is the possibility that the biases resulting from many types of station inhomogeneities may be random and thus trends averaged over large areas may reflect reality. A notable exception is possible biases arising from the 10:1 snowfall to liquid equivalent precipitation ratio rule of thumb. On average, the actual ratio is greater than 10 at most locations. Thus, application of this rule will result in an overestimate of the liquid equivalent. Since there is a decreasing trend in the frequency of 10:1 ratio reports, there must be either negative biases in winter precipitation trends or positive biases in snowfall trends, or even biases in both. Indeed, assuming that the biases occur in winter precipitation, an empirical adjustment of long-term time series of precipitation from snowfall for snowy locations makes a substantial change in the long-term trend. This is a particular concern for studies of snow liquid equivalent in the central and eastern U.S. covering the entire 20th Century, but may be of lesser importance for the western U.S. (e.g. Knowles et al., 2006) where there is little trend in the frequency of 10:1 ratio reports.

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