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Snowpack variability and trends at long-term stations in northern Colorado, USA

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Abstract. The individual measurements from snowcourse stations were digitized for six stations across northern Colorado that had up to 79 years of record (1936 to 2014). These manual measurements are collected at the first of the month from February through May, with additional measurements in January and June. This dataset was used to evaluate the variability in snow depth and snow water equivalent (SWE) across a snowcourse, as well as trends in snowpack patterns across the entire period of record and over two halves of the record (up to 1975 and from 1976).

Snowpack variability is correlated to depth and SWE. The snow depth variability is shown to be highly correlated with average April snow depth and day of year. Depth and SWE were found to be significantly decreasing over the entire period of record at two stations, while at another station the significant trends were an increase over the first half of the record and a decrease over the second half. Variability tended to decrease with time, when significant.

1 Introduction

The Natural Resources Conservation Service (NRCS) has taken monthly snow depth (d_s) and snow water equivalent (SWE) measurements at snowcourses since the mid-1930s across the Western United States to aid in spring and summer runoff forecasting (USDA, 1988, 2013). The snowcourses are manual measurements taken at 10 to 15 stations over a 100 to 300 m transect (USDA, 1984). Measurements include average snow depth, SWE, and density (ρ_s) for a particular date, and are available online www.wcc.nrcs.usda.gov. The monthly data are usually collected on or about February, March, April, and 1 May (Julander, 2005), with some 1 January, 1 June, and mid-month measurements collected at stations with more snow.

The snowcourse data collected on or about 1 April are used to represent peak accumulation across most of the Western United States. These data have been used to understand annual trends related to climate and climate change (e.g., Cayan, 1996; Stewart et al., 2005). However, few studies have used the individual measurements at a snowcourse to understand the variability associated with these data. Wells and Doyle (2004) examined long-term measurements at specific snowcourse stations relative to forest growth and found no significant trend in peak SWE.

The snowcourse data are an average of measurements over 100 s of meters while automated snowpack measurements, such as the NRCS Snow Telemetry (SNOTEL) network, are essentially a point in space, as those cover an area of 10 m^2. However, snowpack variability exists across different scales (Blöschl, 1999). For example, correlation lengths for lidar-based snow depth were 10 to 40 m depending on the terrain and the presence and density of the canopy (Deems et al., 2006; Trujillo et al., 2007). The snow station data are assimilated in different models (e.g., Ikeda et al., 2010; Clow et al., 2012), but the stations are often not representative of the surrounding areas (Kashipazha, 2012; Meromy et al., 2013).

Table 1. Northern Colorado snowcourse data used in the analysis. The years of data are for 1 April measurements, with February, March and 1 May having almost as many samples. Some data are available for 1 January, 15 May and 1 June at all stations except Big South and Chambers Lake.

site	station number	elevation (m)	latitude (deg N)	longitude (deg W)	year initiated	sampling points	years of data	avg 1 Apr d_s (m)	avg 1 Apr SWE (mm)
Big South	05J03	2621	40.62	105.82	1936	9	79	0.282	77
Cameron Pass	05J01	3135	40.52	105.89	1936	10	79	1.865	664
Chambers Lake	05J02	2743	40.61	105.84	1936[a]	8	50	0.643	203
Lake Irene	05J10	3261	40.42	105.82	1938	16[b]	75	1.620	514
Milner Pass	05J24	2972	40.4	105.83	1952	10	62	1.095	323
Phantom Valley	05J04	2752	40.4	105.85	1936[c]	17	55	0.932	278

[a] Historical field notes were not available for Chambers Lake prior to 1965, [b] the most recent data available from Lake Irene and only had 6 sampling points, [c] the Phantom Valley snowcourse was discontinued and replaced by a SNOTEL station in 1991.

Depth tends to vary the most of the snowpack variables, with density variation across space being considered conservative (Elder et al., 1991). Yet, snow density variability can also be substantial (López-Moreno et al., 2013).

The individual snow depth and SWE measurements from six Northern Colorado stations in close proximity to one another (Table 1) were used to investigate the snowpack variability across a snowcourse, and snowpack trends. Specifically, the following questions were addressed: (1) can the snowpack variability be identified and systematically correlated to known variables, and (2) do snowpack trends exist and are they a function of the period of record.

2 Study sites

Almost 80 years of data were collected at the six stations that are all within 20 km of one another and span a 640 m elevation range (Table 1). However, at the lowest station (Big South), snow typically peaks on or before 1 April at an average SWE of 77 mm and snow depth of 0.282 m, while 10 km away at Cameron Pass, an average peak SWE of 664 (d_s of 1.865 m) occur on or after 1 May, except in very low accumulation years. Across the six stations the average SWE on 1 April is 343 mm with an average snow depth of 1.073 m.

3 Methods

For the six stations, the individual snow depth and SWE measurements were digitized from the NRCS field notes. The digitized data were checked by comparing the computed snowcourse average snow depth ($d_{s,i}$) and SWE (SWE_i) from all individual measurements to those computed in the field notes. Statistics were computed for each station from each month of snowcourse measurements; all extreme values were manually examined to ensure proper digitizing of the field notes.

The five stations established in the 1930s initially had between 15 (Big South) and 40 (Cameron Pass) individual measurements. This was reduced to the current number (Table 1) between the years 1945 and 1959. Only points that are currently measured were used in this analysis.

Density for each individual measurement was computed as the ratio of SWE to snow depth. For the snowcourse measurements, density should vary between about 150 and 450 kg m^{-3} (Fassnacht, 2011). These ρ_s bounds were also used to check the individual measurements. Some higher densities were computed for shallow, melting snowpacks. These were deemed to be a function of the precision of the measurements; d_s and SWE are measured to the nearest 2.5 cm and 12.7 mm, respectively. The coefficient of variation (COV) was computed for the three snowpack variables (d_s, SWE, ρ_s) from the average and standard deviation of the individual measurements at each station for each month over the entire period of record. The average of d_s and SWE were compared to the COV to determine if snowpack variability could be estimated from the snowcourse average.

To identify statistically significant monotonic trends in the snowcourse data, the nonparametric Mann-Kendall Test was used (Gilbert, 1987). When a trend was significant at the 5 or 10 % confidence level, the rate of change was computed as the Sen's slope (Gilbert, 1987). Trends were evaluated for the time series of individual months at each station; the Seasonal Kendall Test (Helsel and Hirsch, 2002) was not used to evaluate seasonal trends. However, the period of record used to evaluate a trend may influence its significance (Venable et al., 2012) so the entire period of record (1936–2014 in most cases) as well as the early period (1936–1975) and late period (1976–2014) were each investigated. These shorter periods approximately match the global temperature patterns indicating cooling from the mid-1940s through mid-1970s and rapid warming since.

4 Results

4.1 Variability

Even for 1 April, (395 station-months of data), there is substantial variability across the stations. The average snow

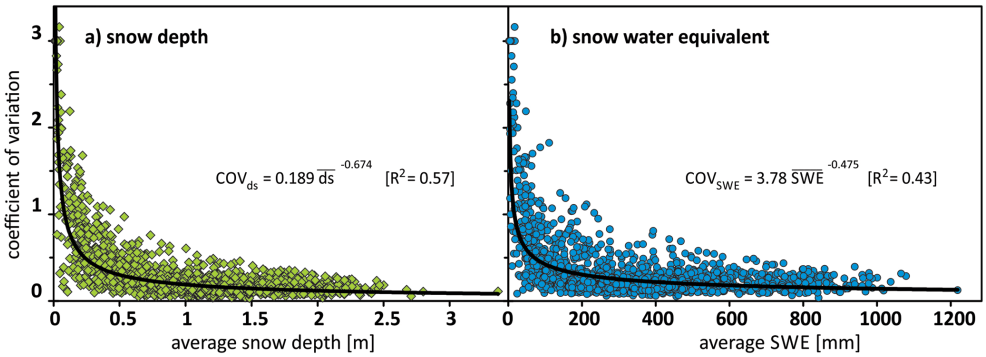

Figure 1. Correlation of the coefficient of variation with the snowcourse average for **(a)** snow depth, and **(b)** snow water equivalent.

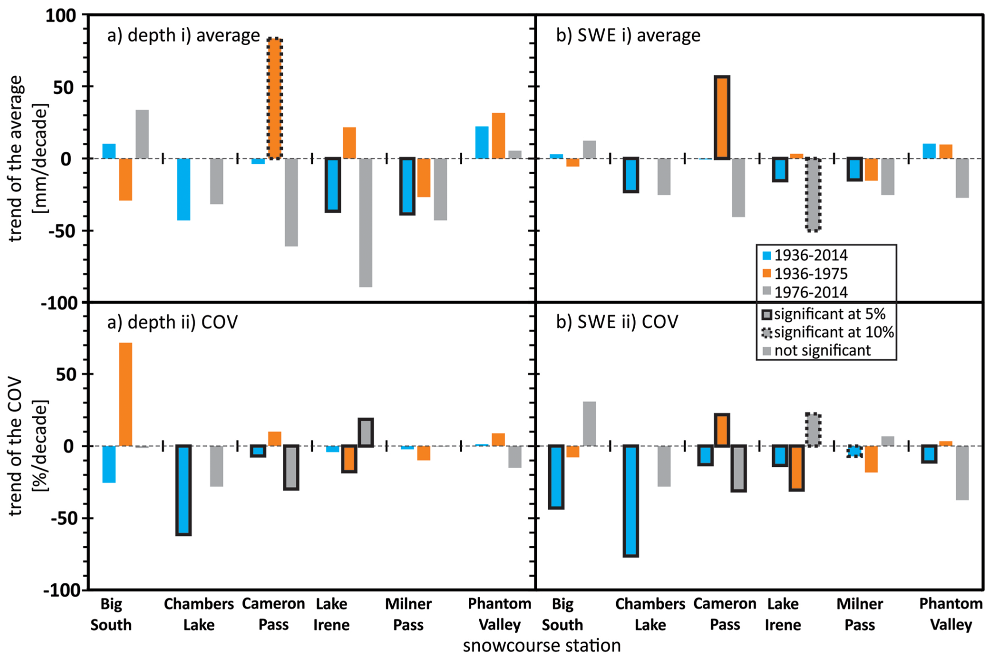

Figure 2. Summary of **(a)** snow depth and **(b)** SWE trends for the six stations over the entire period of record (1936–2014) and the two halves (1936–1975, 1976–2014) for (i) the average and (ii) the coefficient of variation. Trends are significant at the 5 % (solid outline) or 10 % (dashed outline) level. Non-significant trends have no outline.

depth was 1.073 m and ranged from 0.008 to 2.675 m, while the average COV was 0.315 ranging from 0.037 to 3.0. The variation in SWE was about the same with COV(SWE) averaging 0.35 and ranging from 0.062 to 3.0. However, density variation was much less with COV(ρ_s) averaging 0.0117 and ranging from 0.008 to 0.597. The largest COV is usually for a shallow snowpack, often where partial melt-out has occurred yielding some individual measurements of no snow.

While there is scatter in the correlation between the COV and average, a power function can be fitted (Fig. 1). The relation was better for depth than SWE with R^2 values of 0.57 and 0.43, respectively. A power function was also fitted to each station's dataset using all monthly measurements with similar constants of 0.1 to 0.28 individually versus 0.19 for all depth data, exponents of −0.58 to −0.96 individually versus −0.674 for all depth data, and R^2 values from 0.32 to 0.74. The power function did not fit as well for SWE (R^2 values from 0.03 to 0.52).

Using six monthly time periods (February through 1 June plus 15 May) for all stations yielded better results with a smaller range of constants (0.16 to 0.31) and exponents (−0.55 to −0.77) and improved R^2 values (0.46 to 0.75) for snow depth. For SWE, using the distinct time periods improved the fit of the power function (R^2 values from 0.41 to 0.65).

Since COV decreased as the average increased (Fig. 1), the average 1 April depth ($\overline{d}_{s1\ \mathrm{Apr},\,i}$) at station i and the day of the year (t) were used to adjust the power function constant and

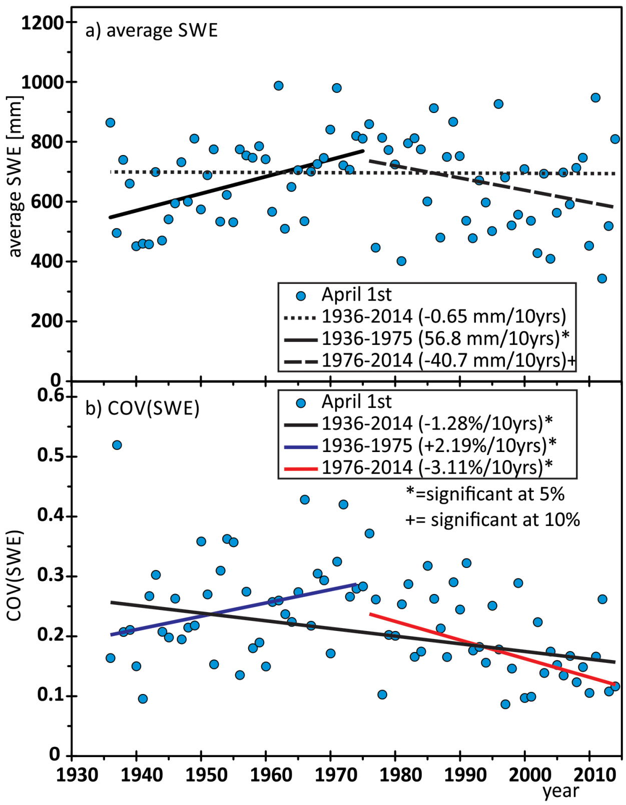

Figure 3. Trends in 1 April SWE at the Cameron Pass snowcourse over the entire period of record (1936–2014) and the two halves (1936–1975, 1976–2014) for **(a)** average, and **(b)** coefficient of variation.

maintain the exponent (Fig. 1a), yielding a snow depth coefficient of variation, COV($d_{s,i}$), that is a function of the snow depth averaged over the transect of individual measurements ($d_{s,i}$):

$$\mathrm{COV}(d_{s,i}) = \left[1.32 \times 10^{-2}\overline{d}_{s1\ \mathrm{Apr},\,i} + 1.31 \times 10^{-4} t + 0.188\right] d_{s,i}^{-0.674}. \quad (1)$$

Using all 1568 station-months of non-zero snow depth data, Eq. (1) has been modified from the equation shown in Fig. 1a yielding an R^2 value of 0.71 (and a Nash–Sutcliffe efficiency coefficient of 0.71).

4.2 Trends

Over the entire period of record, depth and SWE is decreasing significantly at two and three snowcourses, respectively (Fig. 2ai and bi), while both variables increase significantly for the first half of the record at the Cameron Pass snowcourse (Fig. 3a and b). Over the second half, depth and SWE significantly decrease. In general, there is a decrease in variability over time (Fig. 2aii and bii), but as with the averages, this depends on the period of record.

5 Discussion

Snowpack variability can be large, even over small scales (Blöschl, 1999). Depth and SWE tend to vary more as the snow season progresses (Fig. 1; Fassnacht et al., 2008), with quantity of snow and thus spatial variability being important (Eq. 1; Fassnacht et al., 2008). The individual snowpack measurements could be used to identify variability of the point or average measurements, especially since the point is often not representative of the surrounding area (Kashipazha, 2012; Meromy et al., 2013). Assimilation of the point data into models may force an alteration of the driving meteorology due mostly to the mis-representivity (Meromy et al., 2013).

The halving of the period of record matches the global temperature patterns that illustrate cooling from the mid-1940s through mid-1970s and then rapid warming since. The different direction in trends for some stations and variables (e.g., Fig. 3) may match temperature trends, but data are not available at these specific high elevation locations. Temperature trends tend to be less obvious at such higher elevations where snow accumulation is substantial (Pepin and Lundquist, 2008).

It is important that the conditions at the locations of the individual point measurements remain constant over the years so that the data collected from year to year accurately reflects snowfall Wells and Doyle (2004). If the snowcourses remain constant over time, for example the location of the individual point measurements or the forest overstory, then the variability between the individual measurements should also remain constant. However, over a 79 years, such as this period of snow data collection, there can be changes in the forest structure, since snow courses are predominantly located in forests that grow and die over time. Changes in the canopy could influence snow accumulation and ablation patterns and rates, yielding non-climate based snowpack trends (Julander and Bricco, 2006). Photographs were available the Big South, Chambers Lake and Cameron Pass snowcourses from 1941 and 1943 taken during data collection by Ralph Parshall (Jagelka, 1953) and colleagues http://hdl.handle.net/10217/23340. Visits to these three snowcourse in 2007 and 2014 showed that the Big South was still mostly in a meadow with Aspen (*Populus tremuloides*) trees at the north and south ends, and that the Chambers Lake snowcourse was still in an open meadow. The Cameron Pass site was and still is forested, and the canopy cover appears to be similar over the 70 years. No historical photographs were found for the other three snowcourses. Two of these snowcourses (Lake Irene and Milner Pass) have seen a significant decrease in both depth and SWE (Fig. 2) while Phantom Valley has not. However, the latter station was discontinued in 1990. Therefore, it is possible that canopy changes have occurred at these sites and further investigation in warranted.

1 April is usually not when peak snow accumulation occurs (Bohr and Aguado, 2001). The data used in this analysis

were collected on average 3.3 days prior to 1 April with the earliest 11 being measured on 24 March and the latest 2 being measured on 5 April. These deviations from 1 April were considered in computed Eq. (1), and can have an impact on the evaluation of trends (Pagano, 2012).

6 Conclusions

Across the Western United States, 1 April is used to represent peak snow accumulation using manual snowcourse measurements of the snowpack. These snowcourses consist of a set of 10 or more individual depth and SWE measurements. The variability across these individual measurement can be large and illustrate the uncertainty with use of the average across all the points. Peak snow depth and time of sampling can be used to estimate this variability.

Over the 79 year period of record (1936 to 2014), there is a significant decrease in depth at two snowcourses and SWE at three. When the entire period of record is divided into two halves (up to 1975 and from 1976), the trends tend to be increasing for the first 40 years and decreasing over the last 39, though often not significant. These opposite trends are more obvious with the coefficient of variation for both depth and SWE. Variability in SWE across the individual measurements is decreasing significantly at all six snowcourses over the first 40 years.

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