# Regional Changes—Global Connections
# Monitoring climate variability and change in the western United States

Henry F. Diaz
Climate Diagnostics Center, NOAA/OAR, Boulder, CO

## Introduction

Mountain ecosystems of the western United States are complex, and include cold desert biomes, such as those found in Nevada, to subpolar biomes found in the upper treeline zone, and tundra ecosystems, occurring above timberline. Many studies (e.g. 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 represents an analogue 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 species of birds, trout and salmon. High relief and high gradients make mountain ecosystems very vulnerable to slight changes of temperatures and to extreme precipitation events.

Likewise, the source nature of the mountains in providing life-sustaining water for western U.S. society means that climatic and other environmental changes in the mountains of the western United States will have a large impact, not only on the region, but for the rest of the country as well. In essence, mountain regions provide a discreet quantifiable domain where relatively small perturbations in global processes, can cascade down to produce large changes in most or all of the myriad interdependent mountain systems, from its hydrological cycle to its complex fauna and flora, and 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 to 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 to develop in our mountain heritage?

**Monitoring Climate Processes in the Western United States**

As in any complex geophysical system, to be able to adequately address questions about the past, present, and future status of mountain environments in the U.S. West, one must be able to have a focused effort to monitor and anticipate any ongoing changes, and be able to provide historical context for the measurements. Information on fundamental processes along with patterns of local and regional change can be used to assess impacts of climate variability and mountain ecosystem vulnerability. This information is vital in order to better manage mountain ecosystems, maintain its biodiversity, sustain the use of mountain resources and ecosystems, and preserve the social and economic well being of mountain communities in the western United States.

To meet the challenges of observing, understanding, predicting, and verifying changes in our mountain environments, requires sustained and stable funding and institutional support for long-term multidisciplinary, multi-institutional efforts. Climate monitoring in mountain regions can be a difficult undertaking; to develop the type of 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-time scale variability; hence, changes in variability arising from changes in the observing system can obstruct efforts at detection of climate change.

Figure 1 illustrates the present coverage of weather observing stations in the western United States (area west of the 100$^{th}$ meridian) as a function of elevation. I have conservatively assumed that each station is representative of a 100 km$^2$ area. The curve depicts the proportion of area that is occupied by the equivalent topography, in 1000-ft. increments using a high-resolution digital elevation model (DEM) of the western United States. according to elevation. This is simply the relative proportion of stations binned by 1000 ft (~300 m) intervals. Of course, while the relative proportion of station is similar to that of the topography, the actual physical coverage of those stations is rather meager. A sample area of 100 km$^2$ is perhaps overly restrictive with respect to surface temperature, which tends to be correlated to a relatively radius. However, in regions of complex topography typical decorrelation scales are often less than 100 km. Figure 1 shows clearly, that the alpine regions of the US West are grossly undersampled, and there is an obvious need for the development of a comprehensive climate monitoring program that would complement other long-term observations programs, such as, for example, the Long-Term Ecological Research program.

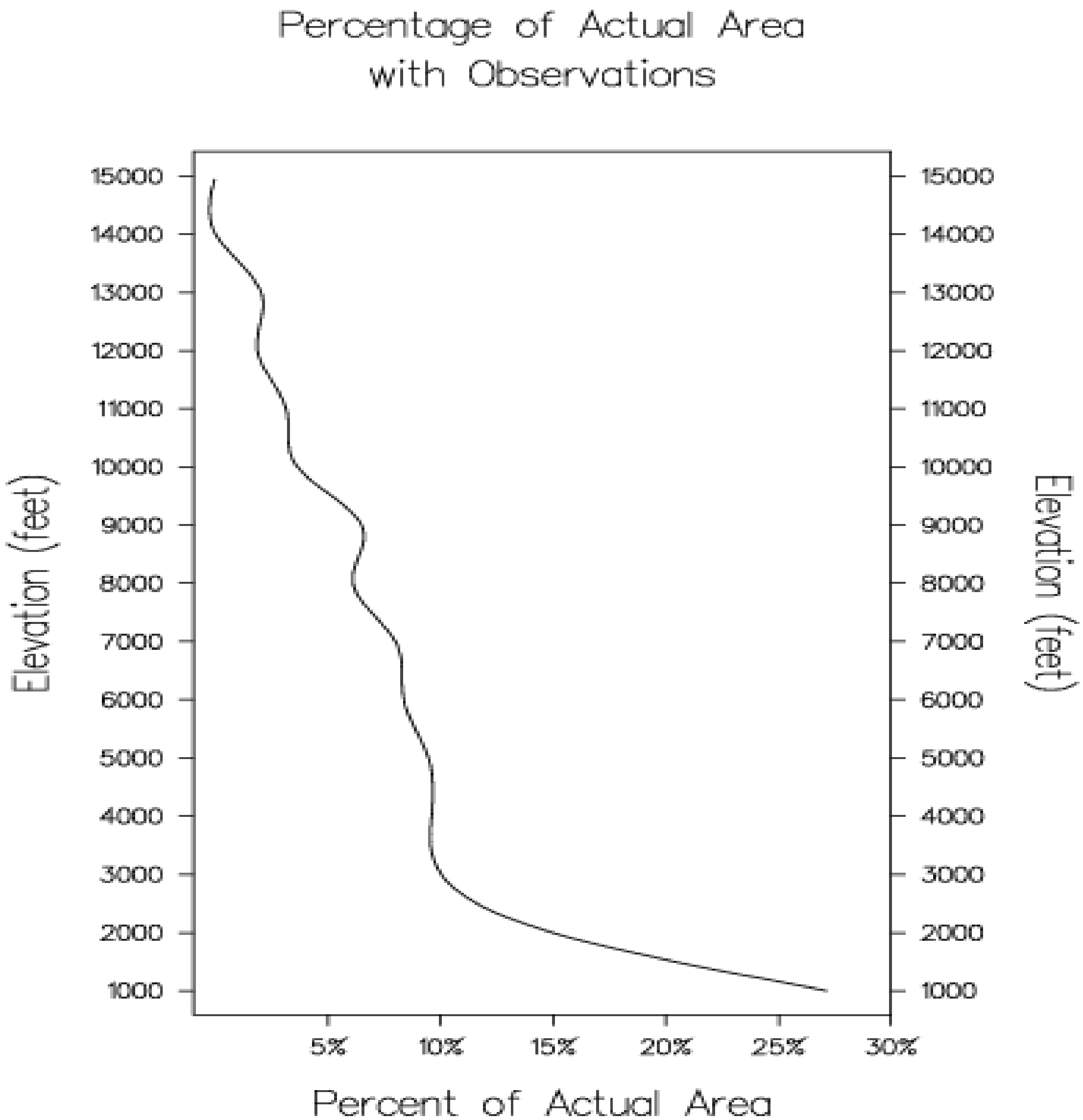


Figure 1. A conservative estimate of the percentage of actual area coverage with observations in the western United States. Values calculated assuming that each station is representative of a 100-km$^2$ area. Corresponding area is based on a high-resolution DEM of western U.S. topography.

We have calculated 50-year surface temperature trends for the western United States based on the available long-term (stations with POR ≥ 30 years) observation network, which contains 2092 stations. The results are illustrated in Fig. 2. The statistical significance of the trends (not shown) vary from greater than 10% below 7000 ft (~2135 m) to not significant above that. The positive trends are fairly uniform with elevation averaging ~1˚C/century over the entire region. The trends of mean minimum temperature are even larger, amounting to ~1.5˚C/century over the entire region. These changes have significant implications for ecosystems and water resources management in the West.

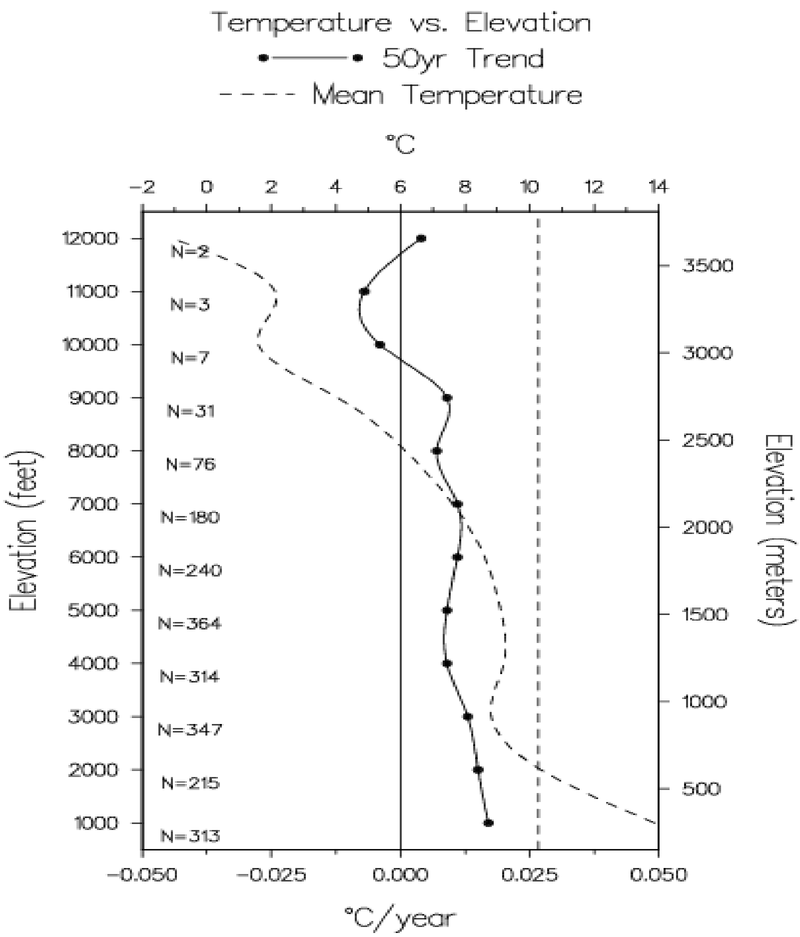


Figure 2. Median 50-year trends (1950–2000) of annual average surface temperature. Values are shown as a function of elevation for 2,092 stations in the western United States (west of 100˚W), and are plotted in 1000-foot (~300 m) increments, and smoothed using a rigid spline. The trend values are plotted 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.

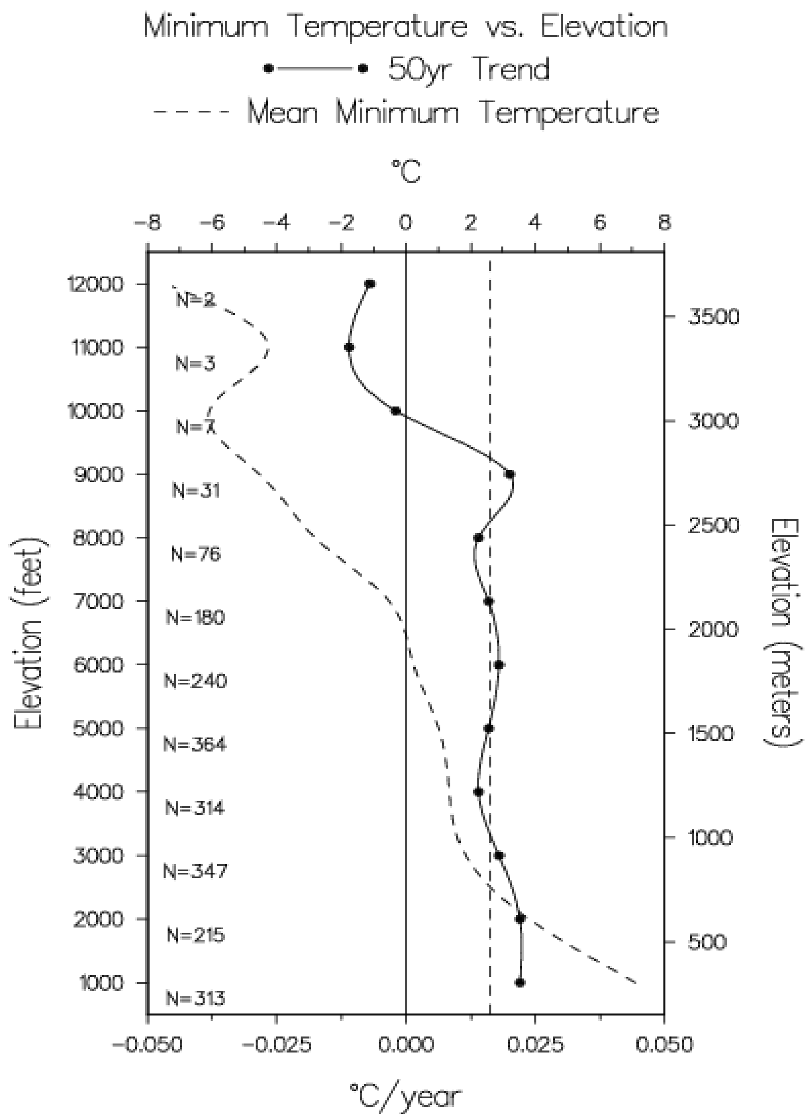


Figure 3. As in Figure 2, but for average annual minimum temperature.

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 3000 ft elevation; not shown) indicates a reduction of ~10% over the last 50 years in the number of such days. This is consistent with other studies (Cayan *et al.* 2001) documenting the advance of spring flowering of several western shrub species in the West during the last several decades.

A U.S. program to develop a long-term climate reference network for the purposes of climate change monitoring and detection may provides 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, which are, incidentally, taken from these very pristine environments. The integration of measurement programs at these mountain research sites will ensure 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 may represent some of the earliest signs of large-scale climate change. The cryospheric variables not only serve as indicators of change but also provide powerful feedbacks through changes in albedo. Timely and detailed knowledge of the on going 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 elevation of the American Cordillera. Observation and modeling studies of the alpine regions of the western United States will help document 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 to 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.

A major problem in carrying out routine observations in high mountains, which are often located in remote areas that require major efforts to visit and keep the measurements going, is often the lack of adequate resources to do the job. Well-established technical means are available, and various innovative technologies are either already available, or in need only of minor development and field-testing for applications. In order to monitor adequately for 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 would be improved definition of surface and subsurface flows and transports of water-quality constituents, which will lead to improved 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 last 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 and 1800 A.D., which have been accompanied by significant elevational shifts of lake levels and alpine treelines, as well as temperature and rainfall. One advantage to supporting studies with high-resolution paleorecords of these relatively recent events, is that by determining the surface spatial distribution of climatic effects it may be possible to infer the past atmospheric driving forces.

It is not clear yet whether climate changes in high elevation regions will exhibit an amplification of the global warming signal. It behooves the scientific community to definitively address this important question. To do that, however, a variety of high quality records will be needed. Based on the current sampling network of climate monitoring in the mountainous regions of the western U.S., it appears that the spatial coverage is inadequate 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 ecosystem 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 the same interconnected manner that the real system operates in.

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 provide adequate monitoring capabilities of the alpine regions of the West, which is the source of most its water. This implies the development and maintenance of improved networks to adequately sample, both spatially and temporally, all the critical elements needed to define the state of the region's climate state, to understand its past, present, and future behavior.

The climate observing system should be linked to ongoing research across the region and be able to support the needs of other users and to accommodate a broad range of uses of the data. The observing system should have the ability to adapt to the use of new technologies as they become available to 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 are the foundation of understanding global climate change and variability, and to provide an adequate temporal context for extreme events. Efficient access to comprehensive observational, paleoenvironmental, and to model data is also required.

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