

Regional Changes and Global Connections: Monitoring Climate Variability and Change in the Western United States¹

Henry F. Diaz²

Mountain ecosystems of the Western United States are complex and include cold desert biomes, such as those found in Nevada; subpolar biomes found in the upper treeline zone; and tundra ecosystems, occurring above timberline. Many studies (for example, Thompson 2000) suggest that high-elevation environments, comprising glaciers, snow, permafrost, water, and the uppermost limits of vegetation and other complex life forms, are among the most sensitive to climatic changes occurring on a global scale. The stratified, elevationally controlled vegetation belts found on mountain slopes represent an analog to the different latitudinally controlled climatic zones, but these condensed vertical gradients are capable of producing unique hotspots of biodiversity, such as those that serve as habitat for a variety of species ranging from butterflies, frogs, and toads to birds, trout, and salmon. High relief and concomitant environmental gradients make mountain ecosystems very vulnerable to slight changes of temperatures and extreme precipitation events.

Likewise, the role of mountain regions in providing life-sustaining water for communities in the western United States means that climatic and other environmental changes in these mountains will have a large impact not only on the region but in many other areas as well. In essence, mountain regions represent a discrete quantifiable domain where relatively small perturbations in global processes can have cascading effects on most or all of the myriad interdependent mountain systems, from hydrological cycles to complex fauna and flora distributions and abundances, to the people that depend on those resources.

What will changes in global climate mean at the regional scale? Are we monitoring the right things? Is the observing system adequate for the task? Can we find some critical systems at risk—"canaries in the mine"—that will alert us to imminent and perhaps irreversible changes starting in our mountain ecosystems?

Monitoring Climate Processes in the Western United States

As in any complex geophysical system, questions about the past, present, and future status of mountain environments in the western United States must be addressed through focused efforts to monitor and anticipate any ongoing changes and provide historical context for the measurements. Information on fundamental processes and patterns of local and regional change can be used to assess impacts of climate variability and mountain ecosystem vulnerability to change. This information is vital for optimal management of mountain ecosystems, conservation of their biodiversity, sustainable use of mountain resources and ecosystems, and preservation of the social and economic well-being of mountain communities in the western United States.

Meeting the challenges of observing, understanding, and predicting changes in our mountain environment requires sustained and stable funding and institutional support for long-term

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² Climate Diagnostics Center, NOAA/OAR, Boulder, CO.

multidisciplinary, multi-institutional efforts. Climate monitoring in mountain regions can be a difficult undertaking; developing the long baseline of observations needed to properly assess environmental changes on multiple time scales requires a long-term commitment to quality and stability. Climate-related signals can be subtle and are sometimes obscured by short-term variability; hence, changes in variability arising from changes in the measuring system can obstruct efforts to detect climate change.

Figure 1 illustrates the present coverage of weather-observation stations in the western United States (area west of the 100th meridian) as a function of elevation. I have conservatively assumed that each station is representative of a 100-km² area. The curve depicts the proportion of area that is occupied by the equivalent topography, in 1000-foot increments, using a high-resolution digital elevation model (DEM) of the western United States. This is simply the relative proportion of stations grouped by 1000-foot (approximately 300-meter) intervals. Of course, although the relative proportion of stations is similar to that of the topography, the actual physical coverage of those stations is rather meager. A sample area of 100 km² is perhaps overly restrictive with respect to surface temperature, which tends to be correlated to a relative radius. In regions of complex topography, however, typical decorrelation scales are often less than 100 km. *Figure 1* shows clearly that the alpine regions of western United States are grossly undersampled, and there is an obvious need for the development of a comprehensive climate monitoring program that would complement other long-term observation programs, such as for example, the Long-Term Ecological Research program.

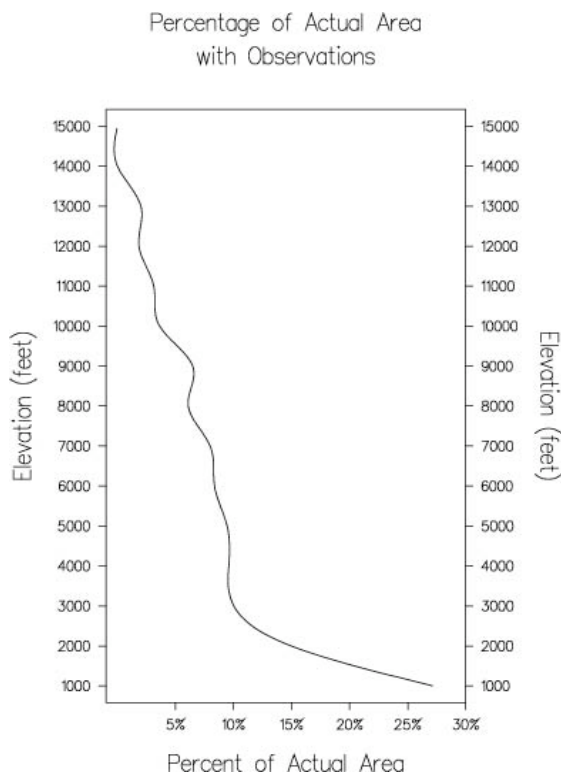


Figure 1— A conservative estimate of the percentage of actual area coverage with observations in the western United States. Values calculated assuming that each station is representative of a 100-km² area. Corresponding area is based on a high-resolution digital elevation model of western United States topography.

We have calculated 50-year surface temperature trends for the western United States based on the available long-term (stations with period-of-record ≥ 30 years) observation network, which contains 2,092 stations. The results are illustrated in *figure 2*. The statistical significances of the trends (not shown) vary from better than 10 percent (that is, $p < .10$) below 7,000 feet (approximately 2135 m) to not significant above that (possibly because of so few stations at higher elevations). Temperature increases fairly uniformly with elevation, averaging about 1°C per century over the entire region. The increases in mean minimum temperature are even slightly larger, amounting to about 1.5°C per century over the entire region (*fig. 3*). These changes have significant implications for the management of ecosystems and water resources management in the West.

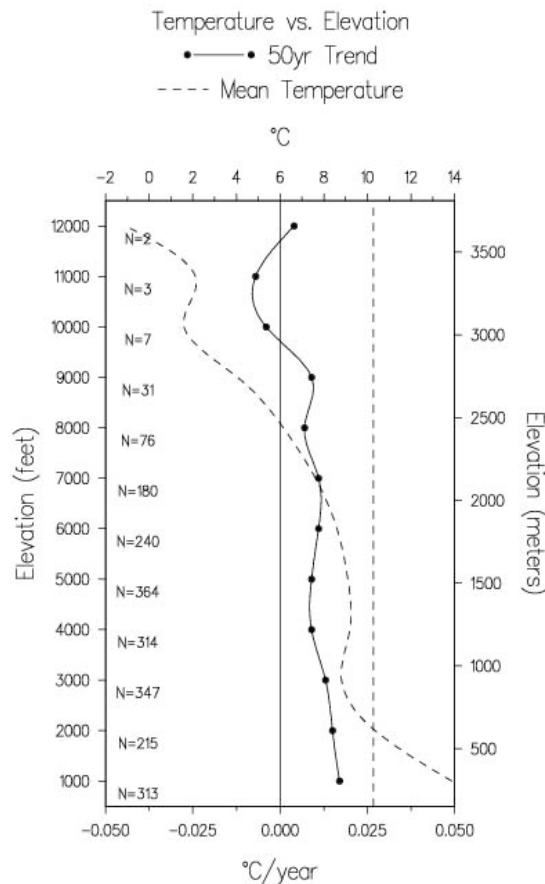


Figure 2— Median 50-year trends (1950–2000) of annual average surface temperature. Values are shown as a function of elevation for 2,092 stations in the western United States (west of 100°W) and are plotted in 1,000-foot (approximately 300-m) increments and smoothed using a rigid spline. The trend values are plotted against the annual mean temperature of the stations (dashed curve), averaged for each vertical segment, and based on the number of stations shown on the left side of the graph.

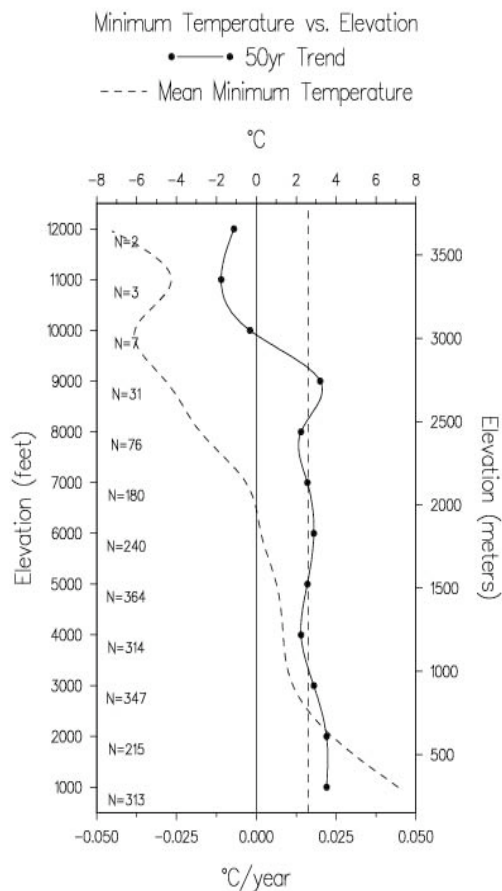


Figure 3— Median 50-year trends (1950–2000) of average annual minimum temperature. Values are shown as a function of elevation for 2,092 stations in the western United States (west of 100°W) and are plotted in 1,000-foot (approximately 300-m) increments and smoothed using a rigid spline. The trend values are plotted against the average annual minimum temperature of the stations (dashed curve), averaged for each vertical segment, and based on the number of stations shown on the left side of the graph.

An analysis of changes in the number of days with mean temperature below freezing in the Sierra Nevada region (using a set of 88 stations located above 3,000-foot elevation; not shown) indicates a reduction of approximately 10 percent over the past 50 years in the number of such days. This is consistent with the results of other studies (Cayan and others 2001) that documented the advance of spring flowering of several western shrub species in the West during the past several decades.

A United States program to develop a long-term climate reference network for the purposes of climate-change monitoring and detection may provide an opportunity to incorporate into the reference network some of the mountain sites where currently active research programs utilize multidisciplinary data sets of high quality. The integration of measurement programs at these mountain research sites will ensure that the data are state-of-the-art and continue to meet research requirements for studies of climate variability and change.

Changes in the alpine cryosphere (the portions of the Earth's surface where water is in a solid form) may represent some of the earliest signs of large-scale climate change. The

cryospheric variables (glaciers, ice flows, snowfields, etc.) not only serve as indicators of change but also initiate powerful feedback loops through changes in albedo. Timely and detailed knowledge of the ongoing changes, coupled with modeling of the effects, will allow managers and policy makers to plan for the impacts arising from such changes. At present, there is great uncertainty regarding the amplitude of recent climatic changes and their future course at high elevations of the American Cordillera. Observation and modeling studies of the alpine regions of the western United States will help researchers quantify and understand the impacts of global climate change in our mountain regions.

Lack of water-flow and water-quality data in critical climate-sensitive areas, such as the mountain regions of the West, impairs our ability to understand and model hydrologic processes governing climatic land-atmosphere-ocean interactions. The information is needed to make reliable projections and assess the impacts of variability and change in climate and water resources. Streamflow observations are inadequate, and stations are being discontinued. Areas where data are particularly lacking include discharge of freshwater to the oceans and precipitation, snowmelt, and runoff in high mountain basins, which contribute disproportionately to the flow of many rivers.

Insufficient resources often limit efforts to make regular, long-term observations in high mountains, where sites are remote and often difficult to access. However, some well-established technical means are available, and various innovative technologies either are already available or in need of only minor development and field-testing before application. In order to monitor adequately the changes in the natural environment that may be occurring as a result of global climate change, it will be necessary to establish *in situ* streamflow gauging stations, ground-water observation wells, and water-quality measurement sites in selected climatically sensitive basins in the West. The payoff will be improved definition of surface and subsurface flows and transports of water-quality constituents, which will enhance understanding of hydrologic processes and how they might respond to global climate changes in the future.

Studies have shown that since 1950, the snowmelt season in some watersheds of the western United States has advanced by about a month. This change to an earlier melting of the snowpack has been noted at mid-elevation watersheds of the Sierra Nevada in California (Dettinger and Cayan 1995, Dettinger and Diaz 2000). Global change projections indicate that Western snowpacks will diminish markedly over the next century and this crucial spring-summer portion of the runoff will be sharply reduced. Besides having direct economic impact, this change in mountain hydroclimate would presumably affect ecosystems, both up- and downstream. A better multi-faceted observational system is needed to monitor and understand these changes as they occur.

Continued support of paleoclimate studies is needed to help establish a scale for what can be considered normal variation by looking back at climatic variations in the recent past. Results from paleoclimate studies have shown that during the past 2000 years climate variation has resulted in both warming and cooling events, the Medieval Warm Period, at around 1000 A.D., and the Little Ice Age at around 1500 to 1800 A.D. Both were accompanied by significant elevational shifts in lake levels and alpine treelines, as well as temperature and rainfall. Studies that produce high-resolution paleorecords of these relatively recent events would clarify the surface spatial distribution of climatic effects and possibly allow us to infer the past atmospheric driving forces.

It is not clear yet whether climate changes in high-elevation regions will represent an amplification of the global warming signal. It behooves the scientific community to address this important question definitively. To do that, however, a variety of high-quality records will be needed. The current sampling network of climate monitoring in the mountainous regions of the western United States provides inadequate spatial coverage to answer that question.

Implications for Mountain Resources Management

Because of the fundamental complexity of mountain regions, progress in understanding the response of both natural and human ecosystems to climatic variation and change will require the integration of various disciplines into a more cohesive intellectual framework. In the mountainous western United States, there is a need to develop a more holistic view of the processes affecting the physical and biological systems comprising the region. The problems must be tackled in an interconnected manner, reflecting the operation of the real system.

To meet the major water resources challenges facing the West, as a result of its rapid population growth (see Diaz and Anderson 1995), it will be necessary to develop an adequate monitoring system for the alpine regions that provide most Western communities with their water. This implies the development and maintenance of improved networks to sample, both spatially and temporally, all the critical elements needed to define the state of the region's climate and understand its past, present, and future behavior.

The climate-observing system should be linked to ongoing research across the region, should be able to support the needs of other users, and should accommodate a broad range of uses of the data. It should also have the ability to adapt to the use of new technologies as they become available at lower costs, add new variables as needed, etc. Finally, the climate-observing system must adhere to the principles for climate monitoring, as outlined in a U.S. National Research Council report (NRC 1999), and to the management guidelines that are required to implement them. Adequate monitoring of critical environmental variables and processes forms the foundation for understanding global climate change and variability and provides an adequate temporal context for extreme events. Efficient access to comprehensive data derived from observations, paleoenvironmental records, and models is also required.

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