SNOTEL sensor upgrade has caused temperature record inhomogeneities for the Intermountain West: Implications for climate change impact assessments

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Motivation

The motivation for this briefing is to examine the large inhomogeneity (step shift) in the observed temperature record at the SNOw TELemetry (SNOTEL) stations in the Intermountain West—Colorado, Utah and Wyoming—and its implications for climate, hydrology and ecological research in the region. This issue impacts the entire SNOTEL network across the 11 Western states, as demonstrated by Jared Oyler of the University of Montana and his colleagues in Oyler et al. (2015). Here we build on that work by performing finer-grained analyses, and identifying the implications for climate studies that have incorporated SNOTEL temperature data. In doing so, we intend to promote a broader awareness of this issue among the climate impacts assessment community.

We find, like Oyler et al. (2015), that this inhomogeneity is primarily introduced because of temperature sensor upgrades at SNOTEL sites between the late 1990s and mid-2000s. Our analysis focuses on Colorado, where these sensor upgrades occurred between 2004–2006, and indicates a positive shift of 1.7°C (3°F) in daily minimum temperature (Tmin), a negative shift of -0.5°C (-0.9°F) in the daily maximum temperature (Tmax), and thus a -2.2°C (-4.0°F) shift in the diurnal temperature range (DTR) following the year of sensor upgrade. In general, this effect artificially amplifies the average warming trend in the SNOTEL temperature dataset and other products that incorporate the SNOTEL data, including popular gridded products such as PRISM and DAYMET.

Introduction

The Soil Conservation Service, now the Natural Resources Conservation Service (NRCS), was congressionally mandated to measure snowpack in the mountainous West for the purpose of forecasting water supply. The program began in the mid-1930s with manual snow course measurements. Automated SNOTEL sites were first installed in the late 1970s, many of them co-located with manual snow courses in areas that had strong correlations between snowpack and spring and summer streamflow. Because of NRCS's mandate for water supply forecasting, their monitoring network has primarily focused on precipitation and snow-water equivalent measurements, while temperature measurements have received fewer resources and quality control. The SNOTEL network, including the temperature sensors, were not designed for long-term climate monitoring, but rather to assist in seasonal snowpack monitoring and streamflow forecasting. Early SNOTEL temperature readings were of limited value because measurement times were constrained by infrequent data transmission. Not until the mid-1980s was the capability to record and transmit daily maximum (Tmax) and minimum (Tmin) temperature added to SNOTEL sites. Over the next 15 years, SNOTEL temperature measurements suffered from less consistency in the instrumentation (e.g., mounting and radiation shields) and less data quality assurance compared to the higher-priority measurements of snow water equivalent and precipitation (Doesken and Schaefer 1987; Julander et al. 2007). In an effort to better capture extremely low temperatures, a new sensor was installed—including a new algorithm to convert from millivolts to ^{o}F—and the mounting and radiation shielding were standardized between the late 1990s and mid 2000s. The sensor change appears to be the primary factor that introduced the inhomogeneity discussed here.

Examining SNOTEL temperature records, Oyler et al. (2015) found that minimum temperatures averaged across the 11-state western region increased steadily by a total of ~1.5^{o}C (2.7^{o}F) between 1997 and 2007. By looking at selected subregions of the West separately, they found that most of this increase occurred when new sensors were installed between 1997 and 2000 in Montana and between 2004 and 2006 in Colorado, and furthermore that these increases were not consistent with temperature trends at National Weather Service (NWS) COOP stations in the region.

Climate studies in recent decades have suggested that temperatures have been increasing faster at higher elevations in mountain regions (e.g., Diaz and Bradley 1997; Liu et al. 2009; Ohmura 2012). This issue has been reviewed in Rangwala and Miller (2012) and Pepin et al. (2015), and they discuss potential reasons for this enhanced warming at higher elevations for various mountain ranges globally. In the Rocky Mountains, many of the studies that have investigated this phenomenon have employed SNOTEL data directly (e.g., Clow 2010) or gridded products that assimilate SNOTEL data (e.g., Diaz and Eischeid 2007). However, the Oyler et al. (2015) study indicates that much of the signal related to the amplification of warming at high elevations in these studies is an artifact of the recent inhomogeneity in the SNOTEL data.

This briefing provides additional detail on the temperature changes in Colorado and shows clearly how the minimum and maximum temperatures changed after the new sensors were installed. Oyler et al. (2015) averaged the SNOTEL temperatures across Colorado and showed that there was a significant and steady increase in temperature between 2004 and 2006. We have extended their analysis for Colorado by dividing the SNOTEL sites into three clusters according to the year in which the sensor was upgraded, and examining the clusters separately. Later in this briefing, we discuss implications for climate impacts studies and recommendations for data users, as well as, how do these findings affect our understanding of climate change in high elevation regions of the Intermountain West.

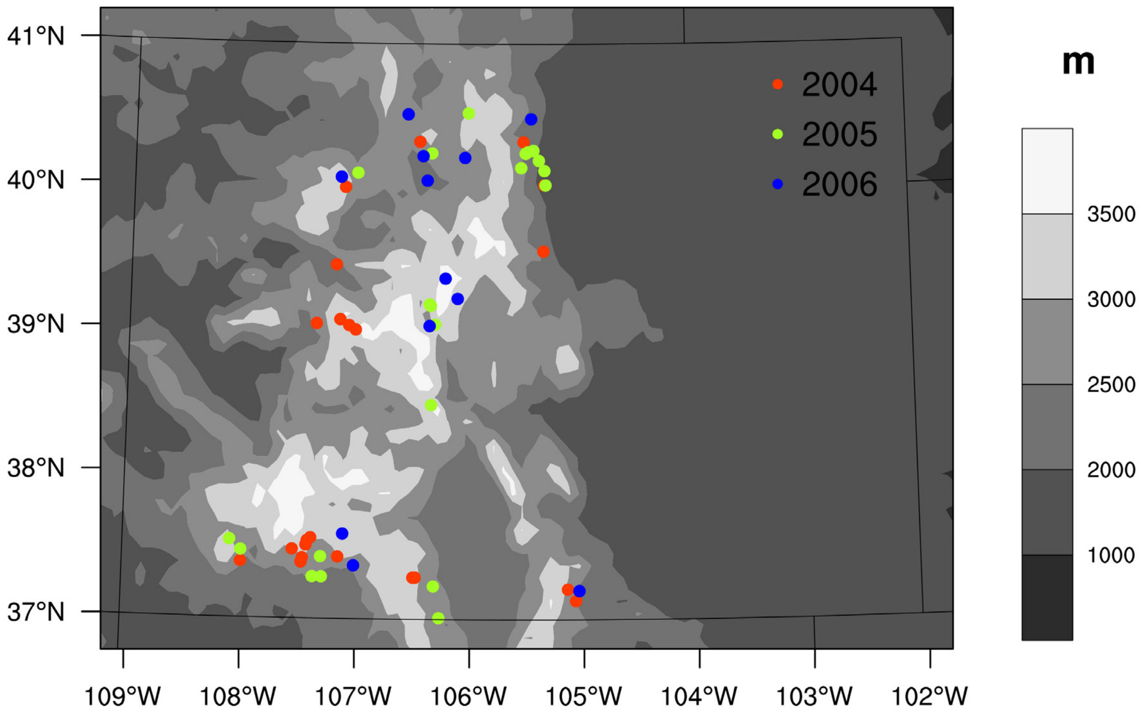

Figure 1. *Locations of the SNOTEL stations (n=55) in Colorado used in this study. The color of the dot indicates the year that the temperature sensor was upgraded. Filled contours show the elevation in meters. See Appendix A for more information on the SNOTEL stations.*

Analysis of SNOTEL Stations across Colorado

We extracted the daily records of Tmin and Tmax from SNOTEL sites across Colorado (see Figure 1 and Appendix A) and performed a quality control. As described in Rangwala and Miller (2010), we examined the daily record for erroneous values and omitted them in calculating the monthly averages of Tmin and Tmax, which are used in the analysis described in this section. Moreover, Rangwala and Miller (2010) also found strong correlations ($r > 0.9$) between the NWS COOP and SNOTEL mean temperature anomalies for the 1984–2005 period, both annually and seasonally, suggesting broad agreement in the interannual variability and multi-year trends between the two datasets for that time period. We examined each station's metadata for changes in instrumentation, and specifically documenting the year of the most recent temperature sensor upgrade. For Colorado, these upgrades occurred mostly between 2004 and 2006.

The plots in Figures 2 and 3 show the time series of anomalies in the annual temperatures averaged among the stations that had a sensor upgrade during the same year. We calculated the step shift in Tmin and Tmax as the difference between the average temperature for the years following the upgrade year, and the average temperature from 1994 to the year preceding the upgrade year. The reason for selecting the period since 1994 is because large positive temperature anomalies have been observed over most of Colorado since then using the NWS COOP stations (Rangwala and Miller 2010; Lukas et al. 2014). Our intent was to exclude the relatively colder period prior to 1994 in the SNOTEL record in calculating the artificial shift in temperatures following the sensor upgrade. We then calculated the weighted average of the shift from the three clusters of stations, sorted by the year of upgrade, to estimate the overall mean step shift in Tmin and Tmax associated with sensor upgrade.

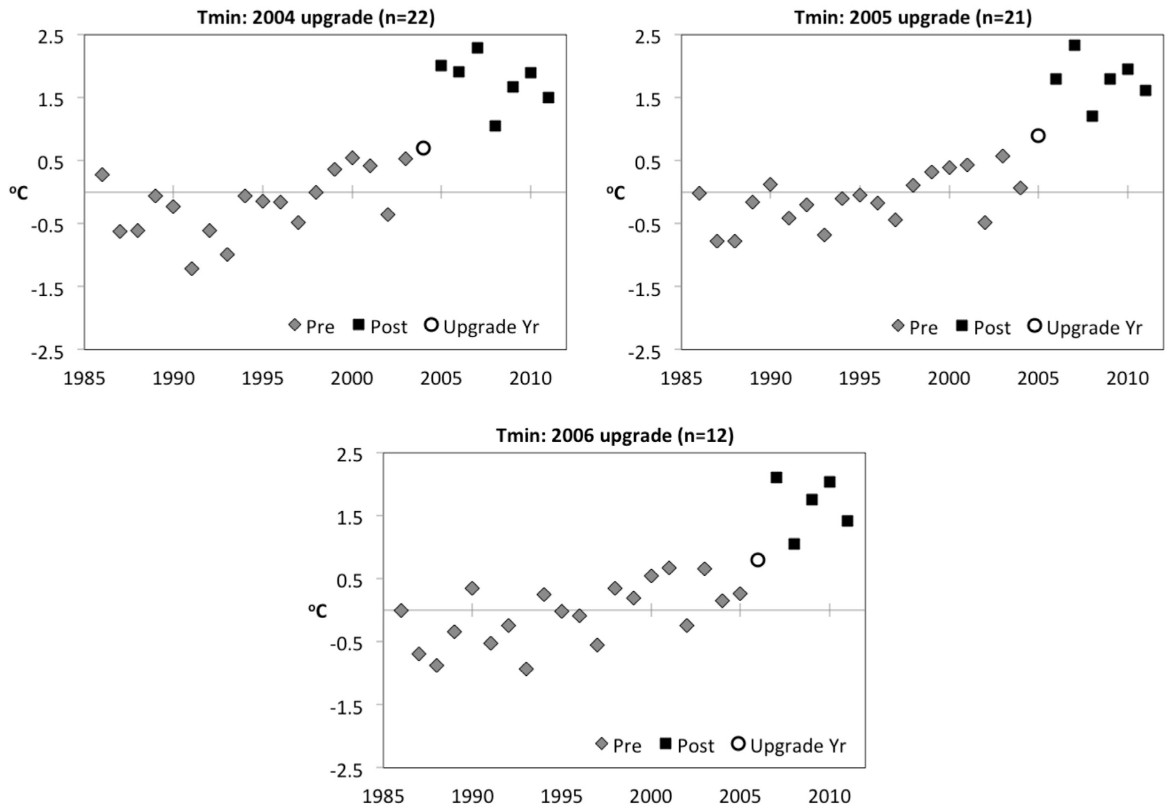

Figure 2. *Anomalies in the annual averaged Tmin relative to the 1990-2005 period. The different symbols show these anomalies for the years before, during, and after the sensor upgrade.*

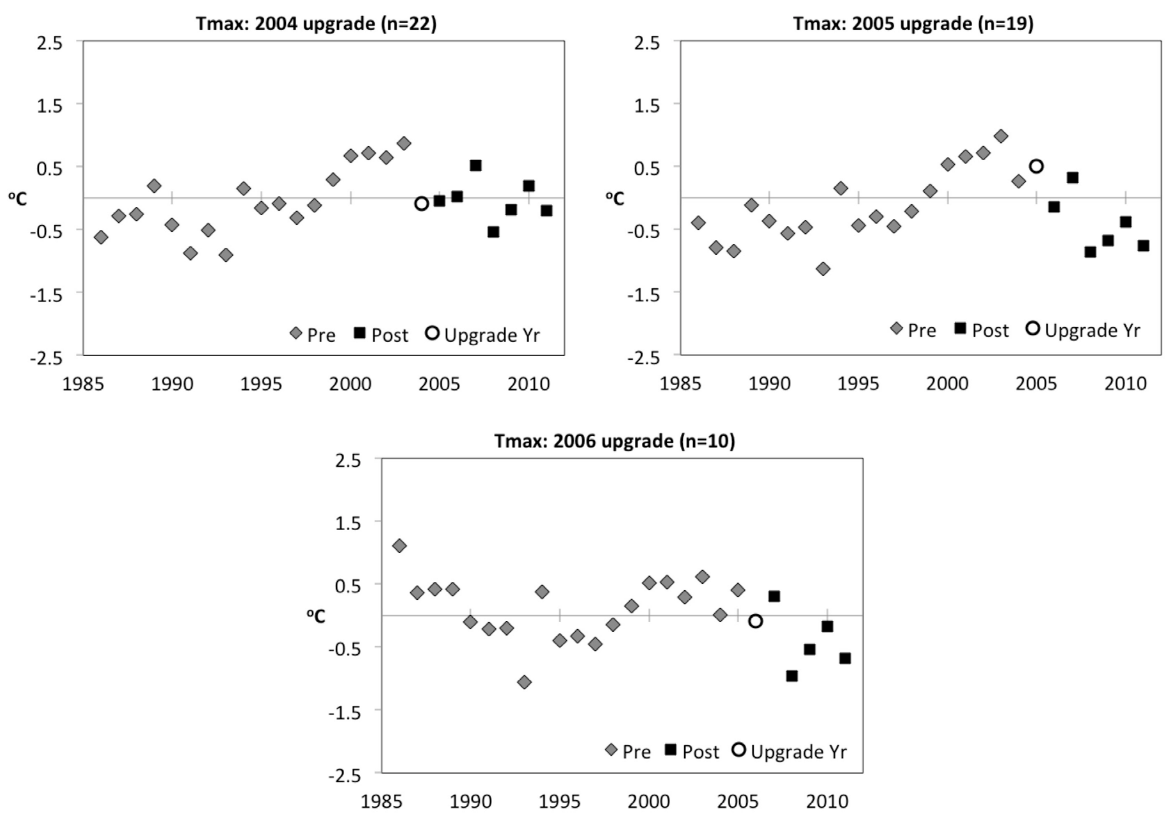

Figure 3. *Same as in Figure 2, but for Tmax.*

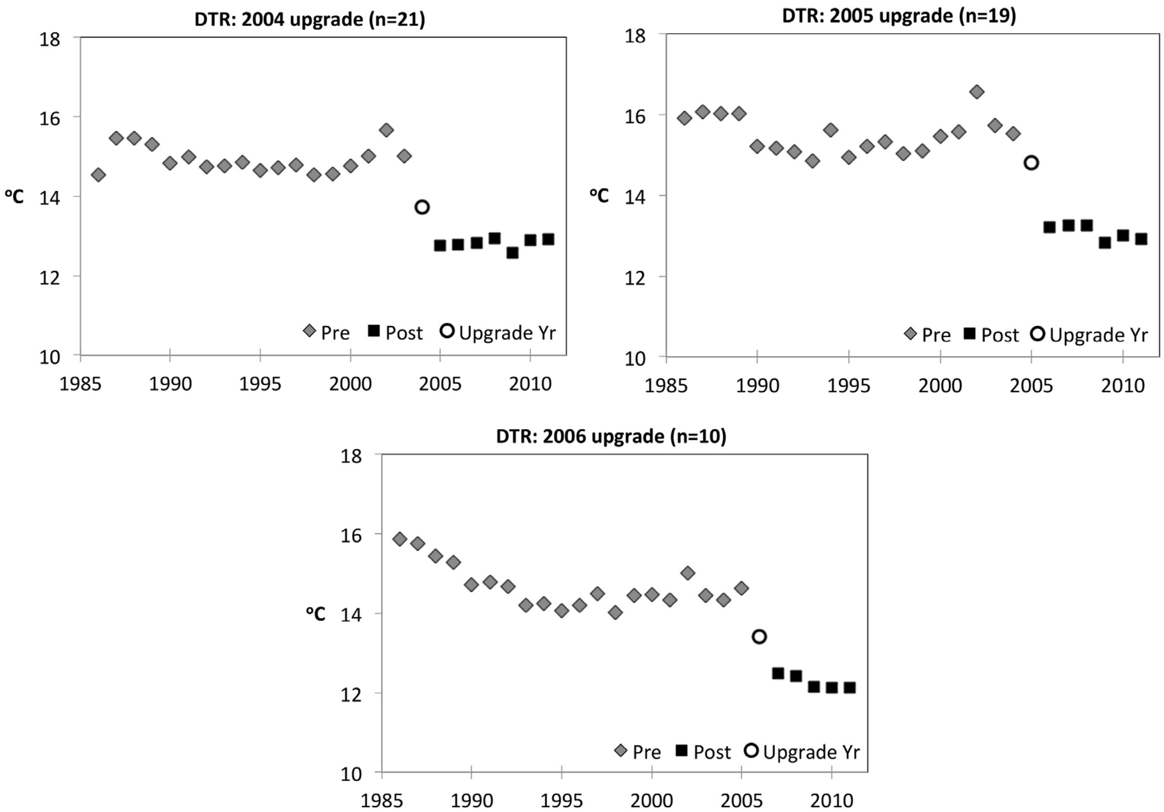

Figure 4. *Same as in Figure 2, but for diurnal temperature range (DTR).*

The upper left plot in Figure 2 shows the time-series of Tmin anomalies for the 22 SNOTEL stations for which sensors were upgraded in 2004. The temperature anomalies for the seven years after 2004 are significantly higher than for the years between 1994 and 2003 ($+1.8^{o}$C vs. $+0.1^{o}$C). The results are similar for stations where sensors were upgraded in 2005 and 2006 as shown in the other plots. For all three cases considered together, the temperatures increased by about 1.7^{o}C following the sensor upgrade.

Figure 3 shows the corresponding changes in Tmax for the same set of stations, although the number of stations is slightly smaller than for Figure 2 because some Tmax records were missing. Unlike Tmin, for which there were significant increases in the anomalies after the sensor upgrades, the Tmax anomalies decreased by about -0.3, -0.6, and -0.5^{o}C for stations with upgrade years 2004, 2005, and 2006 respectively, and -0.5^{o}C for all cases considered together. These diverging shifts in Tmin and Tmax affect the trends in the diurnal temperature range (DTR). Figure 4 shows the DTR time-series for the three clusters. Overall, the DTR decreased by 2.2^{o}C after the upgrades. These shifts are also fairly consistent across the different seasons.

Implications and Recommendations for Data Users

Clearly, these artificial step shifts in Tmin and Tmax measurements will affect the estimation of trends in studies that use SNOTEL data directly, or indirectly through gridded data that incorporate SNOTEL temperature observations, such as PRISM. In general, as seen in Figures 2 and 3, the 25-year trend in the minimum temperatures is enhanced, and the trend in maximum temperatures reduced, by these step shifts after the sensor upgrades. The trend in mean temperatures is also enhanced, but less than that for the minimum temperatures.

Potential users of SNOTEL temperatures should be very careful about the time periods used in their analyses, particularly when looking at trends.

Figure 5 compares the time series of Tmin anomalies for four regions in the Intermountain West (2 in Colorado, 1 in Utah and 1 in Wyoming) based on two different gridded datasets, PRISM (which incorporates SNOTEL temperature data; Daly et al., 2008) and Maurer (which does not use SNOTEL; Maurer et al., 2002). We find that the anomalies are fairly similar between PRISM and Maurer until the early 2000s and then start to diverge with PRISM showing higher positive anomalies. For some regions, such as northwestern Wyoming, this difference is much greater. One reason for this could be that the PRISM data over Wyoming become increasingly more weighted by the SNOTEL observations.

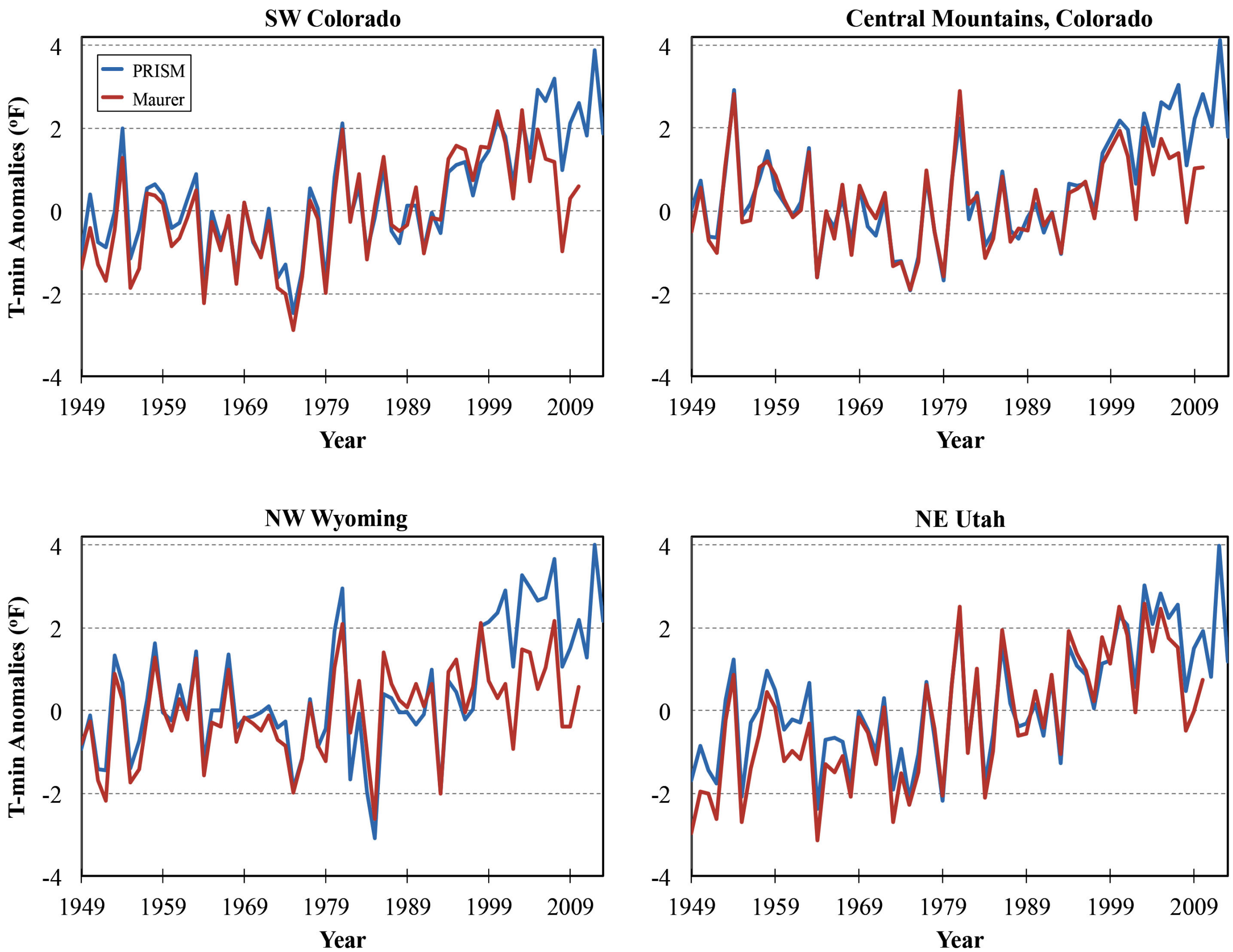

Figure 5. *Anomalies in the annual averaged Tmin, relative to the 1961-1990 period, from PRISM and Maurer gridded data for four selected regions in the Intermountain West.*

Data users need to be aware of this change, and until an adequate solution and correction is found and applied, should (1) avoid using uncorrected SNOTEL temperatures for trend analyses and (2) use extreme caution when using gridded data sets that incorporate SNOTEL data for trend analyses. Owing to limited resources and the need for further investigation, it is unlikely that a permanent fix or correction will be applied quickly. Investigators should examine metadata and, if needed, request additional information from the NRCS regarding the dates and types of changes to instrumentation that may impact their analyses. We suggest that those who have utilized SNOTEL temperature data in previous studies should re-interpret their results in light of these findings. Some specific suggestions include: (a) if you notice a step change in the impacts-related response, verify if that response is synchronous with the timing of the step shift in SNOTEL temperature, (b) if your system is sensitive to Tmin, then large trends in Tmin could introduce an amplified response within your system, (c) if your study requires you to assess temperature trends, it is better to extract those trends from NWS COOP stations for that region and apply them to higher elevation regions; Rangwala and Miller (2010) found that at least on an annual basis the temperature trends are very similar between COOP and SNOTEL stations.

Possible Technical Causes for Inhomogeneity and Steps for Correction

While multiple changes occurred during the sensor upgrades, including changes to the location, height, and radiation shielding, the majority of the shift has been attributed to the sensor itself, including the algorithm used to convert from voltage to temperature. This conclusion is based on parallel measurements from the old and new sensors using the same mounting and shield conducted by the Idaho NRCS office. Additionally, although different state offices migrated to the new sensor in different ways, the temperature shifts after the changes were similar. At all sites, a new algorithm was used to convert voltage readings to temperature when the new sensor was installed. This may be responsible for a portion of the documented temperature shift, but further investigation is required to properly attribute the shift between the sensor and algorithm.

NRCS has plans to conduct both field and environmental chamber experiments to test the old and new temperature sensors as well as the current and manufacturer's recommended algorithm. These experiments should shed light on the most appropriate corrective actions and determine whether the old or new sensor more accurately reflects the actual temperature. Additional investigations by the research community may lead to a homogenization model adequate to adjust both the Tmin and Tmax changes caused by the new sensors.

Implications for Regional Climate Change Assessments

We would like to emphasize that SNOTEL data are *not* generally part of the datasets used by climate scientists for the analyses of temperature trends found in regional, national and international assessment reports such as the National Climate Assessment and the Intergovernmental Panel on Climate Change (IPCC) reports. These assessments typically employ selected and high-quality observations that are run through a homogenization process to minimize the impact of sensor changes and other sources of step shifts. These include databases such as the Global Historical Climatology Network (GHCN) and U.S. Historical Climatology Network (USHCN). SNOTEL data, in contrast, are assimilated in the high-resolution gridded products such as PRISM and DAYMET that are widely used by the climate impacts community to run their impact models. That said, some other widely used gridded products do not incorporate SNOTEL data, including the Maurer, University of Delaware, and GHCN gridded data.

Oyler et al. (2015) have pointed out that many previous studies of recent climate trends in the Mountain West (e.g., Diaz and Eischeid 2007; Clow 2010; Pederson et al. 2010) have relied heavily on SNOTEL data or high-resolution gridded products that assimilate SNOTEL data for assessment of warming trends in high elevation regions. They have made a strong case that these datasets cannot be relied upon to give a true picture of how the temperatures are changing at high elevations, i.e., for Colorado, Utah, and Wyoming, above 9,000' (2,700 m). We have few long-term climate observations above 9,000' in most of the Intermountain West unless we include SNOTEL data, and even SNOTEL observations are rarely available at elevations above 11,000' (3,350 m). While it is clear that using un-corrected SNOTEL temperature observations leads to an overestimation of warming trends, we would like to caution readers that this does not mean that amplified warming is not occurring at higher elevations in the Intermountain West, but just that the available observations are insufficient to confirm or refute that higher elevations are warming faster than lower elevations.

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Appendix A

Table listing the NRCS SNOTEL stations (n = 55) used in the analyses.

Station Name	Station ID	Lat	Lon	Tmin	Tmax	Sensor Upgrade Year
Bison Lake	345	39.46	107.21	✓	✓	2004
Cascade	386	37.39	107.48	✓	✓	2004
Dry Lake	457	40.32	106.47	✓	✓	2004
Idarado	538	37.56	107.40	✓	✓	2004
Joe Wright	551	40.32	105.53	✓	✓	2004
Lake Eldora	564	39.56	105.35	✓	✓	2004
Lizard Head Pass	586	37.48	107.56	✓	✓	2004
McClure Pass	618	39.08	107.17	✓	✓	2004
Mineral Creek	629	37.51	107.44	✓	✓	2004
North Lost Trail	669	39.04	107.09	✓	✓	2004
Overland Reservoir	675	39.05	107.38	✓	✓	2004
Red Mountain Pass	713	37.54	107.43	✓	✓	2004
Schofield Pass	737	39.01	107.03	✓	✓	2004
Scotch Creek	739	37.39	108.01	✓	✓	2004
Spud Mountain	780	37.42	107.47	✓	✓	2004
Trapper Lake	827	40.00	107.14	✓	✓	2004
Trinchera	829	37.21	105.14	✓	✓	2004
University Camp	838	40.02	105.34	✓	✓	2004
Upper Rio Grande	839	37.43	107.16	✓	✓	2004
Upper San Juan	840	37.29	106.50	✓	✓	2004
Whiskey Creek	857	37.13	105.07	✓	✓	2004
Wolf Creek Summit	874	37.29	106.48	✓	✓	2004
Bear Lake	322	40.19	105.39	✓	✓	2005
Beartown	327	37.43	107.31	✓	✓	2005
Brumley	369	39.05	106.32	✓	✓	2005
Columbine	408	40.24	106.36	✓	✓	2005
Copeland Lake	412	40.12	105.34	✓	✓	2005
Crosho	426	40.10	107.03	✓	✓	2005
Cumbres Trestle	431	37.01	106.27	✓	✓	2005
El Diente Peak	465	37.47	108.01	✓	✓	2005
Kiln	556	39.19	106.37	✓	✓	2005
Lake Irene	565	40.25	105.49	✓	✓	2005
Lily Pond	580	37.23	106.32	✓	✓	2005

Lone Cone	589	37.54	108.11	✓	✓	2005
Nast Lake	658	39.18	106.36	✓	✓	2005
Niwot	663	40.02	105.33	✓		2005
Park Cone	680	38.49	106.35	✓	✓	2005
Phantom Valley	688	40.24	105.51	✓	✓	2005
Roach	718	40.52	106.03	✓	✓	2005
Stillwater Creek	793	40.14	105.55	✓	✓	2005
Stump Lakes	797	37.29	107.38	✓	✓	2005
Vallecito	843	37.29	107.30	✓	✓	2005
Willow Park	870	40.26	105.44	✓		2005
Apishapa	303	37.20	105.04	✓	✓	2006
Deadman Hill	438	40.48	105.46	✓		2006
Elk River	467	40.51	106.58	✓	✓	2006
Fremont Pass	485	39.23	106.12	✓	✓	2006
Indepedence Pass	542	39.04	106.37	✓	✓	2006
Lynx Pass	607	40.05	106.40	✓	✓	2006
Middle Creek	629	37.37	107.02	✓	✓	2006
Rabbit Ears	709	40.22	106.44	✓		2006
Ripple Creek	717	40.07	107.18	✓	✓	2006
Slumgullion	762	37.59	107.12	✓	✓	2006
Vail Mountain	842	39.37	106.23	✓	✓	2006
Willow Creek Pass	869	40.21	106.06	✓	✓	2006