OBSERVED HYDROLOGIC CONSEQUENCES OF CLIMATE CHANGE IN WESTERN NORTH AMERICA

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ABSTRACT

Measurements of spring snowpack, corroborated by a physically-based hydrologic model, are examined here for climate-driven fluctuations and trends during the period 1916-2002. Much of the mountain West has experienced declines in spring snowpack, especially since mid-century, and despite increases in winter precipitation in many places. Analysis and modeling shows that climatic trends are the dominant factor, not changes in land use, forest canopy, or other factors. The largest decreases have occurred where winter temperatures are mild, especially in the Cascade Mountains and Northern California. In most mountain ranges, relative declines grow from minimal at ridgetop to substantial at snowline. These results are further corroborated by observed changes in streamflow toward earlier peak snowmelt, lower summer flow, and higher winter flow. Taken together, these results emphasize that the West's hydrologic resources are already responding as Earth's climate warms.

INTRODUCTION

Winter and spring temperatures have increased in western North America during the 20th century (e.g., Folland et al. 2001), and there is ample evidence that this widespread warming has produced changes in hydrology (Cayan et al., 2001; Regonda et al., 2004; Stewart et al., 2004), as is expected in a warming climate (Hamlet and Lettenmaier, 1999). Mote (2003a, 2003c) analyzed snow course data for the Pacific Northwest and showed substantial declines in snowpack at most locations. Relative losses depended on elevation in a manner consistent with warming-driven trends, and statistical regression on climate data also suggested an important role of temperature both in year-to-year fluctuations and in longer-term trends at most locations.

The present paper expands the spatial extent of analysis to incorporate the entire West and corroborates the analysis of snow data using a hydrological model. Trends in observed snow data may reflect climatic trends or site changes (e.g., growth of the forest canopy around a snow course) over time; using the model, we attempt to distinguish the causes of observed trends.

DATA

Snow course data through 2002 were obtained from the NRCS Water and Climate Center (www.wcc.nrcs.usda.gov/snow/snowhist.html) for most states in the U.S., from the California Department of Water Resources for California (cdec.water.ca.gov), and from the Ministry of Sustainable Resource Management for British Columbia (srmwww.gov.bc.ca/aib/wat/rfc/archive /historic.html). A total of 1,144 data records exist from the three data sources for the region west of the Continental Divide and south of 54°N. At a number of locations a SNOTEL site has replaced or augmented a snow course with sufficient overlap that statistical estimation of the one value is possible in the absence of the other; in these cases NRCS provides two complete time series, with the estimated values flagged. In these cases both are candidates for inclusion because the estimates of long-term trends turn out to be slightly differ-

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ent. Of the 1,144 data records, 824 have April 1 records spanning the time period 1950-1997 and are used in most of the analysis. For some analyses, a larger subset of the 1,144 snow courses was used.

As in Mote (2003a), the April 1 SWE measurements are compared statistically with observations at nearby climate stations for the months November through March, which roughly corresponds to the snow accumulation season. These climate observations (see also Mote, 2003b) are drawn from the US Historical Climate Network (USHCN) (Karl et al., 1990) and from the Historical Canadian Climate Database (HCCD) (Vincent and Gullett, 1999). Climate data from the nearest five stations are combined into reference time series. There are a total of 394 stations with good precipitation data and 443 with good temperature data.

MODEL

The Variable Infiltration Capacity (VIC) is a physically-based hydrologic model (Liang et al., 1994; Hamlet and Lettenmaier, 1999) that accounts for fluxes of water and energy at the land surface and includes three soil layers and detailed representations of vegetation to simulate movement of soil moisture upward through plants and downward through the soil by infiltration and base flow processes. The simulation presented here covered the entire West from the Continental Divide to the Pacific, from the Columbia Basin to the international border with Mexico, at a resolution of 0.125° (longitude) × 0.125° (latitude); details may be found in Hamlet et al. (2004) and Mote et al. (2005).

RESULTS

We first examine the spatial distribution of trends by considering the slope of linear fits to April 1 SWE for 1950-1997 (Figure 1) for both observations and VIC, and for the entire VIC simulation (1916-1997). For the 1950-97 period, negative trends prevail at roughly 75% of snow courses and 73% of VIC grid cells. The largest relative losses (many in excess of 50%, some in excess of 75%) occurred in western Washington, western Oregon, and northern California. Increases in SWE, some in excess of 30%, occurred in the southern Sierra Nevada Mountains of California, in New Mexico, and in some other locations in the Southwest.

Many of the details are similar in VIC and in observations: for example, the mix of increases and decreases on the Arizona-New Mexico border, the increases in central and southern Nevada and decreases in eastern Nevada, and the increases in southwest Colorado. In addition, the VIC simulation shows that in most mountain ranges, the relative losses go from negligible at high elevations to substantial at low elevations, a feature that indicates the role of rising temperature in these changes.

Over the longer period of the entire VIC simulation, the pattern of trends is similar (Figure 1c) to the period since 1950 (Figure 1b), but the relative changes are smaller mostly because the 1950s were very dry in the Southwest and fairly wet in the Northwest. It is clear that changes in SWE are not simply linear, but fluctuate on decadal time series. Spatially averaged (VIC) or aggregated (snow course) data for each of the four regions delineated in Figure 1 show similar interannual and interdecadal variations: correlations between observed and modeled regional SWE are 0.88 for the Cascades, 0.75 for the Rockies, 0.96 for California, and 0.77 for the interior. In all regions SWE probably declined from 1915 to the 1930s, rebounded in the 1940s and 1950s, and despite a peak in the 1970s SWE has declined since mid-century.

CAUSES: THE CLIMATIC CONTEXT

As a starting point for understanding the role of climate in the observed variability and trends in SWE, we calculate linear trends in November-March temperature and precipitation for the periods 1930-1997 (endpoints in low-snow periods) and 1950-1997 (to help interpret Figs 1a-b). Trends in temperature were overwhelmingly positive both from 1950 to 1997 and from 1930 to 1997: almost 90% of stations had positive trends in both intervals, and the rate of warming was faster in the 1950-97 time period. For the 1950-97 period, over half the stations had trends exceeding 1°C per century, and about half the stations had statistically significant trends, with a mean warming of 1.6°C per century.

For each snow course, we further clarify the separate roles of temperature and precipitation by calculating the correlation during the entire period of record between April 1 SWE and reference time series of November-March temperature and precipitation (see Data section for details). Throughout the West, the correlation with precipitation is positive, as expected. In the warmer parts of the domain – Washington, Oregon, Northern California, and the southwest – there is a substantially negative correlation with temperature and in some cases the correlation with temperature is stronger than the correlation with precipitation. Almost nowhere is the correlation with temperature positive, and nowhere greater than 0.2: warming by itself essentially never leads to greater snow accumulation.

The implication of these results in conjunction with Figure 1 is that the mountains in the Cascades and northern California have the greatest sensitivity to temperature, and regional warming in the absence of strong increases in precipitation would produce large declines of spring snowpack. Some locations in the interior West and Rocky Mountains are also susceptible to warming, but most are so cold that a warm winter has little effect on spring snowpack and winter precipitation is the major driver.

In order to quantitatively compare the roles of changes in precipitation and temperature in the long-term trends in SWE (Figure 1), we used simple multiple linear regression to characterize April 1 SWE at each snow course as a function of November-March temperature and precipitation from the nearest 5 climate stations:

$$SWE(t)=a_T T(t) + a_P P(t)+\varepsilon(t)$$

where a_T and a_P are the regression coefficients for temperature and precipitation respectively, and $\varepsilon(t)$ is the residual. We calculated these regression coefficients for every time series that had data for 1960-2002 and derived a climate-derived SWE value, then compared these with the observed SWE: the mean of the correlations between these pairs of time series is 0.71, and only 3% have correlations below 0.3; most of these are in Wyoming, where USHCN precipitation is sparse, or southwestern British Columbia where SWE may be more sensitive to the details of landfalling storms than to the mean climate conditions during the season.

The trends in observed SWE can then be compared with trends estimated by $a_T\langle T\rangle + a_P\langle P\rangle$, where $\langle x\rangle$ is the trend in x. For most snow courses, the estimated trend is of the correct sign but somewhat smaller magnitude. Examining the terms separately (not shown) reveals that at virtually every location, the term $a_T\langle T\rangle$ is negative, indicating that warming has acted to reduce SWE. In many places, negative trends in SWE resulted from competition between negative trends in $a_T\langle T\rangle$ and positive trends in $a_P\langle P\rangle$.

Further confirmation of the dominance of temperature trends in many areas comes from examining a VIC hydrologic simulation in which precipitation totals were forced to be the same each month of the year but temperature was allowed to vary as observed. In this "fixed-precipitation" run, the broad pattern of trends (Figure 1) is rather similar (not shown, but see Mote et al. 2005), but most grid points have negative trends and the elevation dependence suggested by Figures 1b and c is more widely evident. These results strongly suggest that essentially the entire mountain West would be experiencing negative trends in SWE were it not for increasing precipitation trends counteracting the effects of observed positive trends in temperature.

SUMMARY

The trends and variability in SWE can be seen approximately as the result of competition between fairly monotonic warming-driven declines at all but the highest altitudes, and more precipitation-driven increases and decreases. In the Southwest and in spots elsewhere in the West, high precipitation in recent decades has produced big increases in snowfall, resulting in higher SWE despite higher temperatures. In the Cascades, very large declines resulted from a double blow of decreases in precipitation and large increases in temperature in a region where snow courses have high temperature sensitivity (Figure 4). These declines are consistent with advances in the timing of spring snowmelt (Cayan et al., 2001; Stewart et al., 2004) and with elevation-dependent declines in snowpack noted in the Swiss Alps (Scherrer et al., 2004), and with projections of future declines in snowpack related to global climate change (e.g., Hamlet and Lettenmaier, 1999).

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