The West's Snow Resources in a Changing Climate

Testimony before the U.S. Senate Committee on Commerce, Science, and Transportation
May 6, 2004

Philip W. Mote, PhD*
Joint Institute for the Study of the Atmosphere and Ocean
Climate Impacts Group
University of Washington

Summary

Warming trends in the western U.S. have already produced significant changes in snow-driven hydrology. In the past 50 years, dates of peak snow accumulation and of peak snowmelt-derived streamflow have shifted earlier, typically by 10-40 days, and spring snowpack has decreased in most of the West (total decrease of 11% since 1950). Although a direct causal connection between the observed changes and rising concentrations of greenhouse gases cannot yet be established, it is likely that the declines reflect human influence. In many important respects, these observed changes are consistent with projections of future change in a warming world, where losses in the West's total April 1 snowpack are likely to exceed 40% by the 2050s. These observed changes point toward further reductions in summer water supply and increased demand.

Snow Resources

> "Snowpack is the lifeblood of the West and provides about 75% of the water supply in the West."
> – *Natural Resources Conservation Service, US Department of Agriculture*

In much of western North America, snow provides the primary means for storage of winter precipitation, effectively transferring water from the relatively wet winter season to the typically dry summers. Built storage (dams and reservoirs) and snow storage play varying roles in different parts of the West: built storage is largest – several times the annual flow – in the middle and lower Colorado River basin, and helps buffer California against large year-to-year variations in precipitation. Conversely, reliance on snow storage is substantial in the Northwest, where reservoirs on the Columbia River can store only about 30% of the annual flow and reservoirs in the Cascade Mountains store only about 10% of the annual flow.

Since the 1970's (e.g., ref. 5) scientists have pointed out that mountain snowpack would be reduced in a warming world. Recent research, summarized in this document, indicates that warming in much of the West during winter and spring has already produced declines in mountain snowpack (-11% averaged over the West), earlier snowmelt runoff, and lower summer streamflow. These changes have taken place in most of the mountainous West, except in places where large increases in precipitation have offset the

---

* This document prepared by Philip Mote with contributions from Alan Hamlet (UW), Iris Stewart (Scripps Institution of Oceanography (SIO), UC San Diego), Andrew Wood (UW), Tom Pagano (Water and Climate Center, USDA Natural Resources Conservation Service), Dan Cayan (SIO/UCSD), Lara Whitely Binder (UW), Dennis Lettenmaier (UW), and Martyn Clark (Univ. of Colorado).

warming-induced decline. The observed declines in snowpack and summer streamflow, and shifts toward earlier streamflow timing, have been largest in the mountains of Washington, Oregon, and northern California[6-9].

Trends in Snow and Snowmelt During the 20th Century and the Role of Temperature

In order to provide water supply forecasts for summer water users, the USDA Natural Resources Conservation Service (NRCS), California Department of Water Resources, and partner agencies collect measurements of snowpack each spring, most commonly around April 1. Analysis of these snowpack data indicate that much of the mountain West has experienced declines in spring snowpack (Figure 1), especially since mid-century, despite increases in winter precipitation in many places[3,6-8]. Analysis and modeling also shows that climatic trends are the dominant factor in the declines, not changes in land use, forest canopy, or other factors[7].

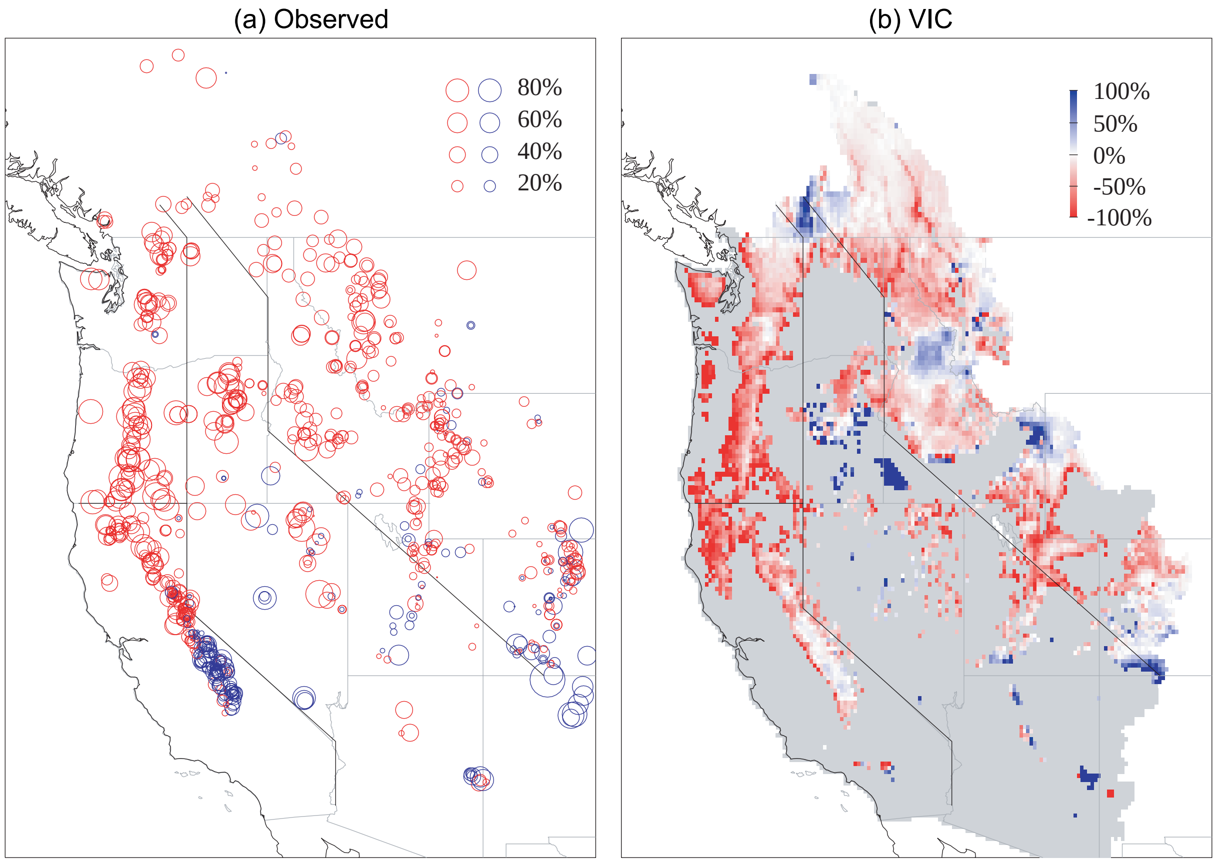
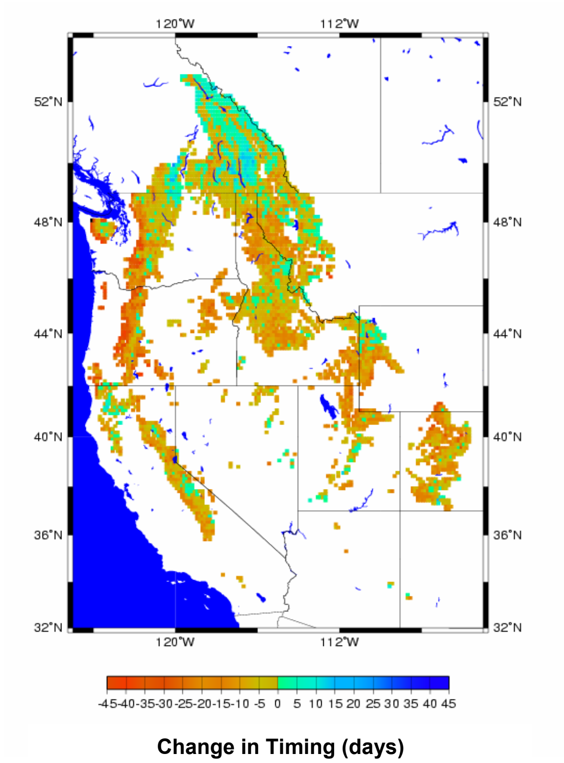


Figure 1. Linear trends (1950-1997) in April 1 snow water equivalent (SWE) relative to the starting value for the linear fit, (a) at 824 snow course locations in the western U.S. and Canada, with negative trends shown by red circles and positive by blue circles; (b) from a simulation by a hydrologic model (domain shown in gray).

Accompanying these declines in April 1 snowpack are trends toward earlier peak snowpack[6] (Figure 2) and earlier spring snowmelt, as measured by streamflow timing[1,8,9]. As a result, March flows have tended to increase and June flows have tended to decrease[9] (Figure 3), a pattern that is consistent with trends toward earlier peak snowmelt.

The largest decreases in snowpack and largest advances in snowmelt timing have occurred where winter temperatures are relatively mild (Figure 4), especially in the Cascade Mountains and Northern California, while cold high-elevation basins remain well below freezing even under considerable warming. In most mountain ranges, trends are minimal at ridgetop and grow to be substantial at snowline[7]. These local and regional patterns of trends point to a dominant role of temperature trends: snow accumulation and melt at locations with winter temperatures near freezing are most sensitive to temperature.



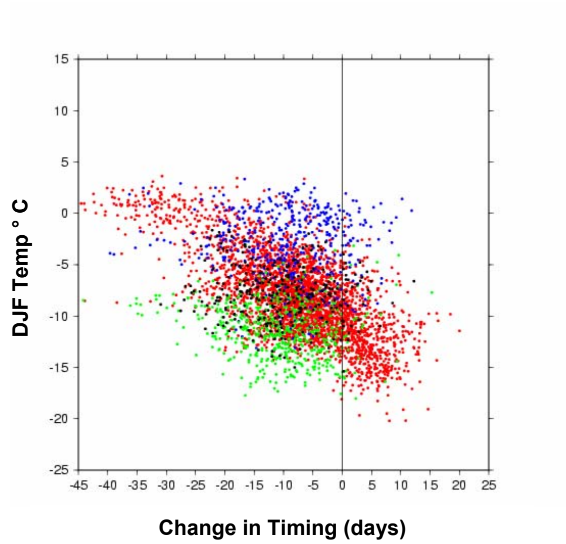


Figure 2. Trends (1916-1997) in timing of peak snow accumulation (left), in days, and (top) plotted against December-February temperature (°C). Red dots for points in the Northwest, blue for California, green for Colorado River basin, black for Great Basin.

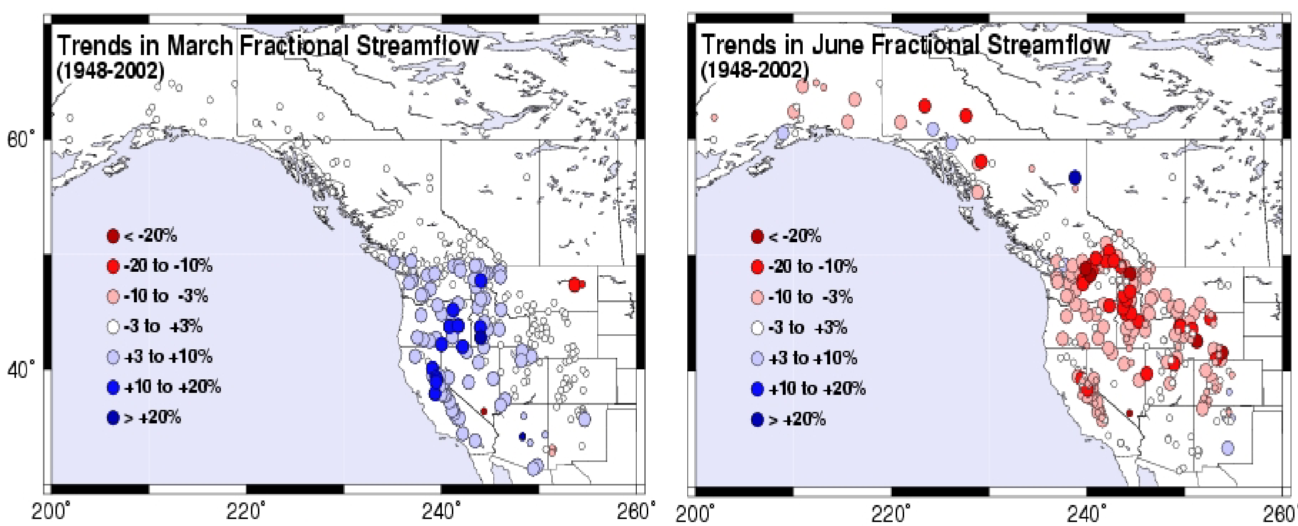


Figure 3. Trends in March (left) and June (right) snowmelt-derived streamflow as a fraction of annual total flow. The colored dots represent the percentage of change for a given monthly flow over the 1948-2002 period. Generally, March flows have been increasing and June flows decreasing, consistent with trends toward earlier peak spring flow. From Stewart, I.T., D.R. Cayan, and M.D. Dettinger (2004). Changes toward earlier streamflow timing across western North America, submitted to *Journal of Climate*.

2004 Record Losses

Between March 1, 2004 and April 1, 2004, many snow observation sites in the western U.S. posted record or near-record losses of snowpack (Figure 5). Unusually warm and dry weather, not necessarily long-term climate change, were responsible. These large drops in springtime snowpack exacerbate a drought that is in its seventh year in much of the West, and underscore the necessity of preparing to manage water in a warmer world with reduced snow storage.

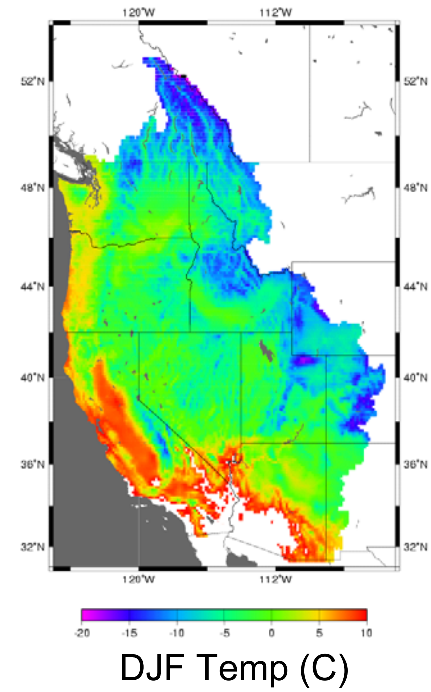


Figure 4 *(above).* Average December-February temperature. In addition to the Rockies, the southern Sierra Nevada mountains are quite cold and the Cascades and the mountains of northern California are milder and more susceptible to warm years or warming trends.

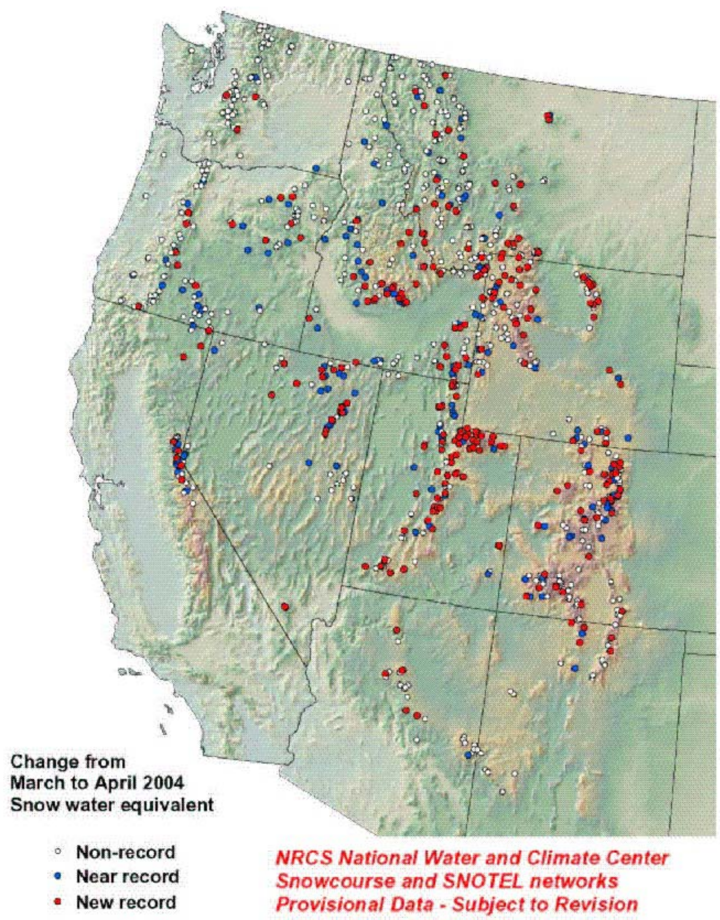


Figure 5 *(left).* March 2004 saw record (red) or near-record (blue) losses in snow at most snow observation sites in the West, owing to unusually warm and dry weather.

Snow and Streamflow in the 21st Century

Researchers have quantified the effects of higher temperatures on snowpack and streamflow using statistical techniques or numerical modeling (e.g., refs. 2 and 4). Warming inevitably produces declines in snowpack at moderate and lower elevations with earlier peak streamflow and reduced summer flows in a prolonged summer drought period[2, 4]. Under projected temperature increases from a global model that is relatively insensitive to greenhouse gas forcing, hydrologic simulations indicate that spring snowpack in much of the West would be substantially diminished by mid-century[4] (Figure 6). Models having greater response to climate warming produce substantially larger losses of snowpack. In areas where snowpack increased during the 20th century owing to large increases in precipitation, it is unlikely that precipitation will continue to increase fast enough to offset further warming at the pace expected for the western U.S. Even if the overall yearly precipitation did not change in the future, spring runoff that arrives earlier cannot necessarily be captured for summer water supply because of requirements to maintain flood control.

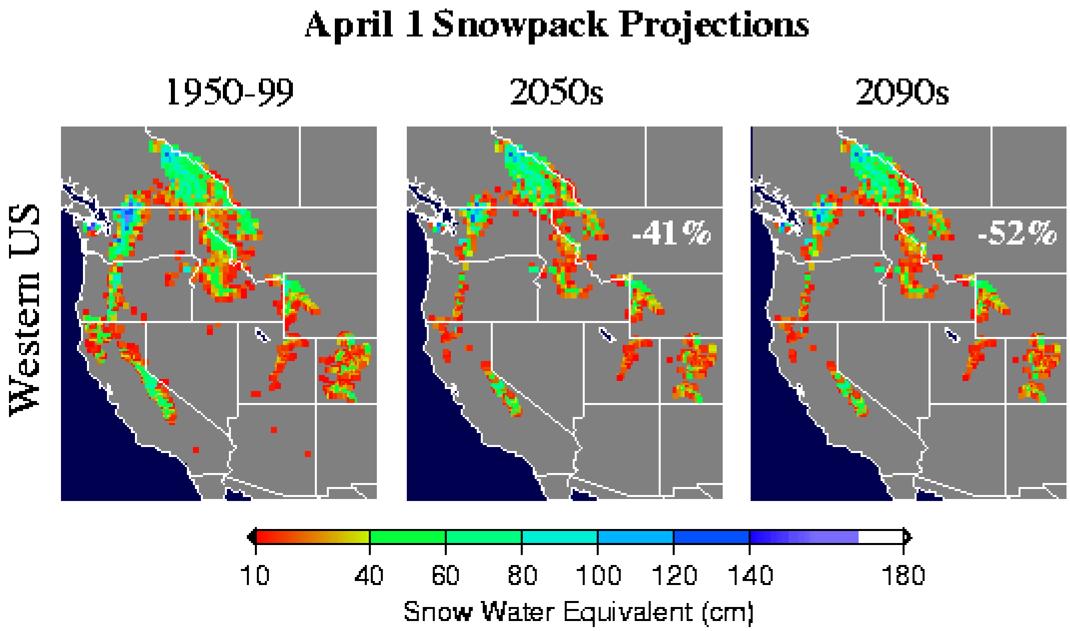


Figure 6. Simulated April 1 snowpack for a baseline (1950-99) climate, and for climate scenarios for the 2050s and 2090s provided by the NCAR Parallel Climate Model, a model with a low rate of warming. Percentage declines in total snowpack are shown.

The pattern of these simulated future changes is broadly similar to the observed trends in the 20th century, indicating that the stresses on western water resources experienced in recent years are foreshadowing much larger stresses to come. Even without the very likely increases in demand for water driven both by population growth and by the higher evaporative needs of plants, declines in summer water supply and shifts toward earlier peak snow will affect irrigated agriculture, instream flows for fish and wildlife, hydropower production, flood control, navigation, recreation, forest growth, severity of forest fires, and many other aspects of western economic and environmental health[2,4].

Adaptation

Agencies that manage water resources must begin to come to grips with the implications of warming, especially the likely reductions in summer flow[4]. New federal legislation may be needed to enable or require agencies to adapt to the changing flow regime: for example, to revise rule curves that govern the management of dams to aim for earlier reservoir refill, or to make decisions about water availability in the process of relicensing dams, to name just two examples. Consistent and widespread monitoring of climatic and hydrologic conditions is also critical.

References

Papers published in peer-reviewed journals

1. Cayan, D., S. A. Kammerdiener, M. D. Dettinger, J. M. Caprio, D. H. Peterson, Changes in the onset of spring in the western United States. *Bull. Amer. Meteorol. Soc.* **82** 399-415 (2001).
2. Hamlet, A.F., and D.P. Lettenmaier, Effects of climate change on hydrology and water resources in the Columbia River basin, *J. Amer. Water Resour. Assoc.* **35,** 1597-1623 (1999a)
3. Mote, P.W., Trends in snow water equivalent in the Pacific Northwest and their climatic causes. *Geophys. Res. Letts.,* **30**, DOI 10.1029/2003GL017258 (2003a).
4. Payne, J.T., A.W. Wood, A.F. Hamlet, R.N. Palmer, D.P. Lettenmaier, Mitigating the effects of climate change on the water resources of the Columbia River basin, *Climatic Change,* **62,** 233-256 (2004).
5. Gleick, P.H., Methods for evaluating the regional hydrologic impacts of global climatic changes, *J. Hydrology,* **88,** 97-116 (1986).

Papers submitted to journals

6. Hamlet, A.F., P.W. Mote, M.P. Clark, and D.P. Lettenmaier, Effects of temperature and precipitation variability on snowpack trends in the western U.S., submitted to *Journal of Climate*.
7. Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier, Declining Mountain Snowpack in western North America, submitted to *Bulletin of the American Meteorological Society*. philip@atmos.washington.edu
8. Regonda, S.K., B. Rajagopalan, M. Clark, and J. Pitlick, Seasonal cycle shifts in hydroclimatology over the western U.S., submitted to *Journal of Climate*, 2004. clark@vorticity.colorado.edu
9. Stewart, I.T., D.R. Cayan, and M.D. Dettinger, Changes towards earlier streamflow timing across western North America, submitted to *Journal of Climate*, 2004. istewart@meteora.ucsd.edu