Non-Precipitation Variability of the Western United States Snowpack

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Abstract

Snowpack is crucial to water supplies in the western U.S. and it integrates the full range of climatic factors that affect snow accumulation. Changing climate may alter annual snowpack in many locations due to changing accumulation and ablation rates, the result of changing synoptic circulation patterns (differing air masses). Ablation depends upon the combination of many factors, including temperature, relative humidity, wind, cloud cover, solar inputs, and radiative balances. Many of these factors behave in a linear manner, but in combination they become chaotic in nature, thus the value of an index that integrates them. Precipitation is easily enough measured and independently evaluated on its own, but variability resulting from many of the other factors is more elusive. This study introduces a snowpack index (SI) as a way to evaluate the role of snowpack influencing factors beyond simply precipitation. Effectively, the SI is a measure of the winter precipitation that is sequestered in the snowpack. This paper examines the trends and variability of snowpack and its influencing components, precipitation, non-precipitation snowpack (SI) components, temperature, and elevation, for the western U.S. as a whole and by mountainous region for the past two decades (1979-1999).

Introduction

This paper examines changes in non-precipitation factors which impact the sequestration of winter precipitation in the form of snowpack in the mountainous western United States. Because winter precipitation will only be available in the spring and summer if it is sequestered in the snowpack (or captured in reservoirs), it is important to know if these non-precipitation variability factors are changing. The consistent global warming since the late 1970s has the potential to alter these factors, altering the ablation/accumulation balance. It is important to eliminate the effect of precipitation variability to accurately make such an assessment. Thus, this study uses the snowpack index (SI) which controls for precipitation variability. As an additional tool, plots of the SI as a function of temperature control for temperature variability as well, yielding a graphical picture of snowpack influencing factors independent of both precipitation and temperature. These factors include amount of solar radiation, cloud cover and type, night-time (long wave) radiation balance, relative humidity, wind speed and turbulence, and reflect synoptic conditions and air mass types.

Data

Snowpack snow water equivalent (SWE), precipitation (PPT), temperature data, and site elevations were obtained from the Natural Resources Conservation Service (NCRS) SnoTel database. SnoTel sites were used exclusively in this study because SWE, precipitation, and temperature are all measured at the same location. It is important for SWE and precipitation measurements to be co-located for accurate SI computation, as both variables are very heterogeneous over short distances. Table 1 lists
the number of stations used for April 1 data for the west as a whole and for each region. First of the
month values were used from January through June for the years 1979-1999, the study period.
Precipitation values are cumulative from October 1, and average SWE and PPT are the 1971-2000 mean. Cumulative temperature, used in this study, is the average maximum, minimum, or mean temperature from October 1 to the given date. Cumulative temperature more closely matches the snowpack exposure than other temperature summations.

Table 1 Number of stations used for April 1 data for the west as a whole and for each region

<table>
<thead>
<tr>
<th>Region</th>
<th>Total</th>
<th>SI Index</th>
<th>SWE</th>
<th>PPT</th>
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<tr>
<td>West U.S.</td>
<td>621</td>
<td>555</td>
<td>614</td>
<td>610</td>
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<td>Arizona (AZ)/New Mexico (NM)</td>
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<td>25</td>
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<tr>
<td>New Mexico/Colorado (CO)</td>
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<td>41</td>
<td>43</td>
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<tr>
<td>Colorado</td>
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<td>Utah</td>
<td>70</td>
<td>67</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Idaho (ID)/Montana (MT)</td>
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<td>200</td>
<td>221</td>
<td>214</td>
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<tr>
<td>Oregon (OR)/Washington (WA)</td>
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<td>97</td>
<td>116</td>
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<td>California (CA)</td>
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<td>Wyoming (WY)</td>
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<td>19</td>
<td>23</td>
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</tr>
</tbody>
</table>

Analysis

The snowpack index (SI) is the percent of average snowpack divided by the percent of average cumulative precipitation on any given date. An SI of 1.0 indicates there are no changes in non-precipitation snowpack development factors. Values of less than one indicate an increase in these factors that ablate snowpack, and values greater than one an increase in these factors that accumulate snowpack (independent of precipitation). To further clarify, an index value of one indicates non-precipitation factors on snowpack development are unchanging. This is true even if the actual snowpack is higher or lower than average on any year. An index value of less than one indicates that less of the winter precipitation is being stored in the snowpack, and a value greater than one indicates more is stored. Thus, the SI is a standardized index, normalizing for precipitation variability, and integrates the remaining variability factors, such as temperature, cloudiness, wind, relative humidity, solar and radiative effects.

In addition to analysis of the west as a whole, SWE, precipitation, and SI analysis was done for the four quadrants of the western U.S., separated at 40° north latitude and 112° west longitude. Then, eight smaller regions, roughly corresponding to mountain ranges, were used. Five of these roughly correspond to the spatial patterns identified by Cayan (1996) based on April 1 SWE rotated principal components analysis. Cayan’s regions were named Idaho, California, New Mexico, Oregon, and Colorado in descending order of variance. The corresponding regions in this paper are ID/MT, CA,
NM/CO, OR/WA, and CO, respectively. This work also has AZ/NM (southern Arizona/New Mexico), Utah, and Wyoming regions, because they are spatially separate groups of mountain stations with reasonable statistical depth. The CA (California) region is not representative of the entire state, because only SnoTel stations were used, and these form a tight cluster of stations near the Nevada border at the bend in the state line (39°N 120°W). Although there are many excellent snow reporting sites in California, only SnoTel stations were used because of their co-located SWE and precipitation measurements.

The SI was also computed for different elevations and temperatures.

**Results and Discussion**

**Full Western U.S.**

Bi-linear saddle surface trend analysis shows an SI gradient from northeastern Montana (SI>1) to southern California and New Mexico (SI<1) (Figure 1a). Similar analysis shows minimum temperatures (Figure 1b) to be strongly longitude dependent (warmer to the west). The maximum (Figure 1c) and mean (Figure 1d) temperatures are coldest in northeast Montana, and increase toward southern California, where they are warmest.

Annual trends for April 1 data were significant for both cumulative maximum (0.15°C/year at 100% level) and minimum (-0.261°C/year (98.7% level) temperatures. This indicates the range of cumulative temperature is increasing with time, counter to global and many regional trends. It may be that the higher, remote locations are not experiencing the same temperature trends of the lower lands where many of the other temperature records originate. Increasing max-min temperature ranges could be from a decrease in both day and nighttime cloudiness. However, since precipitation is not declining (see later) in these areas, perhaps the storms are shorter and more intense (increasing hydrologic cycling?).

The SI trend was -0.007, but not significant at the 85% level. Similarly, SWE and cumulative precipitation trends were not significant.
Figure 1 Surface Trend Analysis of April 1 conditions. (a) SI are highest in the upper left with the SI=1 contour across west Montana and NE Wyoming. They trend to the lowest values in the south. (b), (c), (d) are the surface trends for cumulative mean, maximum, and minimum temperatures, respectively. The 0°C maximum contour is roughly in the same place as the SI=1 contour.
The spatial distribution of SI (Figure 2) shows values >1 in the interior regions, and lower values at regions closer to the Pacific Ocean. The Arizona and New Mexico values > 1 are most likely statistical artifacts due to low sample size in the earlier years. This supposition is consistent with regional analysis which shows the values to be lower than one in the 1990s. Also, the areas of SI>=1 west of longitude 118°W, are without station data, therefore suspect of being artifacts.

Figure 3a shows a tendency for SI to be lower at low elevations and higher at upper elevations. Below about 1300 meters, there are more SI values less than 1, and the frequency of values greater than 1 increases at higher elevations. This relationship is consistent with more maritime mountain ranges dominating the signal at lower elevations. The snowpack is more vulnerable to slight temperature fluctuations in regions where the mean temperature is close to the melting point. This is the case in more maritime regions compared to interior, continental areas where maximum temperatures stay well below zero centigrade most of the winter. Figure 3a shows little time evolution of the SI, consistent with the finding that there is no significant trend with time. SWE (Figure 3b) and total winter precipitation (Figure 3c) are highest in the middle and low elevations, reflecting the increased moisture supply in the mountains closest to the Pacific Ocean compared to the higher and drier ranges of the interior west. There may also be a slight trend toward increasing SWE and precipitation at the low to middle elevations.

Figure 2 Location of the SnoTel sites used in this study (small triangles) and contours of the April 1 SI. SI values of one or greater are more prevalent in the interior western U.S.
Figure 3 Elevation versus time distributions of SI (a), SWE (b), and cumulative precipitation (c) on April 1. In all cases, there is more elevational variability than temporal.
Temperature dependence on elevation and time is shown in Figures 4 a-c. The correlations of temperature and elevation are significant at the 0.0000 level for mean, maximum, and minimum temperatures. Possible temporal trends of possible cooling at elevations of 1750-2800 meters, and slight warming above 3000 and below 1500 meters, particularly for minimum temperatures, are suggested.

Figures 5 a-c show the relationship of SI to time and cumulative winter temperature (Oct 1 - Apr 1). These figures show SI temporal variability at any given temperature. In effect, we are controlling for temperature with such a plot, and the SI controls for precipitation. The result exposes snowpack sequestration factors independent of both precipitation and temperature variability. An overall decline in SI is particularly noticeable in the mean temperature plot, below -15°C and above 5°C. There is also a band of increased SI, often greater than 1, near 0°C for mean and minimum and around 8°C for maximum temperatures. The decline at the coldest temperatures may suggest increased clear skies and windiness, often following storms in continental areas at least. Both factors can increase ablation. The band of increasing SI mentioned above could reflect temperatures during a snowstorm (increased cloudiness and decreased wind). The depressing effect of cloud and wind (and other factors) on ablation is apparent since the SI is precipitation invariant. By this same course, factors decreasing ablation are seen to dominate at 0°C and those that increase ablation at less than -15°C.

**Western U.S. Monthly Results**

Figure 6 shows the percent of average SWE, precipitation, and SI by month. The mean 1979-99 precipitation is about average for every month, but mean SWE declines from January to June, the decline in Jan-Mar being quite small compared to May and June. This is reflected in the SI values of less than one in every month. This decline in the amount of moisture sequestered in the snowpack is the result of less snowfall, not less precipitation.

Correlations of SWE to mean SWE and precipitation to mean precipitation (Figure 7) show that average conditions are most likely to exist on April 1 for SWE and May 1 and June 1 for precipitation, and that SWE is more variable than precipitation.
Figure 4 April 1 cumulative temperature distribution as a function of elevation and time: mean, maximum, and minimum (a), (b), and (c) respectively. All temperatures are significantly correlated with elevation (100% level), but not with time. This figure suggests temperature are increasing at lower elevations and are decreasing at higher elevations.
Figure 5 April 1 SI distribution as a function of cumulative temperature (mean, maximum, minimum (a), (b), (c) respectively) and time. Reading across horizontally eliminates temperature variability and the SI eliminates precipitation variability, allowing inspection of snowpack factors other than these two major ones. Such factors include relative humidity, wind, solar radiation, long wave radiation flux, and cloud cover. There is a band of maximum SI values. This is around zero mean and minimum, and 8°C for maximum temperature.
Figure 6 Conditions on the first of each month, Jan-Jun. Precipitation values remain normal all months, but the SWE and especially the SI decline as the winter progresses.

Figure 7 Monthly correlations of SWE and cumulative winter precipitation with their respective average values. Snowpack correlations are lower than precipitation correlations suggesting greater variability in snowpack than precipitation.

**Western U.S. ENSO Results**

Figure 8 shows the percentage of SWE, precipitation, and SI by ENSO phase. Most striking is that La Niña is the only ENSO phase to positively affect the SI (greater than one). This is due to an increase
in SWE, not precipitation. Analysis by quadrant (Figure 9) shows this to be entirely a Pacific northwest contribution. Figure 9 also shows the northwest is most variable and the northeast region the least, by ENSO phase.

Figure 8 April 1 conditions by ENSO phase. SWE and SI are vary more by ENSO phase than precipitation, and are lower in all phases except during La Niña when they exceed normal levels (they are greater than one). Cumulative precipitation is also greater than average (normal) during La Niña and neither (neutral) ENSO phases.

Figure 9 April 1 SI is declining (<1) during all ENSO phases in all quadrants of the western U.S. except in the northwest during La Niña.
Results by Quadrant

SWE, precipitation, and SI were analyzed in the four quadrants of the western U.S., separated at 40° north latitude and 112° west longitude.

Figure 10 shows the variability of SWE, precipitation, and the SI by quadrant. SWE and SI variability were greatest in the northwest, consistent with the SI results of Figure 9, but precipitation variability was greatest in the southwest. The least variability of all three factors was found in the northeast quadrant.

Figure 11 shows 1979-1999 precipitation to be greater than average (1971-2000) in both southern quadrants and less than average in both northern ones. The relative proportion of winter moisture (1979-1999) sequestered in the snowpack, however, is less than average (1971-2000) in all quadrants; the greatest decrease is in the southeast, and least in the northeast ones. This is not because of a decline in winter moisture, since the southwest has received 103% of average, and the southwest 104% for the comparable period. In these regions there has been an increase in precipitation, but a decrease in the relative amount that fell as snow, resulting in the low SI values. The northeast quadrant appears to have the least change in SWE, precipitation, and SI. This may reflect its position relative to large scale (synoptic) circulation, being more removed (north) from the boundary of shifting jet stream tracks, than the other three quadrants. So, although the northeast appears to be the least changeable in the past two decades, all quadrants show decline in the relative proportion of winter precipitation sequestered in their snowpack.

Figure 10 Variability (standard deviation) of April 1 SWE, cumulative precipitation, and the SI. Precipitation is least variable in all quadrants, and SWE is most variable. The northeast is the least variable quadrant, and the northwest the most. Variability in the south is virtually the same in the east and west quadrants.
Results by Region

Analysis of the eight regions (Figure 12) suggests the strongest temporal trends are in southern AZ/NM and northern NM/southern CO, where the SI declines strongly over time at all elevations. Much of this decline is from SI values of greater than one to less than one. Colorado and Utah also show similar, but weaker, trends at middle to lower elevations. The SI in the ID/MT (Idaho/Montana) area is relatively stable over time, but SI less than 1 is more frequent than SI greater than 1. The SI in the OR/WA (Oregon/Washington) area is also fairly stable with time, but the SI may be increasing at elevations above 1600 meters. The Wyoming (central and eastern) SI values are less than one below 2400 meters, and declining below 2600 meters. The SI is greater than one between 2600 and 2800 meters, and also above about 2950 meters, and increasing at all elevations above 2600 meters. In the California group (clustered about 39°N 120°W) the SI is increasing at all elevations, and greater than one at most heights, particularly between 1950 and 2400 meters. Note that this is not spatially representative of California, but it is the strongest signal of winter precipitation sequestration in snowpack at any of the eight areas and also a region of high absolute snowpack, representing significant amounts of water.
Figure 12 Depiction of the April 1 SI by elevation and time in eight regions of the western U.S. In general, the SI values are least changing (SI=1) at higher elevations, and in the earlier years. Southern regions show the largest change, and this is at all elevations. Northern regions show the least change, and possibly even an increase (SI>1) in the higher elevations of Oregon/Washington.
Summary
The SI provides a way to eliminate precipitation variability when looking at the factors effecting the sequestration of winter precipitation in snowpack. The study results suggest that winter precipitation sequestered in western U.S. mountain snowpacks is declining, and this is not due to reduced precipitation, nor is it evenly distributed by elevation or region. Often the decline is greater at lower elevations, and in the southern portion of the western U.S.

Reference