

Relationships between Atmospheric Circulation, Mountain Snowpack and Adjacent Lowland Precipitation in the Western U.S.



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Introduction

High elevation snowpacks provide vital water sources for an increasing population in the western U.S. Some of the many issues related to montane snowpack include recreation and tourism, hydrology and water supply.

Hence there is continued interest in monitoring of snowpack changes (Cayan 1996, Serreze et al 1999, Clark & Serreze 2001, Mote et al 2003).

This research examines past variability in snowpack, as measured by Apr 1 Snow Water Equivalent (SWE), in three mountain ranges: The Northern Colorado Rockies (NCR), Northern Sierra Nevada (NSN) and Northern Oregon Cascades (NOC). The relationship with simultaneous lowland winter precipitation (LWP) is also examined.

- Individual analyses examine:
- Past trends in SWE & LWP, and their relationship
 - Differential Circulation controls on SWE
 - Anomalous circulation associated with extreme years (high and low SWE) in each mountain range

Conclusions regarding the relative sensitivities of snowpack in the three locations to environmental change are obtained.

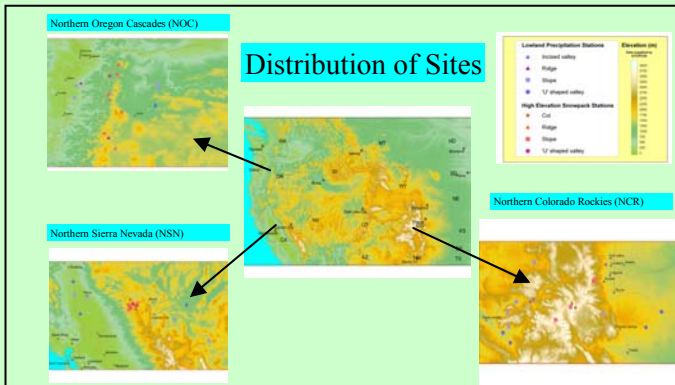
Data

Apr 1 SWE for 1937-2000 inclusive was obtained from U.S. Snow cover records, available from the National Resources Conservation Service (NCRS) for Colorado and Oregon, and the California Department of Water Resources for California.

For each mountain range, we divided the sites into east and west slopes, since transverse variability along each mountain range is much smaller than that across it. To eradicate specific site influences on snowpack we selected sites without incised topography and used the mean of several sites to characterise each slope (Table 1). Urban sites were not used.

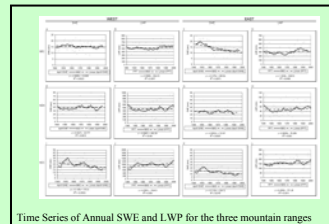
LWP is the total cumulative October 1 – April 1 winter precipitation (solid and liquid) obtained from National Weather Service (NWS) Stations through the National Climatic Data Center (). Details of lowland sites are given in Table 2. Again the mean of several sites was calculated as representative of the "slope". Most lowland sites are in valleys or relatively flat basins.

Both SWE and LWP only represent a small part of the mountain range in which they are situated.



Trends in SWE and LWP

Long term trends in annual SWE and LWP were examined for 1937-2000 (see below). In most cases there is decoupling between SWE and LWP. SWE shows significant decreases in three cases (eastern slope of the NCR and both slopes of the NOC) but in each case LWP fails to show an attendant decrease.



Lowland precipitation is not the major influence upon montane snowpack because:

- Depending on the elevation of the freezing level, heavy rain at low elevations can mean heavy snow at higher elevations, or strong ablation in heavy rain.
- Orographic enhancement of precipitation depends on synoptic conditions
- SWE is not just a function of accumulation but also ablation, which is also influenced by cloud cover, radiation balance and wind temperature.

Discussion and Conclusions

We analysed Apr 1 SWE and LWP on both the east and west slopes of three mountain ranges in the western U.S.: the Northern Colorado Rockies (NCR), Northern Sierra Nevada (NSN) and Northern Oregon Cascades (NOC).

Trends in LWP and SWE were found to be decoupled. Although SWE is decreasing in three locations (both slopes of NOC and the east slope of the NCR), LWP does not decrease.

The relationship between SWE and circulation is assessed through representation of anomalous 700 mb circulation for years of high SWE minus years of low SWE. Required flow directions are dissimilar in each case. LWP signatures on the other hand are more similar. In each case the circulation signature in the NCR is weak.

- This implies that
- The Colorado Rockies are the least sensitive to future changes in circulation, both because of the low mean winter temperatures at snowsource elevation and more than one precipitation source. In contrast, the Northern Oregon Cascades the most sensitive.
 - Even in future changes in lowland winter precipitation are similar, attendant changes in upland snowpack will differ.

Local Circulation Analysis

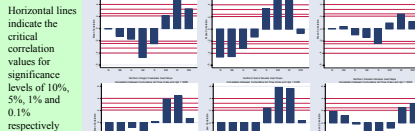
At each locality the daily 700 mb circulation pattern was classified using an objective scheme (Hulme et al 1993) designed to replicate the Lamb classification. Such a scheme takes isobaric curvature and airflow direction into account. Indices were then accumulated based on a scoring system (example below) to represent the tendency towards a particular flow direction in a season (ONDJFM).

Index scoring for raw northerly airflow index (other airflow directions are treated similarly). Synoptic types with flow direction corresponding to the named flow in the index, are scored as 2, and adjacent flow directions as 1. Scores are added up for each day for the five months preceding April 1. Vorticity has no influence on the raw airflow index scoring.

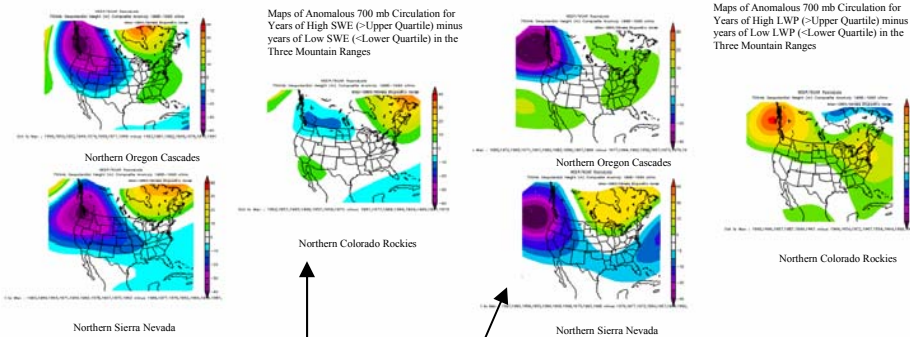
| | | | | | | | | | |
|-------------------------|----|-----|----|-----|----|-----|----|-----|---|
| Synoptic Category Score | N | NE | E | SE | S | SW | W | NW | U |
| | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| Synoptic Category Score | CN | CNE | CE | CSE | CS | CSW | CW | CNW | C |
| | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| Synoptic Category Score | AN | ANE | AE | ASE | AS | ASW | AW | ANW | A |
| | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |

The figure below shows the correlation between Apr 1 SWE and the raw airflow indices in each mountain range, illustrating the importance of flow direction in controlling snow accumulation in each case. Strong relationships in the Cascades and Sierra are informative. An important difference between the two cases, is the shift towards westerly and north-westerly flow in the Cascades (as opposed to south-westerly in the Sierra), and the strong negative relationships experienced under northerly and north-easterly flow in the Sierra but not in the Cascades. Thus flows from the Nevada basin must accelerate ablation in the Sierra (as well as being lacking in new accumulation).

Correlations between raw air flow indices and Apr 1 SWE in the three mountain ranges



The Rockies show very weak relationships, indicating that snow accumulation can take place both under westerly and easterly regimes. The well-known influence of large upslope events on the eastern slope in bringing heavy snow to the lower elevations of the Front Range, are not realised in these long-term relationships, possibly because a daily accumulated index for the whole winter season is not unduly influenced by these low frequency events. An alternative explanation is that at the high elevations studied here (3200 m) these events are less influential in building up the Apr 1 snowpack, and frequently occur after this date anyway.



Synoptic Signatures for Unusual Years

The top left set of maps shows the anomalous circulation at 700 mb for years of high SWE (defined as occurring in the top 25% of all years) minus years of low SWE (defined as the lowest 25% of all years) in each mountain range. The maps therefore show anomalous flow associated with high SWE in that particular mountain range. In NOC the anomalous flow is north-westerly over the Cascades and Pacific North-West, whereas in NSN the flow is south-westerly. This even though the position of low pressure is broadly similar in both cases, surface flow shows substantial differences. There is no strong circulation signature for the NCR, suggesting that SWE is largely insensitive to circulation in this region.

The circulation signatures for LWP (top right set of maps) are more similar (comparing NOC and NSN) with south-westerly flow components over the western U.S. in both cases. The low pressure system is situated slightly further south in the later case, transferring the strongest anomalous flow component (and associated storm track) further south.

Finally the maps to the right show the anomalous 700 mb circulation for the year of high SWE in all three ranges (Figure 4). In this year the strong onshore flow covered both NOC and NSN, and the presence of cyclonic curvature close to the Pacific coast, must have ensured that temperatures were low enough for heavy snowfall in the NOC. Figures b, c and d show conditions in years of low SWE in all three ranges. Anomalous high pressure is a feature of all of these, especially strong in the most severe case, 1981.

700 mb Composite Circulation Anomaly Maps for Extreme Snowpack Years: a) 1956 (high snowpack), b) 1981, c) 1977 and d) 1991 (low snowpack)