Arnold Schwarzenegger
Governor

AN ENHANCED CALIFORNIA CLIMATE MONITORING SYSTEM

PIER FINAL PROJECT REPORT

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California Energy Commission
Public Interest Energy Research Program

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

An Enhanced California Climate Monitoring System is the final report for the Enhanced Climate and Hydrological Monitoring for California project (contract number 500-02-004) conducted by the Desert Research Institute. The information from this project contributes to PIER's Energy-Related Environmental Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

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Abstract

Long-term variations in climate (temperature and precipitation) in portions of California are not sufficiently well sampled in some remote areas lacking meteorological or hydrological stations. A combined strategy of small clusters of climate stations arranged from the coast to the mountains was adopted to guide the deployment of a network of new long-term monitoring sites. This strategy for the stations installed as part of this project was suggested through consultation with research and operational entities throughout the state but priority was given to stations located in the coastal environment and high elevations above the average winter snow line. A set of 15 sites had instruments installed to become a part of this study; they provide on-going measurements with 10-minute resolution, at elevations ranging from sea level to over 14,000 feet. Almost the entire range of elevation in California is now sampled for climate monitoring as a result of this project. Most stations are located where future site disruption is judged to be unlikely. A few sites were established to monitor particular climate elements such as wind, temperature or humidity. Coastal sites have shown very large differences in short vertical and horizontal distances, confirming the rationale for close spacing in certain settings. Measure data are posted immediately to the web. Methods to graph, summarize, and download the data have been working very well. Experimental techniques are showing that higher elevations appear to have begun warming significantly over the last 1-2 decades in comparison with lower elevation areas. The project motivated the development of the California Climate Tracker, a method for showing the climate history of the state and 11 subregions for the past 115 years. This tool is intended for a wide audience and can be accessed through the California Climate Data Archive and the Western Regional Climate Center.

Keywords: Public Interest Energy Research (PIER) Program, California, climate, observations, monitoring, data, coast, mountains, California Climate Data Archive, California Climate Tracker, CalClim, Western Regional Climate Center, temperature, precipitation, wind, humidity, solar radiation

Executive Summary

Introduction

California's climate is projected to change as a result of anthropogenic influences (greenhouse gases, atmospheric aerosols, land use changes) and indeed some of these changes have started to occur. The state has given significant attention to climate change, and the issue has been adopted as a state priority. Slow natural variations in climate can easily resemble recent trends caused by human activity, both of which are occurring simultaneously, and it is important to have information that can help distinguish between these two types of causes. The characteristics of climate variability can differ significantly among settings such as the coast, the interior, the mountains, the deserts, and within cities. These places must be adequately monitored to establish baselines and identify trends and variability and to understand why those variations are occurring. Gaps in our monitoring systems and in the system for synthesizing monitoring information affect society's ability to obtain information pertinent to either of these two needs.

Purpose

The main purpose of this project is to improve the ability to track climate in locations of major economic importance within California to better understand why climate varies and to place recent climate events into a longer context. This entails 1) making new observations, and 2) making better use of information that is already accessible.

Project Objectives

This project has two major objectives:

- Extend the coverage of "climate quality" records to under-sampled climates, such as
    - High elevations (water supply areas)
    - Coastlines (large populations astride sharp temperature gradients)
    - Other climate regimes of interest to scientific disciplines or practical applications
- Undertake activities that lead to improved utilization and interpretation of the large volume of existing weather and climate data

Project Outcomes

Consultation with a variety of individuals and groups representing research institutions and agencies managing state resources led to a project strategy of targeted observations arranged as clusters (multiple stations in the same general area) or transects (stations arranged in line to cover the transition from one zone to another) rather than uniform statewide distribution. A coast to mountain transect in the central portion of the state was judged most feasible, with mini-clusters or station pairs embedded. In retrospect this turned out to be a very good approach.

Eleven stations were deployed at elevations ranging from 24 to 4,342 m (80 to 14,246 ft), and four more were augmented in some manner for a total of 15 stations. Two pairs of stations were deployed north and south of San Francisco, others were deployed along Interstate 80 near Donner Summit, with others atop Mt. Warren (3,757 m/12,327 ft) near Mono Lake and White Mountain Summit (4,342 m / 14,246 ft) east of Bishop. Low elevation sites have functioned very well, producing essentially continuous data. High elevation sites have experienced a few outages as a consequence of severe conditions, but this was not unexpected even with significant precautions taken.

The coastal sites have shown remarkable differences over very short distances, both vertically and horizontally. They show that quite close spacing is needed to resolve differences in climate and that high spatial resolution is needed in climate models. Mountain sites were deliberately placed above the average winter snow line, where measurements are much less common. Mountain sites have survived very harsh conditions reaching gusts of 155 and 162 mph at two sites. These sites are well-situated to contribute to high elevation studies of climate and are near biological plots established to monitor long-term global alpine conditions. Reconstruction techniques show that the White Mountain Summit site appears to have warmed significantly over the past two decades and that summers have been much warmer since about 1998 or 1999.

Conclusions

The station placement strategy to develop clusters of stations was certainly the best approach to take. The choice of coasts and mountains as the two primary environments of interest was very good. Because more outages are expected in the harsh alpine settings, sites were placed in close enough proximity to be able to assist with data reconstruction for missing periods at one site or the other. Nearly the entire range of elevations in the state is now covered to within about 250 feet higher and lower than the statewide minimum of -86 m (-282 ft) at Badwater (Death Valley) and +4,418 m (+14,495 ft) at Mt. Whitney (Sierra Nevada).

Data collection, summary, and dissemination processes have worked very well. Data can be readily visualized using some graphical routines and downloaded from the web. The use of high-quality equipment with proven track records in difficult environmental conditions has been important to the success of this project. The linkage to an operational center with expertise in this activity has proven invaluable. Considerable skill, judgment, and experience are necessary to maximize the amount and quality of returned data.

Recommendations

Parts of the state still need some attention. More sites along the coastline would be beneficial. Desert regions are not well enough represented. Station density in the northeast plateau is still low. The San Francisco Bay Delta area, with its complicated meteorology, does not have a long-term climate-quality monitoring network that samples the mainland, prominences, headlands, estuaries, and the water.

This project focused on "natural" environments to the extent possible. Population centers are not "natural" and thus usually avoided. However, cities have climate effects of their own, and there is an opposing rationale that favors specialized urban networks intended to sample climate where people live and perhaps experience different extreme conditions, or where out-migration will lead to new communities in the next 1-3 decades. Irrigation increases (and now decreases) in the Central Valley have clearly changed the summer climate of that area over the last 50-75 years, and no climate network has been deployed to track this difference.

The permit process has become steadily more complex, and favorite locations are not always approved. The permitting process is often taken for granted, misunderstood, or unknown, but must be taken very seriously. Negotiating skills of site surveyors are often just as valuable as mechanical and electronic skills and frequently spell the difference between success and failure.

Most sites in this network were chosen because they would likely not change over upcoming decades. In addition, locations and hosts were usually chosen with considerations of future maintenance possibilities in mind. This is a key issue in retaining a viable network over several decades. Expectations about future maintenance were significantly undermined by changing economic conditions in 2008. However, viable prospects for continued servicing are being explored, along with ways to leverage other related activities.

Benefits to California

The first truly high elevation measurements in the state have been established where no baseline data existed before. These regions are where snow pack accumulates, and they are expected to warm with time. The coast, with its sharp climate transition, is the home of large human populations whose energy usage can change dramatically over short periods of time. The California Current and its ocean life are driven by this land-sea contrast, and understanding it and predicting its behavior needs fine-scale climate information. The next round of climate models will focus on regional and local simulations and will need fine-scale data for verification and validation.

Numerous researchers have expressed strong interest in data from these sites, and site hosts have been very enthusiastic participants in the program. Efforts to link climate to ecological, water resources, energy, or public health issues require this information. The attention arising from these measurements has led to additional monitoring networks in the state, and to new NSF proposals to deploy stations in more than 20 key research sites. Other Energy Commission projects are planning on adding additional sensors.

This project provided the motivation to develop the California Climate Tracker, a conceptually simple, yet well-grounded and documented, method to portray the history of California temperature and precipitation climate. The Tracker is updated every month to show climate trends in specific regions and statewide and can be readily understood by a wide and varied audience. This and related California climate information are available via the California Climate Data Archive ("CalClim") at the Western Regional Climate Center.

1.0 Introduction

1.1. Background

California's 158,693 square miles encompass a huge diversity of climate types, in many places separated by narrow transition zones exhibiting quite different climate behavior, and therefore different climate histories. These histories have been unevenly sampled by a diverse set of networks, with different missions, instruments, measurement intervals, observational practices, lengths of record, site characteristics, local influences, maintenance practices, attention to quality control, communication pathways, reporting and archival practices. They are also characterized by a variety of sources of time-dependent bias, all with variable quality of documentation through time, so that existing information is seldom adequate for complete evaluation of the quality of the resulting records.

California's climate is projected to change as a result of anthropogenic influences (greenhouse gases, atmospheric aerosols, land use changes) and indeed some of these changes should have started to occur (Dettinger, 2005). The state has given significant attention to climate change and the issue has been adopted as a state priority. Slow natural variations in climate can easily resemble recent trends caused by human activity, both of which are occurring simultaneously, and it is important to have information at hand that can help distinguish between these two types of causes. The nature of climate variability, natural or not, can be different in areas of different economic influences, such as the coast, the interior, the mountains and their snow, the deserts, and even within cities. These places must be adequately monitored, firstly, to establish baselines and identify trends and variability, and secondly, to understand why those variations are occurring. Gaps in our monitoring systems, and in the system for synthesizing monitoring information, affect society's ability to adequately obtain information pertinent to either of these two needs.

With all the attention to climate and to projected changes, it has been very hard for researchers, managers, policy-makers, the press, and average citizens to easily access information on what California climate is actually doing, and why. Heretofore there has been no operational entity that routinely (e.g., monthly or daily) synthesizes and presents data and information about ongoing California climate in a manner intended for wide public consumption. Most such information has been in forms and formats more understandable to research communities.

The main purpose of this project is to improve the ability within the state to track climate in settings of major economic importance to California, in order to better understand why climate varies, and in order to place recent climate events into a longer context. This entails 1) making new observations, and 2) making better use of information that is already accessible.

1.2. Project Objectives

This project had two major objectives:

- Extend the coverage of "climate quality" records to under-sampled climates, such as
  - High elevations (water supply areas)

    - Coastlines (large populations astride sharp temperature gradients)
    - Other climate regimes of interest to scientific disciplines or practical applications
- Undertake activities that lead to improved utilization and interpretation of the large volume of existing weather and climate data

The project called for the Western Regional Climate Center (WRCC) to collaborate with agencies and organizations within the state of California to develop and improve climate monitoring sites and information on the status of the state's climate. The work was entailed the addition of new stations and augmentation and improvement of existing measurement stations. Emphasis was to be given to addressing shortcomings in the present networks that impede the ability to detect slow and subtle, but nonetheless important, changes in climate. A mix of observing strategies was expected, with choices to be made in consultation with state resource managers, energy experts, researchers, operational agencies, meteorologists, and the California Climate Change Center (CCCC) at the Scripps Institution of Oceanography.

2.0 Project Approach

The project had several tasks. These are described and elaborated in each of the following sections.

2.1. Assess Needs and Recommend Sites

This task had the following components:

- Assess locations of existing stations that appear to provide the best quality records for climate monitoring.
- Identify gaps in coverage
- Perform reconnaissance visits to prospective sites (*site surveys*)
- Select locations and determine type of sensing equipment and communication needed for each selected location.

The original plan to assess the quality of records was to utilize an algorithm and software prepared by Arndt and Redmond (2004). One example of the output of this technique is shown in Figures 1 and 2. This example compares the daily record from downtown Sacramento with those from several nearby locations for a 55 year period (20,088 days). The method relies on accumulated sums of daily temperatures at each station, in this case portrayed as departures from the average relation between the different station pairs in order to make the changes more visible. A change in slope (i.e., curvature) indicates a changing relationship between the stations. The U-shaped curves indicate that the test station (here, Sacramento Downtown) gradually warmed with respect to the different comparison stations over this period. These graphs are very illustrative, but it proved difficult to work with hundreds of such diagrams at one time. As the project proceeded, a more comprehensive approach that largely encompassed this technique began to look more efficient.

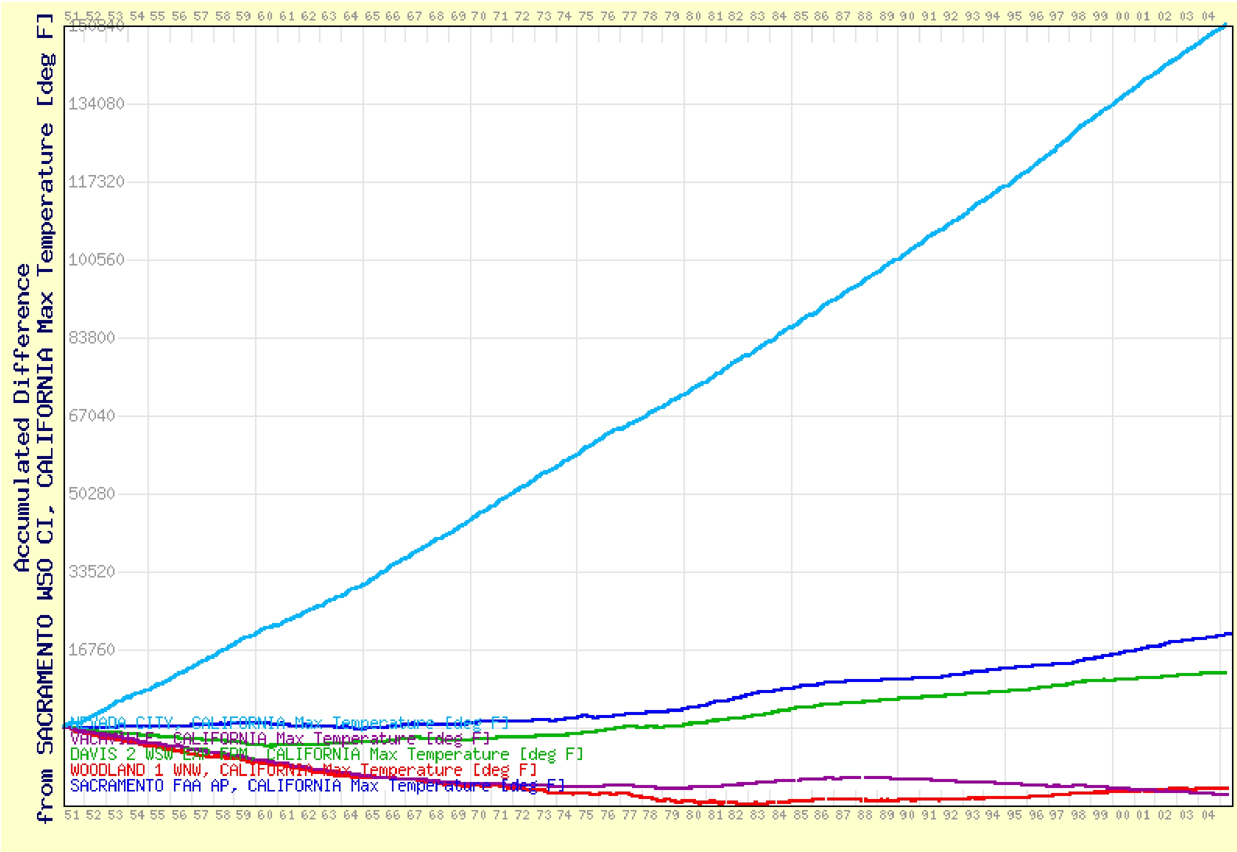


Figure 1. Maximum temperature at Sacramento City minus various nearby locations, as daily accumulations from Jan 1, 1951 to July 2005. **Curves that are above the flat zero line indicate that Sacramento downtown is overall warmer than that site. The important behavior concerns *changes in slope*, indicating a change in relationship between two stations. A line above zero means the reference station is generally (climatologically) warmer than the comparison station. Curvature up or down indicates relative warming or cooling between two stations. Upward curvature indicates that the Sacramento city site is becoming warmer faster than the comparison site, and downward curvature indicates that the city site is becoming cooler faster, or is warming more slowly, than surrounding sites are.**

After Arndt and Redmond (2004).

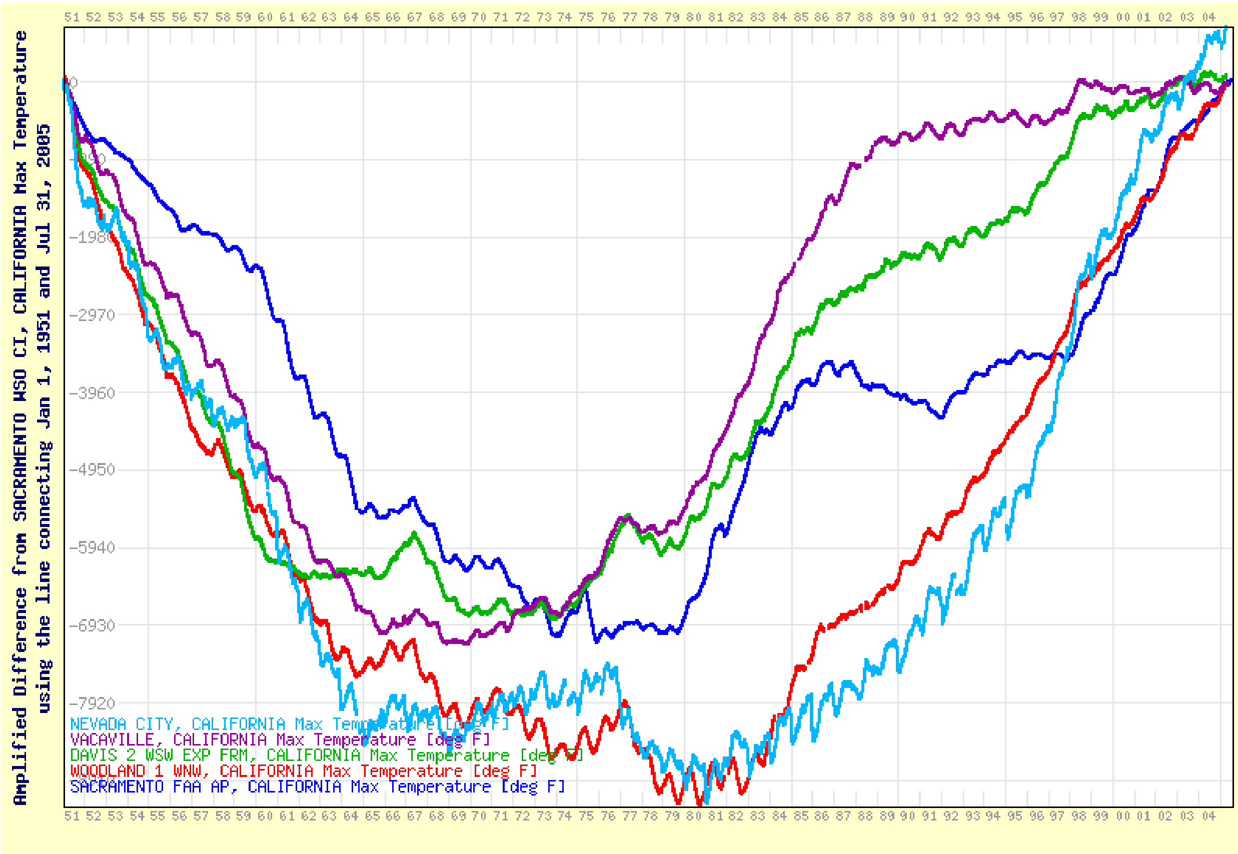


Figure 2. Maximum temperature at Sacramento City minus various nearby locations, daily accumulations from Jan 1, 1951 to July 2005. **Accumulated ("amplified") departures from a straight line on Figure 1 drawn between these two dates. Downward trending lines indicate that the key station is warmer than the comparison station. The behavior of interest concerns *changes* in slope, indicating that the relationship of two sites changes. Simultaneous changes at several stations provide evidence that it is the key station that changed. Slow changes in curvature can stem from vegetation growth, or land use changes in the vicinity. Small wiggles indicate that there are seasonal (winter/summer) differences in how much warmer one site is than another. This site appears to be warming preferentially to Woodlands and Nevada City, and of late, faster than with respect to Vacaville and Davis. There are obviously major changes in the relationship of Sacramento City temperature to surrounding locations.**

After Arndt and Redmond (2004).

Gaps in coverage include data gaps in time, incomplete suites of reported climate elements (i.e., enough precipitation, but insufficient temperature measurements), missing geographic areas or climate zones.

Reconnaissance can be either a virtual (desk survey) or physical (field survey) activity or both. The purpose is to obtain documentation such as a complete set of compass photos, GPS coordinates, and site characteristics (vegetative cover, susceptibility to change in land use or ownership, slope, aspect, airflow and air drainage patterns, topographic influences, proximity to artificial influences affecting the site, and so forth).

At the start of the project, the intent was to install two or three California contributions to the federal Climate Reference Network managed by the National Oceanic and Atmospheric Administration (NOAA). The CRN network has very high standards for site locations (NCDC, 2009), and not all of these criteria needed to be present for the California sites to still produce very good data. WRCC project personnel had surveyed all of the existing sites in California; 4 installed sites were present at the time in the state, an outcome of several dozen surveys in the state.

The cost of equipment used by a CRN station had escalated since the original scoping of the project, and the cost of installation grew also, to a price much greater than the initial estimate of $19K for hardware and $5K for installation, up to around $27K for the station and several tens of $K for installation. The original plan to obtain three CRN stations no longer was viable with the available resources. In addition, CRN sites do not measure all climate elements of interest. Full stations that measured many more climate elements to quite adequate standards could be obtained and installed for much lower cost.

Another element of the observing strategy involved the spatial distribution of stations. The sites could either be distributed more or less uniformly (in latitude/longitude locations) around the state, or be targeted to help answer specific questions and address particular gaps in knowledge. Resources could provide for about 10-12 sites, and it did not seem that the addition of a dozen uniformly spaced sites to several hundred existing sites would greatly improve spatial coverage or overall climate knowledge of the state.

The WRCC team sought guidance on a practical deployment strategy from a variety of members of the climate research community, including those with observational and with modeling predispositions, with others involved in day-to-day long-term monitoring within the state, with meteorologists and National Weather Service forecasters, and with the Commission Project Manager. Project personnel also attended meetings of the Central and Northern Coastal Ocean Observing System (CeNCOOS) to solicit view on coastal land-based observational needs, and have since remained as formal members of that group.

As a result of the feedback received from researchers and operational agencies, a different approach was formulated. There is much to be learned from clustering and transects, especially when sharp spatial gradients in climate behavior are present. California has several types of such gradients, the most ubiquitous of which are along the coast, and in the mountains. There are large differences in climate characteristics in different parts of the year in very short horizontal distances, and there are large differences as well in short distances in the vertical. Transects or clusters of observations that span these gradients were thus suggested by WRCC as an observing strategy. The reception to this idea was quite positive.

Practical and logistical concerns must be considered as well. The stations must be either accessible much of the year, or else be robust enough to operate unattended through very harsh conditions for lengthy periods of time. The ability to mesh with other observational efforts, and with ongoing and planned research projects, is a definite advantage.

Biologists in particular frequently complain that stations are too far apart, and are unable to sample the highly diverse structure in long term climate that can occur over very small spatial scales, on the order of meters to tens of meters, the size of living vegetation. A set of closely spaced reference stations would act as a kind of infrastructure that would make possible future more closely spaced measurements designed to meet their needs. Toward the end of this project discussions of that type began to occur.

The general goal thus became to span both coastal and elevational gradients. The most frequently mentioned desire among potential users was for a coast to mountain transect, from essentially the Pacific Ocean to the top of the Sierra Nevada crest and down the east side. Such a transect could approximately follow parallel to and just south of Interstate 80. This orientation is aligned with the general northeastward airflow trajectory of many weather systems. In addition there have been several studies highlighting the importance of understanding the rapid hydrologic response characteristics of the three forks of the American River just above Folsom Reservoir (NRC 1995, 1999; Redmond and Pulwarty, 1997).

A complication in such a transect is the complex land-water-hills pattern of San Francisco Bay and the Bay-Delta area. Wind and temperature patterns are very complicated in this area. However, it also happens that the San Francisco Bay Area is not especially well monitored from a climate perspective. Attempts were made to identify locations at sites such as islands or headlands. Alcatraz, under National Park Service management, met administrative constraints, but the necessary open space and separation from artificial climate influences is simply not present on that island. Angel Island was considered but eventually rejected because of difficulties in access and in deployment, as well as poor exposure for available sites. As it happened a major fire burned slightly over half (380 out of 740 acres) of Angel Island on October 12-13, 2008, and would have extensively altered the site exposure. Bonita Point, a small strip of land jutting southward from the seaward entrance to the Golden Gate and west of the bridge, is an excellent prospect. However, concerns about vandalism, and about a climatically suitable exposure if attached to existing towers and protected infrastructure, as well as permitting requirements by the US Coast Guard, led to the reluctant decision to continue looking elsewhere. Various other sites in, on, or adjacent to San Francisco Bay were examined, but usually rejected because of the prospect of land management changes, excessive human influence on the measurements, servicing and access issues, or significant potential for inability to properly interpret the resulting measurements from a climate variability and change standpoint.

Accordingly, the focus was shifted to locations north and south of the Bay with physically simpler topographic situations. Two sites were with willing hosts were identified and targeted for dual stations.

2.2. Site Locations and Descriptions

At the University of California Big Creek Natural Reserve, along Big Sur south of Monterey, one station location was identified at 124 m (407 ft) above the ocean near Whale Point, on an open bench next to the caretaker's residence, and atop a high bluff overlooking the Coast Highway and the Pacific Ocean. A second station location was identified about 3 km (2 mi) inland from this site atop Highlands Peak, at 753 m (2470 ft). This UC Reserve has a permanent human presence and offered maintenance and security potential. These sites are shown in Figure 3.

Figure 3. (left) Whale Point climate station, Big Sur, 122 m (407 ft) elevation. The short non-standard tripod mounting for the wind observation was mandated by the California Coastal Commission. (right) Highlands Peak climate station, Big Sur, 753 m (2470 ft). Not shown: acres of poison oak.

Photos by Dave Simeral, mid-December 2005.

North of San Francisco Bay at Point Reyes National Seashore, the National Park Service (NPS) enthusiastically embraced the prospect of climate monitoring stations. Accordingly one site that had been previously identified as a potential NOAA Climate Reference Network location was selected, and subsequently endorsed by NPS, next to the RCA Building, at 24 m (80 ft) above sea level, and an excellent exposure. This location is strongly affected by the Pacific Ocean, but also has some continental influence. A second paired location was then identified near the very tip of the Peninsula, atop Lighthouse Rock several tens of meters west of the visitor center, and the site of a decommissioned former US Coast Guard weather station. This site is 160 m (526 ft) above the Pacific Ocean, offers exposure to the ocean in three directions, and was chosen to measure wind, temperature, humidity, and solar radiation. Precipitation monitoring is nearly impossible in the screaming winds and considered pointless. The site provides as close to maritime conditions as can be measured at any location attached to mainland along the entire California coast. Wind conditions are far more severe than at the RCA building 11 km (7 mi) away. Point Reyes has a strong NPS presence and the potential for continued oversight. Figures 4 through 6 show the two stations at Point Reyes.

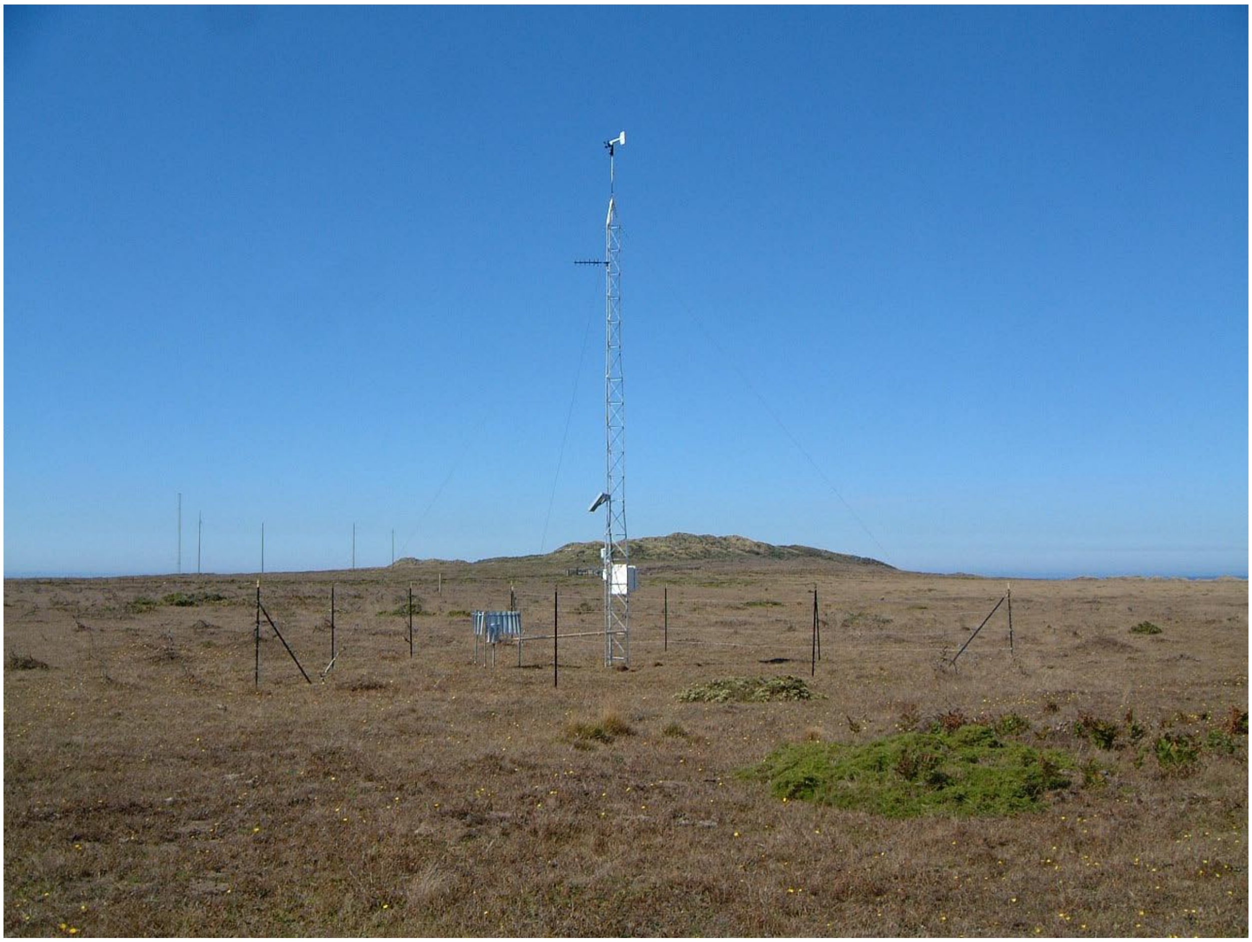


Figure 4. Point Reyes RCA Building Field site, about 300 m west of RCA Building. Looking toward northwest. Ocean is just beyond the hillock in the distance.

Photo by Greg McCurdy.

Figure 5. Point Reyes Lighthouse Rock climate station, 160 m (526 ft) above Pacific Ocean. Looking toward north. For orientation, solar panels always point due south. Point Reyes RCA building and climate station is approximately 11 km (7 mi) distant behind the tower and just below the protective enclosure.

Photo by Greg McCurdy.

A principal goal at Big Creek Reserve was to have one station that is consistently in the marine layer, and another that is consistently either above the marine layer or frequently above that layer. The idea is to straddle the extremely sharp temperature gradient often found along the coast. With its relatively simple geometry, there is hardly a better location than Big Sur to do this along the entire 1239 km (770 mi) coastline of California. This strategy has been a spectacular success, and despite the apparent close spacing, the behavior of the two stations is often radically different.

This paired-station concept was also invoked at Point Reyes. Although it may seem that these two sites are fairly similar, anecdotal and other evidence suggested that there might be systematic differences, and episodically very large differences, between the two sites. This did in fact prove to be the case (example in section 3.0).

Figure 6. Point Reyes National Seashore Lighthouse Rock climate station. Looking approximately toward west from along walkway used by visitors. Visitor Center is small structure in center of photo. Lighthouse itself is beyond the small shelter in the distance, and down a flight of a few hundred stairs. Cliffs and ocean to the left and right, and a steep descent to the ocean beyond Lighthouse Rock.

Photo by Dave Simeral.

In California much concern has been expressed about potential changes in mountain hydrology from climate warming. The CIRMOUNT Committee (2005) has identified the lack of high elevation monitoring sites as a major observational gap. A concerted effort was made to bracket as much of the elevation range of California as possible, and thus to identify as high locations as practical. Such sites could form the upper end of elevation transects.

The UC White Mountain Research Station atop the White Mountains east of Bishop CA offered several sites for consideration. The stone hut atop White Mountain Summit has been used for occasional monitoring in the past. Vehicles can be driven to this point during the warm season, and a snow cat is available in winter. This site is at 4342 m (14,246 ft) and just 76 m (250 ft) lower than the highest point in the continental US, Mount Whitney, across the Owens Valley to the west, and south about 100 km (60 mi). The terrain falls off sharply to the east and west, by about 3000 m (10,000 ft) down to Bishop CA. The peak itself rises about 300-500 m (1000-1500 ft) from other high points along the length of the White Mountains. The setting and the station are shown in Figures 7 and 8. Two other existing sites along the broad crest were augmented, Barcroft Lab (Figure 9) , an astronomical observatory at 3782 m (12,410 m), and the main classroom facility at Crooked Creek (Figure 10) at 3094 m (10,151 ft). These sites are more sheltered but are quite close horizontally and vertically to groves of bristlecone pine, home of the oldest living trees in the world.

Figure 7. White Mountain Summit, the high point to right of center, at 4342 m / 14,246 ft. Bishop CA, Owens River Valley beyond, and High Sierra in background. View toward west from commercial airliner.

Photo by Kelly Redmond.

Figure 8. Long term monitoring equipment atop White Mountain Summit, 4342 m / 14246 ft. Anemometer and temperature/humidity sensors on left mast, solar radiation on right mast. All equipment is solidly bolted to the stone hut. Radio equipment extends above the mast. View from south to north.

Photo by Dave Simeral.

Figure 9. Barcroft Lab (3783 m / 12,410 ft). View toward west. Crest of range is 1 km (1/2 mi) in distance, thus this site is somewhat sheltered.

Photo taken Sept 13, 2005 by Greg McCurdy.

Figure 10. Crooked Creek Research Facility. Elevation 3094 m / 10,151 ft. View from south to north.

Photo taken October 2005 by Greg McCurdy.

Another peak closer to Yosemite National Park and the main Sierra Crest, and a high elevation backup site, was desirable. A US Forest Service radio repeater station atop Mt Warren at 3757 m (12,327 ft), was suggested. This site overlooks Mono Lake and the town of Lee Vining to the east. To the west is the eastern border of Yosemite National Park, and of the uppermost sources of the San Francisco water supply, the Tuolumne River and Hetch Hetchy Reservoir, guarded by Mt Conness on the crest. To the south of Mt Warren are Mammoth Mountain Ski Area, and Mount Dana and Mount Gibbs in Yosemite. To the north is Dunderberg Peak, the Virginia Lake area, and the main Sierra Crest. The site has excellent exposure in all directions and very sturdy mounting posts. Figures 11 through 16 show the station and the views in the four cardinal directions.

Figure 11. Mount Warren climate station. Elevation 3757 m / 12,327 ft. View toward east.
Photo by Dave Simeral.

Figure 12. Mt Warren station from below, looking toward west. Note recently established tufts of grass in foreground.
Photo by Dave Simeral.

Figure 13. View from Mount Warren looking toward north and Dunderberg Peak, elevation 3772 m / 12,374 ft, a GLORIA biological monitoring site at nearly the same elevation.
Photo by Dave Simeral.

Figure 14. View from Mount Warren looking west toward Tioga Crest, and Mt Conness (right center, elevation 3825 m / 12549 ft) and Yosemite National Park eastern boundary.
Photo by Dave Simeral.

Figure 15. View from Mount Warren looking toward south and Mount Dana and Mt Gibbs inside Yosemite National Park, and Mammoth Mountain Ski Area.
Photo by Dave Simeral.

Figure 16. View from Mt. Warren (3757 m / 12,327 ft) looking east toward Mono Lake (1945 m / 6382 ft). White Mountains distant right.
Photo by Dave Simeral.

An important site with a very long history is the Central Sierra Snow Lab (CSSL) at 2098 m (6883 ft), about 3 km (2 mi) west of Donner Summit on Interstate 80 at 2206 m (7239 ft). Measurements have been made within 2-3 km (1-2 mi) of this location since the transcontinental railroad passed through Norden in 1868. This area has the longest continuous snowfall record in the Sierra Nevada. CSSL is connected to the UC Natural Reserve System, and has a human presence most days of the year. The site has specialized in measuring snow for decades, and has a tall and sturdy tower about 8 m (25 ft) off the ground to clear the deepest snows (Figures 17 and 18). Most of the sensors were in place, and this is considered an augmented station, with better anemometers added. The site sits in a small clearing about 1 ha (2 acres) in size, and offers good protection from wind. About 1040 cm (410 inches) of snow fall at this site. Formerly operated for many years by the US Forest Service, the site is now managed by UC Berkeley. The site is nearly at the top of the 115 km (70 mi) long ramp from sea level in Sacramento to the crest of the Sierra. The NRCS Snotel program and NOAA Hydrometeorological Test Bed also have instrumentation at this site.

Figure 17. Central Sierra Snow Lab. Left: View to south. Geonor gage left, Belfort gage right, anemometer above both, snow depth sensor to left. Tower is 8 m / 25 ft high. Right: View to north, tower, snow protection shelter, caretaker residence in back.

Photo by Dave Simeral.

Figure 18. Research equipment at Central Sierra Snow Lab. ECCM equipment on left tower. NRCS Snotel precipitation gauge (white) in center.
Photo by Dave Simeral.

Three other sites were selected nearby to provide more spatial detail. A transect over a single mountain along the Sierra Crest was desired. Sugar Bowl Ski Area offered the use of a tall and sturdy post near its lodge and lift facilities, at an elevation of 2126 m (6975 ft), with the added inducement of always-useful electricity. A second site was later offered on the roof of the lift facility atop the highest point in the area, Mount Lincoln at 2539 m (8330 ft). The base of this site is disturbed and not ideal on windless days, but for much the time the wind is anything but calm at this site. The intent was to obtain information relevant to freezing level variations in the Sierra, and of icing conditions. The Sugar Bowl locations are shown in Figures 19 through 21.

Figure 19. Sugar Bowl Ski Area, looking approximately southward from above Donner Summit. Mt Lincoln is the highest peak at center (2539 m / 8330 ft), and the Mt Lincoln station is located atop the highest ski lift (in orange). The Sugar Bowl base site is located near the clumps of trees next to the white-on-black "R T" symbol at the center of the picture. The Onion Creek site is located on the back side of the two lower peaks to the right, and about 657 m / 2160 ft) below the summit of Mt Lincoln. The left-to-right road at bottom is old US 40, with Donner Pass to the left.

Source: Sugar Bowl Ski Area brochure.

Figure 20. Taylor anemometer direction and speed sensors atop Mt. Lincoln (2539 m / 8330 ft). Mounted on top of summit building housing upper end of chair lift. Looking approximately toward northwest, with Castle Peak and Donner Summit to right, Central Sierra Snow Lab approximately behind left side of third rung of ladder from top.

Photo by Dave Simeral.

Figure 21. Sugar Bowl lower site (2126 m / 6975 ft). View is approximately to northwest. Site has AC power and heated tipping bucket precipitation gauge.
Photo by Dave Simeral.

A third site was identified to the west of this location, in a clearing in the UC Onion Creek Reserve at 1881 m (6173 ft). This site is at the base of the headwall topped by Mount Lincoln, a 600 m (2000 ft) climb that air must make to ascend to top the Sierra, after its journey up the Grand Canyon of the North Fork of the American River (Figure 22). Onion Creek has been a US Forest Service experimental watershed and still has a number of concrete weirs available for research use, and is now part of the UC Natural Reserve System. Permitting is also much easier in an established research reserve such as this. Two nearby precipitation gauges are maintained by the caretaker at the Central Sierra Snow Lab and by researchers working with the NOAA National Weather Service Hydrometeorological Test Bed, which encompasses the North Fork of the American River Basin. This river empties into Folsom Reservoir just above Sacramento, itself the subject of a number of studies over recent years because of the huge flood potential posed to the city of Sacramento (NRC; 1995, 1999). The Onion Creek site is shown in Figure 23.

Figure 22. Final headwall on North Fork American River, which flows downstream from right to left at lowest point in foreground, shortly before it makes its turn westward into the Grand Canyon of the North Fork. Looking approximately from a vantage point about 300 m (1000 ft) above the river. View is eastward toward The Cedars (green open meadow at center right), Mount Lincoln (right center, and atop Sugar Bowl Ski Area), and Mt Disney (just left of center, and atop another portion of Sugar Bowl). In distance at left are the three Castle Crags, just north of Donner Summit and readily visible from Interstate 80. Onion Creek Reserve is centered between the gap in the trees at center. The Onion Creek ECCM station is located near the exact center of the photo.

Photo July 20, 2005 by Kelly Redmond.

Figure 23. Climate station at Onion Creek.

Taken by Dave Simeral mid-October 2006.

Sites away from the ski areas can be very hard to reach for extended stretches in the winter. The site at Onion Creek can be reached somewhat more frequently by Central Sierra Snow Lab personnel in support of occasional research projects.

Three more sites were selected based on their ability to provide additional information in the snow zone and to assist with transect studies. One of these was a platform at Cisco Butte formerly used for weather modification projects, at an elevation of 1959 m (6429 ft), alongside Interstate 80 and accessible by road in summer. Though at about the same elevation as the sites closer to the Sierra crest, this location is farther west, an isolated butte next to (south of) Interstate 80. A permit exists for the present site, but would not allow for a new 10-meter tower to be erected. A site on top of the butte itself would have been preferable, but after investigation a summit site would have led to considerable permitting complexities. The available site is a few hundred meters south of the top of the Cisco Butte on a flatter area. The site has a large corrugated steel container for protecting a computer, very difficult to remove (Figure 24). Equipment is attached above this container to maximize free air movement, and a snow sensor extends to the side. An old power line is present, but electricity is now shut off, mainly needed if snow or ice needs to be melted. This site was chosen to provide wind speed, snow depth, humidity and temperature information, relating to air movement up the Sierra slope, and to freezing level variations west of the main crest. Examination of the data shows some wind channeling by the remaining upper hundred meters of Cisco Butte itself. The site does experience occasional icing.

Figure 24. Photo of Cisco Butte climate station. Steel container formerly used to store equipment.
Photo taken Nov 15, 2006 by Greg McCurdy.

Another site was chosen farther to the south of the I-80 corridor, this one to the north of and relatively close to US 50, which ascends to the east from Sacramento along the South Fork of the American River to Echo Summit. This site has other snow instruments owned and maintained by the California Department of Water Resources (CDWR), and the Sacramento Municipal Utilities District, and is called Alpha, elevation 2334 m / 7657 ft. This site provided a set of meteorological measurements that could complement the existing hydrological measurements. The Alpha site also is fairly undisturbed and therefore a good location for long term climate measurements, and was one of the early CDWR sites for testing snow pillows in the 1970s. This site is higher than Donner Summit, thus well into the snow zone, and is ordinarily not reachable or visited in winter (Figure 25).

Figure 25. Alpha station, elevation 2334 m / 7657 ft. Site has provided snow measurements for California Department of Water Resources for many years. New tower latticework with anemometer is visible just to right of leftmost white precipitation gauge.

Photo by Dave Simeral.

Another station has functioned for many years atop Slide Mountain, elevation 2941 m / 9650 ft. Slide Mountain is next to (south of) Nevada Highway 431, and is accessed from the Mount Rose Summit (2716 m / 8911 ft) along this highway (Figure 26). The Slide Mountain station is very nearly at the highest point on the mountain, one of two nearly equal summits, less visited than the other, and with a commanding view of Lake Tahoe and its basin, and excellent exposure to wind. Earliest meteorological measurements started about 1967. These have been summarized in daily form since about 1983. Nearly complete digital ten-minute records extend from about October 1994; paper records contain ten-minute data extending another 10-15 years but these have never been digitized. The station experiences extremely high winds and a great deal of icing, so the support structure is short, sturdy and compact. The site has no electricity, and in winter the anemometer is frozen in place about 1/3 of the time. The site has not moved since installation, and is off the beaten path, even for skiers riding up from Mount Rose Ski Area. This project augmented this site with better instrumentation, and added a few extra service visits. The site is within several km of Mount Rose, third highest peak in the Tahoe Basin.

Figure 26. Slide Mountain, elevation 2941 m / 9650 ft. Mount Rose (3285 m / 10,776 ft) in the background. Looking toward northwest.

Photo taken March 12, 2007 by Greg McCurdy.

Measurements at elevations representing the areas below the main snow zone (900-1200 m, or 3000-4000 ft, on down to sea level) were not strongly pursued. Snow has a more intermittent presence in the elevation zone. In this increasingly rain-dominated setting, other measurements by other research and operational groups are more likely to be found. Above these elevations, there is increasingly strong reluctance to take on the considerable difficulty involved in measuring heavy snow in remote inaccessible and very steep terrain. These higher altitude zones would thus be locations where a dearth of measurements are likely.

As part of the "Coast-to-Crest" transect, one or two more sites were desired in either the lowest (but "natural") parts of the Central Valley, or in the parallel rows of hills in the Coast Range, successively inland from the Pacific Ocean. A Climate Reference Station has been installed and is running in the lowest part of the Central Valley, at Kesterson Wildlife Refuge near Los Banos. This site has very good temperature and precipitation measurements, but no wind speed/direction, humidity, or solar readings. Numerous attempts were made to establish a climate station on the west side of Pinnacles National Monument. An intervening ridge west of the Salinas River separates this location from the ocean, and the site exhibits a combination of maritime and continental properties. It was thus felt that if climate change led to movement of the ocean/inland climate gradient in either direction, this site would be in a good position to sample that change. Although several surveys and visits were conducted, including a prior very comprehensive survey for a potential NOAA Climate Reference Network site, it was not possible to expeditiously obtain the necessary permits in time to install a station, even though one was ready for installation. Efforts are under way to install this site at Pinnacles with other support.

Prior experience from a number of other measurements programs showed that the entire process of selecting sites involves a range of theoretical, practical, research, operational, physical, logistical, and administrative tradeoffs and considerations. This proved to be once again true during this project. Locations of the ECCM sites are shown in Figure 27 and listed in Table 1.

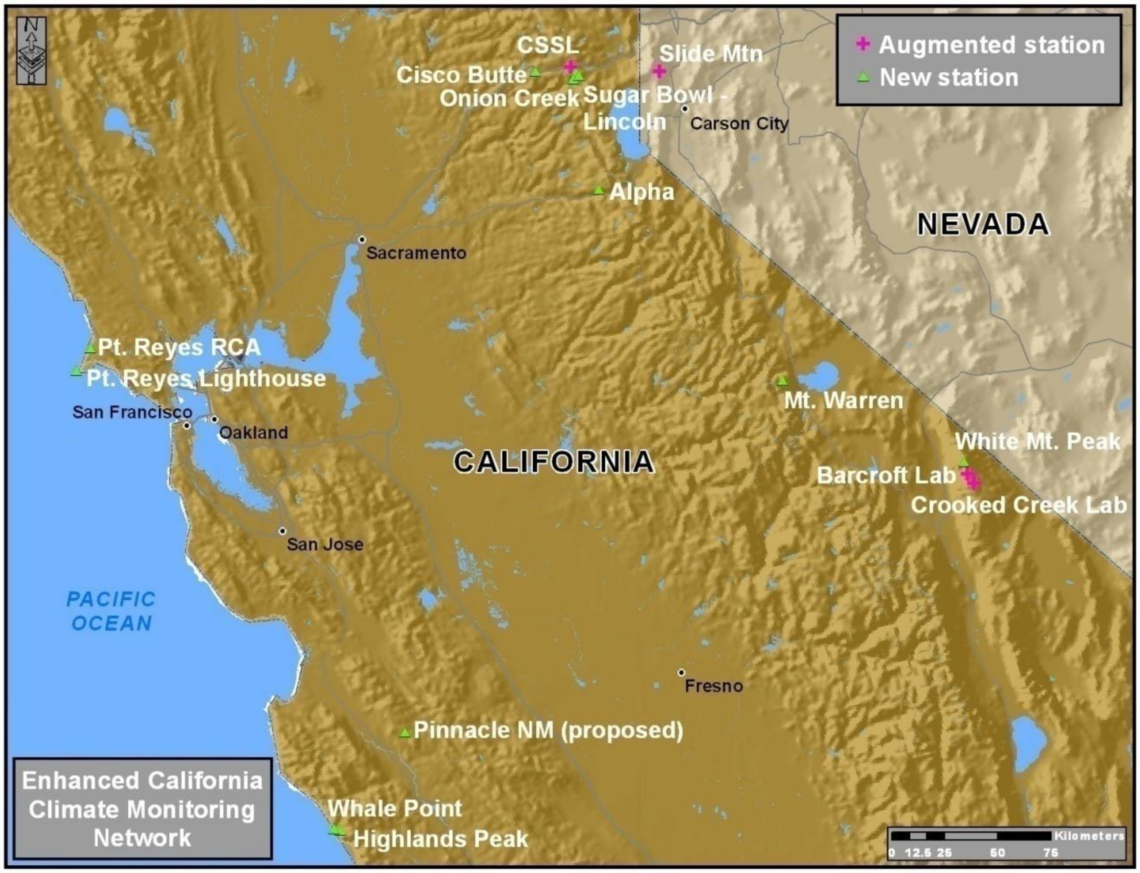


Figure 27. Map of Enhanced California Climate Monitoring sites.
Prepared by Dave Simeral.

Table 1. Climate stations deployed (new) or augmented for Enhanced California Climate Monitoring project.

Name	Latitude	Longitude	Elev (m)	Elev (ft)	New / Aug
Whale Point Big Creek	36.07222	121.59614	124	407	N
Highlands Peak Big Creek	36.06611	121.56111	753	2470	N
Pt Reyes RCA Field	38.09417	122.95000	27	87	N
Pt Reyes Lighthouse Rock	37.99639	123.02056	160	526	N
Cisco Butte	39.30611	120.56278	1960	6429	N
Central Sierra Snow Lab	39.32556	120.36667	2098	6883	A
Sugar Bowl	39.30333	120.34083	2126	6975	N
Onion Creek	39.27444	120.35583	1882	6173	N
Mt Lincoln	39.28861	120.32611	2539	8330	N
Alpha	38.80389	120.21583	2334	7657	N
Slide Mountain	39.30722	119.88389	2941	9650	A
Mt Warren	37.98972	119.22361	3757	12327	N
Crooked Creek (WMRS)	37.54306	118.20444	3094	10151	A
Barcroft Lab (WMRS)	37.58306	118.23722	3783	12410	A
White Mountain Summit	37.63417	118.25583	4342	14245	N

2.3. Acquire Equipment and Install Sites

For each site detailed instrument specifications were developed. The factors governing these specifications include:

- Cost
- Quality
- Reliability
- Serviceability
- Inter-site compatibility
- Lifecycle costs
- Site security
- Site host requirements

With respect to cost, prior experience teaches that a long-term life-cycle approach is necessary. Low up-front costs most often lead to larger long-term costs, or simply lower quality data, which represents a different type of cost in terms of usefulness. Cheaper equipment very frequently results in a loss of data, often in the very conditions of most interest, the extremes. A standard of zero missing or bad data is hard to achieve, but if possible, no more than 10 or 20 hours a year of missing data is a realistic and desirable goal, that is, at least 99.5 percent data recovery. This requires high quality equipment with a track record of proven durability in extremely difficult conditions. As much as possible, site components should be compatible across locations so that parts can be swapped out and readily interchanged, and should thus be the same for given environmental conditions. In some locations, certain devices such as anemometers can be quickly torn apart by prevailing winds. For example, all mountaintop sites were equipped with extremely rugged Taylor anemometers, which can readily measure 89.4 m/s (200 mph) winds, and survive the vibrations and pelting from gravel or ice particles. Pitting of solid aluminum can reach almost a millimeter in depth. Rime ice can build up to a ton or two on certain structures, and is often unbalanced, so short stubby towers are preferred on mountain tops. Data loggers must survive both high and low humidity, high and low temperatures, liquid moisture, and not use much power. Cables and connectors must be firmly mounted to the sturdiest bases, and in some cases protected from flying objects, or from rodents and insects. Salt and corrosion along the coast can reduce bolts to a pile of rust in just a year or two, though the shorter lifetime of towers and anemometers can be extended with special coatings. Every exposed joint or connection needs corrosion coatings.

At all locations Campbell Scientific data loggers were employed. Temperature/humidity sensors obtained through Campbell were manufactured by Vaisala. These loggers record means and extremes of many quantities, including self-diagnostics, over 5- or 10-minute intervals, and must be programmed correctly in every detail. In addition they must interface correctly with the communications method selected. Precipitation gauges were shielded, and consisted of the TB4 made by HSA, the same manufacturer and model chosen by NOAA for backup at Climate Reference Network stations. When AC power was available, these were outfitted with a heater. Wind sensors at “quiet” sites were the propeller and vane type manufactured by RM Young. A marine RM Young anemometer was installed at Point Reyes Lighthouse. At high elevations, Taylor anemometers (two-component separate "mill wheel" and vane) were used at any site where routine winds over about 63 m/s (140 mph) were expected. During the winter of 2008-09 (August 2008 through May 5, 2009), White Mountain Summit wind gusts exceeded 44.7 m/s (100 mph) on 26 days, exceeded 53.6 m/s (120 mph) on 13 days, 58.1 m/s (130 mph) on 8 days, 62.6 m/s (140 mph) on 5 days, and reached a peak of 72.4 m/s (162 mph) one day in December. An ordinary RM Young anemometer at this location, tried as a temporary replacement, was ripped to shreds. For solar radiation measurements, generally Li-Cor pyranometers were installed.

In general an awareness of physical security issues is needed, but for these particular stations and settings no special precautions were considered necessary to protect individual locations from humans. Locations with either very few or very many visitors are considered safer. A few sites were rejected at least in part based on high human exposure and limited nearby oversight and a potential for mischief. One site (Point Reyes RCA) needed barbed wire protection against cattle. The rest are generally protected from large animals by distance above ground, ground characteristics, or human presence.

Hosts often impose requirements, sometimes spelled out in the permitting process. These often include aesthetic considerations, particularly for parks and monuments. There has been some discussion of highlighting, rather than hiding, stations, to educate visitors on the role and necessity of monitoring. The California Coastal Commission has strict standards regarding visibility. Many sites with excellent exposures are rejected out of hand by the WRCC survey process, knowing they would not pass later tests by others. Variances and exceptions are usually very difficult to secure. Instrument housings can be camouflaged, except for thermometer shields (these must be pure white). As a rule, permitting and aesthetics have as much influence as most other purely physical exposure considerations. Hosts are always assured of electronic access to all data. Hosts who have a vested interest in the data for their own purposes are especially sought. Hosts also can provide routine visual inspections, and can be enlisted to download data or perform light-duty maintenance. Some hosts have sufficient technical expertise to assist in more detailed upkeep.

At Big Sur Big Creek Reserve, the California Coastal Commission required that the tower be smaller than the typical 10 m (World Meteorological Organization, WMO) standard, for aesthetic reasons (visible from highway), and so a shorter 3 m (10 ft) tripod was installed. This stipulation has resulted in a noticeable reduction in wind speed. However, temperature, humidity, and solar radiation are of greater interest at this location. The nearby higher site at Highlands Peak required clearing of extensive poison oak, but has a full 10 m (33 ft) tower with very good exposure to wind, and sufficient vegetative cover near the ground to provide good protection for the precipitation gauge, which also has its own shield. Precipitation is greater here at 753 m (2470 ft) than at 126 m (407 ft) at Whale Point.

Vegetation growth will affect air flow near the surface, and thus the precipitation gauge catch efficiency, as well as affecting the vertical wind profile, and thus wind speed and temperature. At an ideal site, vegetation is maintained to always be the same height and mixture every year.

Site surveyors are trained to consider the natural rate of vegetation growth, visualize what a site might look like in 2 or 3 decades, and make suggestions accordingly. Susceptibility to disturbance, particularly fire or wind blowdown, are also considered in choosing locations. This site, as it happened, was close to a major burn in June 2008, but the area near the tower escaped damage, and may have helped save itself; the data were quite helpful to firefighters.

2.4. Reception and Evaluation of Data

This task consists of several activities:

- Initiation and maintenance of communications pathway(s)
- Data ingest
- Checking of data for gross errors
- Immediate entry into storage system
- Web-based access to data
- Provision for on-site backup of data
- Evaluation of data reception and quality

Two way communications without recurrent costs (i.e., phone bills) are always the preferred option. Such arrangements generally involve land lines to nearby computers on the network, and sometimes short distance radios. Communications using CDMA technology was employed at some sites. These have recurrent costs, a drawback. Cell phone technology changes are a risk, and have led to loss of real-time data acquisition in 2009 at two mountain sites. However, two way communications provide a chance to re-acquire data missed during transmission interruptions, allowing complete data without need of a visit, and provide an opportunity to perform field diagnostics, or re-program data loggers.

One way communications, such as GOES satellite uplinks, have large up-front costs but no recurrent fees. The operator must have frequency allocations; WRCC has a number of these. This approach is widely used and quite reliable, with the only stipulation that the satellite not be blocked by trees or terrain. Communications often require more power than the meteorological instrumentation. When batteries are low, stations are instructed to continue to record observations on the data logger, but not necessarily to transmit them until voltage reaches acceptable levels.

2.5. Archival, Display, and Interpretation of Data

The goal of this task is to make the data useful, and entails several steps:

- Retain data in a permanent archive
- Provide for access to the entire record from each site
- Develop tools to obtain data
- Utilize existing and new tools to summarize and visualize data

Data from the stations arrive at WRCC via any of several different pathways. There, they are ingested into the system WRCC uses for storing incoming sub-daily data (hourly, or more frequent). The data are displayed on the screen as a multiple-element trace rather like that produced by a strip chart recorder. Most sites are updated every ten minutes, the basic observing interval. Data from the ECCM sites are intermingled for display purposes with many other types of sites, and can be accessed via www.wrcc.dri.edu/PROJECTS.html under "current weather data plots." In addition to the default graphical display for a station of interest, users can look at numerical listing of the past 24 hours of 10-minute data shown on the screen in text format by selecting "Data table for graphs" above the upper left portion of the graph trace. Alternatively, the user can select "Historical Weather Data" from the same location.

All sub-daily historical data back to the original establishment of the station or data set are available via the web. These can be obtained or viewed in several ways, following choices presented in the left hand frame. For a variety of purposes the 10-minute data can be aggregated into hourly or daily values, and obtained in several different formats. These are generally referred to as *listings*. Any form of data that is not original is considered to be *derived* data. In general original data cannot be recovered from derived data.

The original 10-minute data can be retrieved readily for the past 30 days. To prevent automated systems from roaming the system, an access code is required for original data older than 30 days. At present this must be obtained from WRCC personnel (wrcc@dri.edu). An automated way of obtaining such a code is under design.

Different tools are provided to visualize or summarize data in different ways. Time series of 10-minute readings can be plotted of original data over periods spanning the last 1 hour to the last 2 years (732 days), plotted separately or overlaid. Other tools provide hourly, daily, monthly, and annual frequency distributions, or summarized vector and scalar wind information in the form of graphical *wind roses* and associated text summaries. Period of record climatologies can be formed by controlling the selection criteria. Methods to show records from more than one station on a single graph are under development.

Summary products are usually offered with default settings that can be altered by the user to fit specific needs. Several of these products offer screening filters that reject incoming data not meeting the screening criteria. The general approach is to allow the user as much freedom as possible to summarize data according to specific needs. A few products are intended to be fast and require little thought or effort, such as graphs of the last seven days of principal climate elements. No attempt is made to save or store any of these summaries, since they can be generated fairly quickly in an on-demand mode. A typically outfitted station will have 20-25 measurements every 10 minutes, or about 52,595 10-minute intervals per average year, with about a million sensor values per year.

2.6. Maintenance and Calibration of Data

The principal goals of this task are to ensure:

- Continued reception of data

- Continued operation of station
- Service visits to maintain station
- Calibration of equipment as needed
- On-site visits to download data stored in data logger

All stations have live communications and report at 10-minute intervals. Gaps in communications can occur for a variety of reasons, at the station, at WRCC, or at several stages along the way depending on the exact data pathway. Where two-way communications exist, the WRCC system will request all data after the last interruption, and in general these stations will have more complete records. For stations with one-way communication (e.g., satellite links) there is no way to request a re-transmission of prior data, and these must be inserted later after field visits to the data logger.

Stations that have been set up with careful attention to detail can function for long periods without human intervention. Sites in readily accessible areas are visited once or twice a year. Some can only be visited in the warm (snow-free) season. The goal for these stations has been one visit every 12-18 months. Some visits require coordination of several individuals, and depend on relatively uncommon intersections of busy schedules. Weather conditions frequently cause postponements. The Mount Warren site requires a 1000 m (3000 ft) climb, but is visited once or twice a year by helicopter to service the Forest Service repeater antenna. This much easier mode has been utilized whenever possible, but two flights during this project had to be cancelled for firefighting emergencies elsewhere in California.

The DRI Division of Atmospheric Sciences, which houses WRCC, developed a Meteorology Calibration Lab as a contribution to this project. This facility obtained equipment to calibrate temperature (continuously variable chamber), humidity (fixed low, medium, high values), and solar radiation (Kippen-Zonen, Li-Cor lab sensor, and another instrument that is periodically calibrated by the National Renewable Energy Lab in Boulder, Colorado). For infrared radiation, an Eppley pyrgeometer was obtained as well. In-house methods, the typical approach, have been developed for testing precipitation amounts and rates.

Stations are routinely assembled in the Calibration Lab, the data logger is programmed for the planned complement of sensors and for any special circumstances, and all sensors are connected. This setup is run for a day or two before deployment to the field and installation. The precipitation tipper (if this type of gauge) is tested in the lab with a calibrated field syringe, both for amount and for occurrence (providing the proper number of tips). When possible, communications are tested before going into the field.

Especially in remote sites, adequate supplies of heavy duty batteries are needed. These weigh 80-100 pounds and any kind of non-human transport capacity as close to the site as possible is sought and appreciated.

A routine process is followed during field visits. The station is inspected for missing or misaligned parts, cracks, battery and connection corrosion, moisture, and physical damage to either sensors or the support structure. For field visits, portable calibration and testing kits have been developed. Temperature is compared to two different portable temperature standards (one is from Vaisala). Humidity is compared with a field kit sensor. Pressure is compared with one or two quality barometers (Vaisala PTB101), and solar radiation is compared with a field standard of known quality. The tipper in the precipitation gauge is tipped 200 times to test the switch, and a calibrated syringe is used to test anywhere from 10-50 tips. During the field audit the wind direction is tested in all four cardinal directions, and the speed sensor is examined for vibration, noise and grinding. Solar power panels and solar sensors are cleaned of dust. Usually enclosure housing the data logger is opened and examined. During humid or foggy conditions the protective enclosure is often opened only briefly or not at all, and desiccant is protected in a sealed container from further absorption, or is replaced. Temperature shields are examined for discoloration, and cleaned of mildew, dirt, or other darkening agents, if possible.

Equipment has been obtained to document site visits, including cameras, rangefinders, inclinometers, and GPS units. Sufficient care with pre-installation laboratory practices, deployment and connectivity checks, and preventative maintenance at the site, are integral to continued success of any such atmospheric measurements program.

2.7. Documentation of Existing Sites

- Develop a methodology for station documentation (metadata)
- Document sites
- Make this documentation web accessible

An accurate (within a few feet) GPS latitude/longitude position is obtained for each site. Elevation is determined from either GPS (accuracy varies according to number and elevation angles of available satellites) or from topographic maps. If practical, each site is photographed from eight position angles around the compass, once looking from the station and again looking through the station. Supplemental photos are obtained to show the status of the ground and of nearby vegetation. Other photos are taken to document the condition of the equipment and support structures, and to show such factors as salt corrosion and other factors.

The methodology for station documentation is quite similar to that developed and employed by WRCC for the NOAA Climate Reference Network, and for the ongoing site surveys by WRCC for the NOAA Modernized Historical Climate Network sites.

A method has been developed to maintain a record of site visits and of what took place during each visit, whether for routine servicing or to address a particular problem. This information can be accessed in the same area as the other metadata. An example is shown in Figure 28.

Station Maintenance

add

id	ucan_station_id	maintenance_date	remark
78	1014278	2008-09-23	Station visit: Raingauge cleaned out (ash from summer fires), Solar panel cleaned, AT/RH shield disassembled and cleaned (dirty and sooty), solar rad sensor cleaned (minor residue), wind speed/dir sensor inspected. All equipment operating as expected. AT/RH shield had plastic and foil wrapper around base (Fire crew that cleared site earlier in summer placed around sensor to protect the instrument), removed. Site photographed. Data memory module downloaded.
79	1014278	2008-09-26	Data retrieved from site loaded to database (web). Filled many missing values that were not transmitted. Corrected AT/RH values that were erroneous when the fire crew cleared the site (and bagged the sensor).

Figure 28. Screen shot of recent portion of metadata record (in this case for Highlands Peak).

The default web display for each site is an "electronic strip chart" showing conditions every ten minutes for the past 24 hours. This is constantly updated as new data are ingested. A link that lists the data on the screen is present just above these graphics. Another link to "Historical Weather Data" provides access to the summary software discussed in Section 2.4. Included on the specific station page are links to the station metadata and site documentation. In addition various products and metadata inventories can be used to assess data completeness.

3.0 Project Outcomes

A targeted approach was utilized to successfully deploy a set of 11 new and 4 augmented stations designed to address knowledge gaps about California climate. They are located in the central portion of the state and focus primarily on coastal and mountain environments. Many of the resource management and energy issues affecting California are related to climate behavior in these important areas. The stations have furnished nearly complete data in the less extreme environments and somewhat less complete data in the harshest environments. The overall data quality has been quite good. Equipment is in good working condition.

Sites were selected with considerable input from a variety of sectors within the research community. One goal has been to facilitate and contribute to other research efforts already under way or planned. Coastal sites at the UC Big Creek Natural Reserve and at Point Reyes National Seashore have been incorporated into their respective research and monitoring programs. The Big Creek stations have clearly shown the extremely strong gradient in summer climate that is present along the coast. Climate variability and climate change investigations by ecologists need detailed information in the vicinity of the plants and animals under study. Plans are under way to try to augment the Big Sur stations with enough sites to obtain a full transect with more closely spaced stations, to better understand the plant communities and their relation to temperature, humidity, fog, and wind. Ecologists within the University of California system are planning to add instrumentation for soil moisture and other properties in support of another CEC project involving climate-vegetation interactions.

Mountain sites are contributing to the goals of the Consortium for Integrated Climate Research in Mountain Regions (CIRMOUNT, 2009). Two new GLORIA sites (Global Observation Research in Alpine Environments) were established within short distances and at similar elevations as climate sites at White Mountain Summit and Mount Warren, in order to have decades-long corroborative measurements of the physical environment. This worldwide program follows strict protocols to make detailed fine-scale repeat measurements of biota at high altitude summits. Another GLORIA site near Lake Tahoe will be in the vicinity of the Mount Lincoln, Slide Mountain, and Alpha stations. Several of the sites in the American River basin were selected to help contribute to the NOAA Hydrometeorological Test Bed. Inquiries have been received to add solar and infrared radiation monitoring sensors in support of climate studies.

Several of the climate stations make use of the University of California Natural Reserve System. The UC reserves serve as hosts for a number of environmental research projects, and in addition play a very significant role in teaching and outreach within the state higher education system. As a consequence the Natural Reserve System management teamed with WRCC in 2009 to submit a (pending) proposal to NSF to add climate instrumentation at another 20 of the state's 36 Reserves.

The manager of a NASA Ames project made the following comment on the Big Creek measurements: "These Big Creek weather data sets are a unique and highly valued resource for the research we intend to continue on ecosystems and climate change in that part of the state."

The high elevation stations are used for making Sierra forecasts: "The National Weather Service does indeed use the valuable weather data collected from the Summit and Crooked Creek stations. I'm … a lead forecaster with the NWS in Hanford, California, and we forecast up to the Sierra crest. With no data available in the Sierra above 11000 feet, the temperature and relative humidity data collected in the White Mountains at both 12 and 14k feet is used as base data for our forecasting along the crest of the Sierra. Keep up the good work."

A UC Berkeley researcher noted: "These data will be very useful for my research. I will be using it to relate weather (wind and rainfall primarily) to the spatial usage patterns of elk across Pt. Reyes. I will be able to relate hourly weather data with hourly elk point locations from GPS collars. I believe that future studies such as mine would benefit greatly from having baseline weather data available at no cost. I strongly support additional funding to maintain the weather station network." A vegetation specialist reports: "We use the data for developing ecological models for rare plant species, understanding fluctuations in plant species reproduction, herbicide treatment planning (based on daily/monthly trends in wind speeds), revegetation planning, restoration planning." A range technician notes: "I have made use of the weather climate data to accompany the water quality monitoring data I am collecting for the Tomales Bay Rangeland BMP Pathogen TMDL Implementation Project. Specifically, I am using the historical weather data information (precipitation) to show the the accumulated rainfall (during the rain year starting in October) for each sampling event. This helps to give context to the results of the sampling (both field parameters and Lab -total/fecal coliform, TSS, nutrients etc.) I also refer to the precipitation data to record the amount of rainfall in the 24 and 48 hour period before each sampling event as well as in assessing if the amount of rainfall in a particular storm warrants 'storm sampling'. " The Point Reyes Pacific Coast Science and Learning Center incorporates the climate information into its outreach and education programs.

At all sites, significant efforts have been devoted to cultivating good relations with the site host, and in every case has proven to be successful and effective. This is essential to a well managed network, and helps considerably with maintenance, troubleshooting, and management issues as they arise. Site hosts have uniformly proven to be enthusiastic supporters of this monitoring, especially since they are themselves often much in need of the information provided by the stations. This also underlines the importance of communications to obtain the data in a timely manner.

The stations in extreme environments have generally functioned well, considering the conditions. The White Mountain Summit was struck by lightning, burning a hole in the quarter-inch thick aluminum anemometer, which was repaired, but no other equipment was damaged and some continued to operate. The highly exposed site does have lightning protection, which appears to have helped. Snow has covered the Mount Warren solar panels over part of one winter; these were subsequently raised. Power there is shared with the US Forest Service repeater station. The climate station electronics and power are isolated as much as possible from those of the repeater station to reduce propagating problems. Power disruptions at Sugar Bowl occasionally shut off the precipitation gauge heater during snow events. Anemometers at the highest sites sometimes slow to zero during icing events, usually when the mountain tops are in clouds for extended periods when the temperature is below freezing. During such episodes, wind can easily be blowing 100-150 mph with the anemometer frozen in place and reading zero.

Figures 29 and 30 shows the dramatic difference during the July 2006 heat wave between the upper and lower sites at Big Creek Reserve. The graphs cover the exact same period.

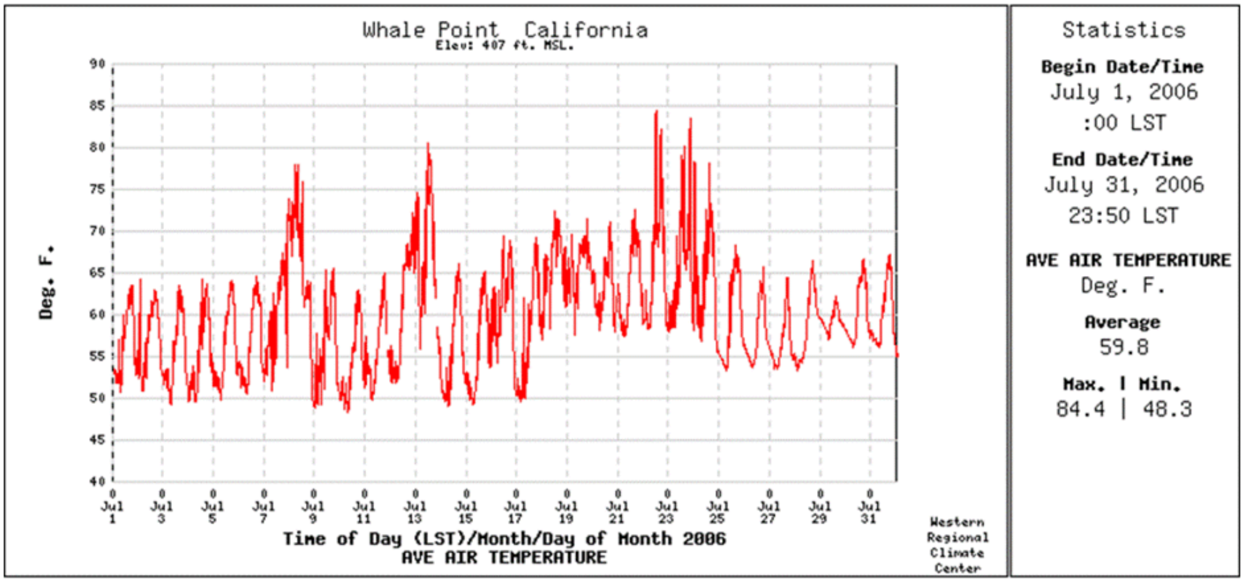


Figure 29. The California heat wave of July 2006 had very different signatures at Big Sur, depending on elevation. At the Whale Point station (124 m / 407 ft), during the warmest period, minimum temperatures were about 7 degrees F warmer than earlier in the month. Most days did not exceed about 72 degrees, though the temperature reached into the 80s for a few hours on the 23rd, 24th, and 25th.

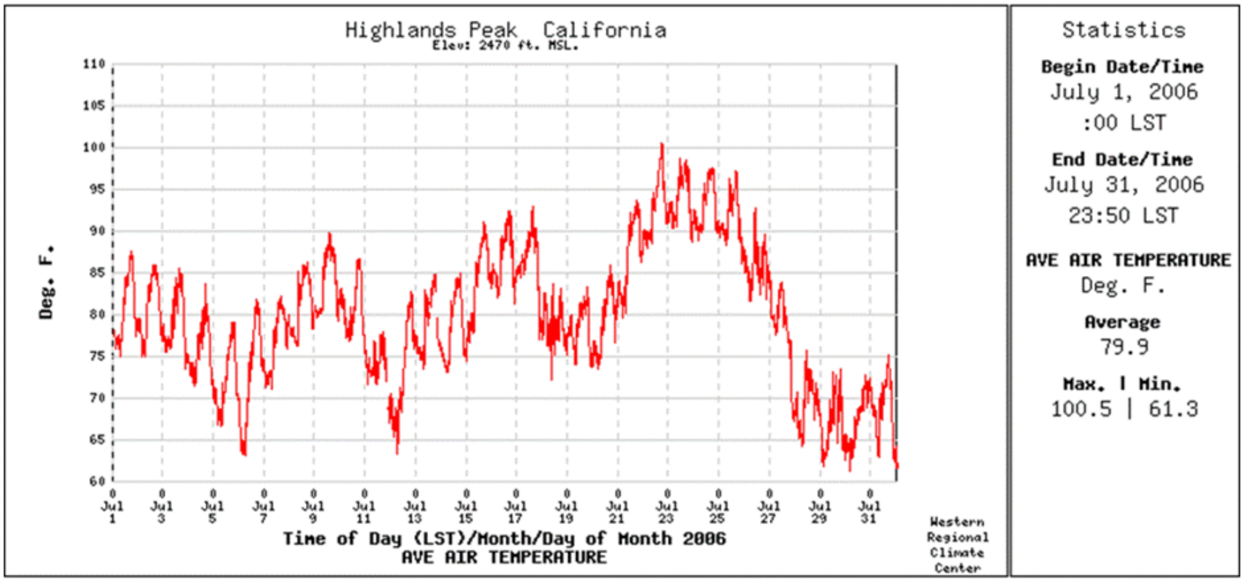


Figure 30. At the Highlands Peak site, 2 miles from Whale Point but 635 m / 2100 feet higher, the month of July was very different. During one 24-hour period the temperature never fell below 90 degrees. Minimum temperatures this high are almost exclusively seen only in the low elevation deserts of the Southwest. For about 4 consecutive days the temperature never fell below about 87 F. The warmest temperature seen was 100.5 F.

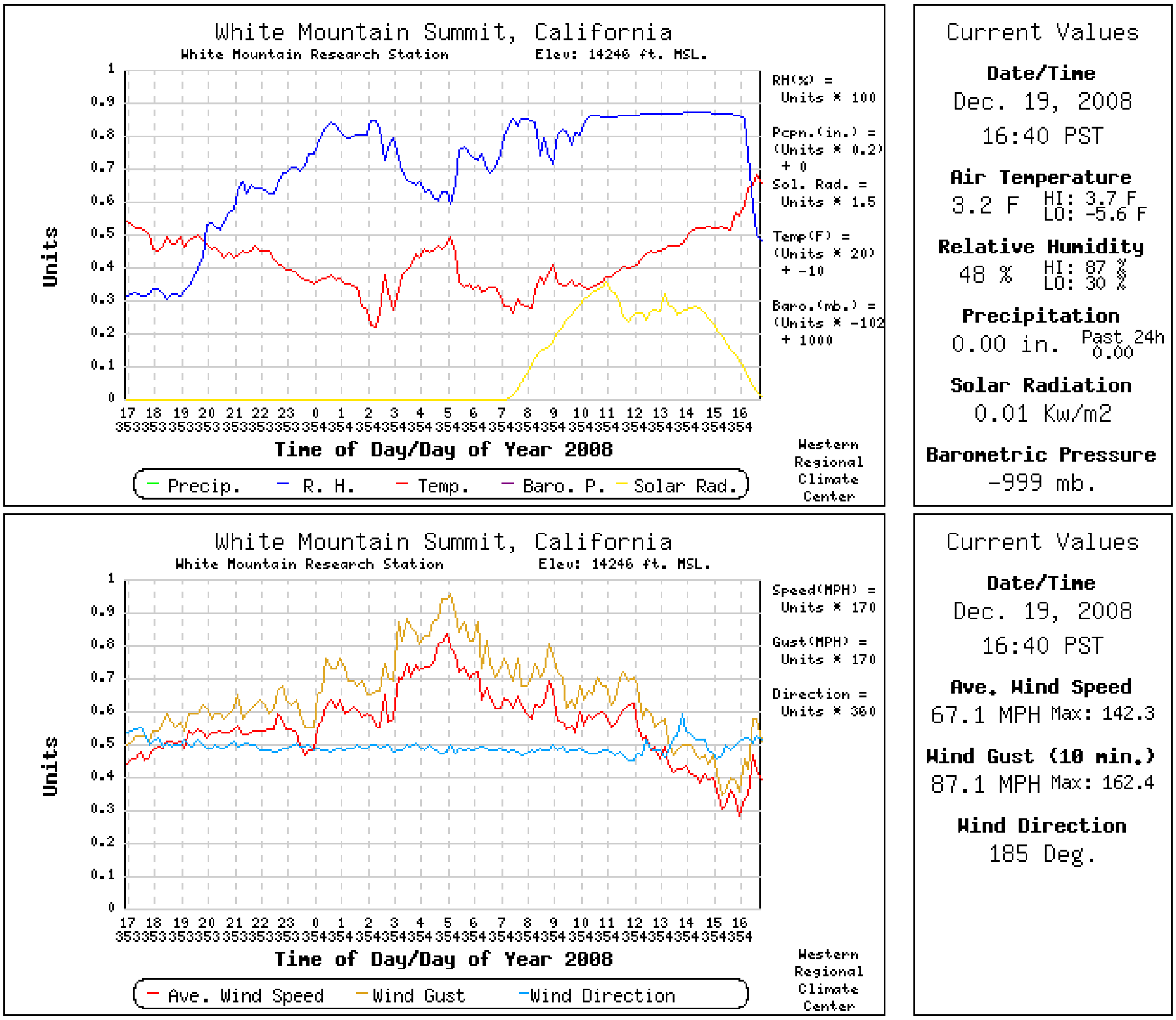


Figure 31. A particularly windy day at White Mountain Summit. About 5 am on December 19, 2008 the wind was blowing at a sustained 142 mph with gusts to 162 mph. The wind is very steady, directly out of the south. The temperature rose to about 0 F about the time of the maximum wind. Top: Temperature (red), relative humidity (blue), solar radiation (yellow). Bottom: Sustained wind speed (red), 10-minute gusts (orange), wind direction (blue).

The wind is a notable climate element at White Mountain Summit (Figure 31). However, the thermometers also reveal interesting behavior. These instruments show that the daily range of temperature at the White Mountain Summit station at 4342 m / 14,246 feet is typically observed to be 15-20 degrees F (maximum minus minimum). The daily range in the nearby free air, taken from the weather balloon (rawinsonde) at Desert Rock NV (next to the Nevada Test Site, just to the east) is only about 1-2 F. Quite clearly, even this rather isolated and steep-sided mountain range has an effect on the immediately adjacent air temperature. The presence of a land surface causes the maximum temperature to be warmer than if there were no surface, and the minimum temperature to be cooler.

Nonetheless, the day-by-day variations in mean temperature at White Mountain Summit are quite similar to the day-to-day variations in the free atmosphere. The Global Reanalysis (GR, Kistler et al., 2001), with a spatial resolution of about 250 km, and the North American Regional Reanalysis (NARR, Mesinger et al., 2006), with a spatial resolution of about 32 km, have 6-hourly and 3-hourly records, respectively, that begin in 1948 and 1979, respectively. The initial data are largely from weather balloons (radiosondes and rawinsondes), aircraft, and satellite, and almost no surface data have been used. Daily mean temperatures since 1948 were obtained from the GR and since 1979 from the NARR data sets. A period of about 1000 days of overlap with the climate station showed that the GR and NARR could be used to estimate the known mean daily temperature at the Summit Station to within about 3 degrees C (5 degrees F) on 99 percent of the days. Regressions were formed for each day of the year and slightly smoothed through the seasonal cycle with a 30-day moving window. The NARR and GR data were then used to estimate a reconstructed temperature back to 1948, as if the station had been functioning the entire time. The results are shown in Figures 32 and 33.

These results show the great value of the surface measurements. Computations were performed by John Abatzoglou of San Jose State University. The analysis shows that temperatures have begun to warm at these high elevations, especially in the last 1-2 decades. Furthermore, the rate of warming is about 30 percent greater than the rate over the same years, averaged over the state of California. This is consistent with expectations, and with other observations from NARR and GR, that higher elevations are warming somewhat faster than lower elevations, and an important issue for snowmelt-driven hydrological systems. In addition, other analyses show that California summers began to be much warmer starting about 1998 or 1999, and the number of days when the mean temperature is above freezing at this altitude has risen considerably in this interval. This is an important time of year, when temperatures are frequently near or above freezing and plant growth becomes possible, so it would not be surprising to expect much increased biological activity, in both plants and animals, at these elevations. In the future, these high elevation sites will likely be extremely useful, and even now appear to be furnishing initial indications of upward movement of climate zones.

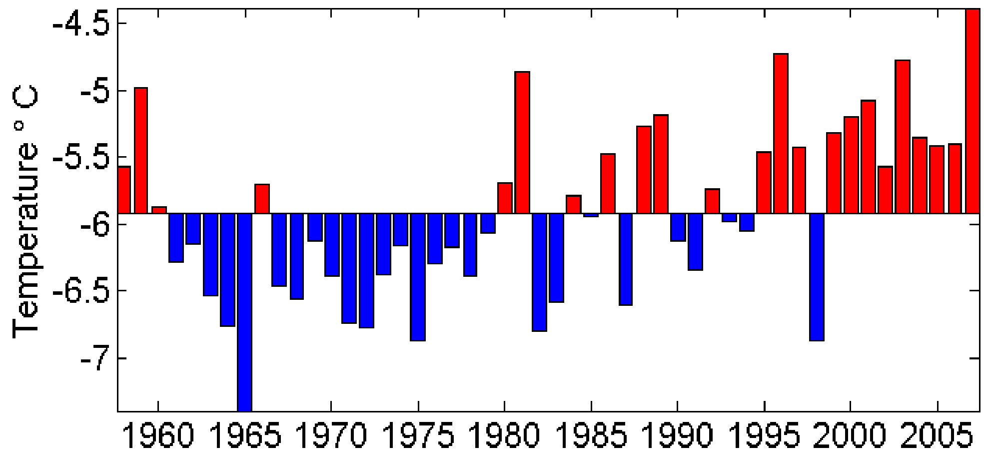


Figure 32. Mean annual reconstructed temperature at White Mountain Summit station, elevation 4342 m (14,245 ft), from 1958 through 2007. Trend over this period is 0.24 degrees C per decade (0.43 F per decade), about 30 percent larger than California as a whole. Approximately 99 percent of the reconstructed values are within 3 degrees C (5 F) of the observed values, when the observations are available for comparison. The recent increase is seen elsewhere in California and other nearby locations.

Figure created by John Abatzoglou.

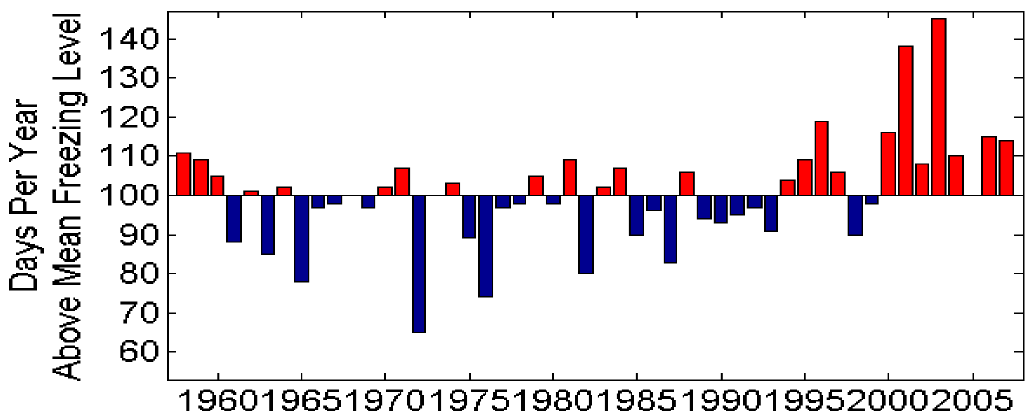


Figure 33. Number of days each year with mean daily temperature above the freezing point, as reconstructed from Global Reanalysis data set, 1958-2007, White Mountain Summit, elevation 4342 m (14,245 ft).

Figure created by John Abatzoglou.

4.0 Conclusions and Recommendations

4.1. Conclusions

The primary purpose of these stations is to address knowledge gaps about the behavior of California climate. The goal has been to use high quality equipment with adequate exposure characteristics, deployed in places that are generally not likely to change appreciably in coming decades, and located in areas where important climate issues are now present or will become important. A few sites are not ideal in every way, but were selected to provide crucial information about an important aspect of local climate or to take advantage of unique circumstances. The choice of instrumentation has proven to be very good.

The strategy of targeting sites to obtain spatially dense information in the form of transects or clusters was certainly the correct way to proceed. Closely spaced locations in regions with strong climate gradients are exceedingly hard to find, and yet can provide information that can be obtained in no other way.

The choice of coasts and higher elevations as a focus of attention was likewise very good. Striking differences in long-term climate are seen in very short distances along the Pacific Coast, and the fortuitous placement of the stations has provided an excellent start to a long-term set of baseline measurements. The mountain stations, all deliberately placed above the rain zone, have encountered the expected difficulties of operating in heavy snow, wind, and rime environments, and yet have provided very good data, with a few exceptions.

With the exception of the very lowest elevations the entire California range of elevations is now bracketed. It was felt especially important to establish several high elevation sites in this regard, despite the extra trouble they cause in maintenance and logistics, and this was accomplished by this project. The White Mountain Summit station is only 76 meters / 250 feet below the highest point in the continental United States, nearby Mt. Whitney at 4418 m / 14,495 ft. One site was offered by the National Park Service at California's lowest point, 86 m / 282 ft below sea level at Badwater in Death Valley, and the hottest (and lowest) location in the Western Hemisphere, but the necessary resources were simply not available to obtain and deploy the equipment. This site would have been strongly considered even though it is somewhat to the side of the main coast to mountain transect.

The data ingest, summary, and dissemination processes have all worked very well, and are expected to continue to do so.

As noted in Section 3, the needs of the research community were accommodated to the extent possible. These needs in large part drove the decision to concentrate the stations in one portion of the state thought to be representative of many parts of the remainder of the state, in the form of a large scale transect and with whatever clustering could be accomplished within resource constraints. This project proceeded in tandem with other WRCC projects funded by CEC, CalFed, and NOAA, and some leveraging opportunities were present.

4.2. Recommendations

The complex climates of California require an extensive and varied monitoring network. A modest project of this size and scope cannot improve the whole system at once. This strategy of addressing specific settings and issues has proven to be more practical and feasible. Future enhancements to the California climate monitoring system are likely to be similarly moderate, and should employ a similar approach.

Parts of the state still need attention. This project, in concert with other studies, clearly shows that the coast needs more sites along its length, with occasional transects from the beach to a short distance inland (to the local limit of the marine influence). Desert regions are still not well represented. The northeast high plateau is not sampled very densely. The coast to mountain transect from Big Sur to the Sierra crest could still use another station or two in the valleys between the coast and Interstate 5. San Francisco Bay has complicated meteorology and this area could use its own long-term monitoring network, including islands, prominences, the waters of the Bay and its estuaries, and the mainland and lower delta. Attempts were made to initiate such a network, but numerous practical and logistical issues must be dealt with.

This study focused on measurement of the "natural" environment. A conscious effort was made to avoid human influences, at local and even regional scales. However, there are reasons to measure human-altered climates as well, because that is where people live and work. The areas involved are not always minor in extent, and the populations involved can be enormous. Cities are generally (though not always) warmer than their surroundings, and this "urban heat island" effect can, for example, exaggerate the rate of photochemical reactions leading to ozone and other pollutants, or can exacerbate health effects of heat waves. Quite clearly, the rise (and now the fall) of widespread irrigation over the past century, and changes in water management practices, have altered the climate of much of the Central Valley over the past 120 years. These effects have been the subject of much discussion (Christy et al, 2006; Bonfils et al., 2006; Bonfils and Lobell, 2007; Bonfils et al., 2007; Lobell and Bonfils, 2008; Lobell et al., 2008a, 2008b). No network has been operating to consistently sample altered and unaltered sites; most studies have taken advantage of a potpourri of measurements taken for different purposes. In the Central Valley the effects of widespread irrigation would be expected to have greatest effects in summer, and in general to cool daytime maximums and to perhaps warm nighttime minimums. Such issues preclude a straightforward interpretation of the observed temperature records, and complicate the attribution of climate history to the several human and natural causes that have been operating simultaneously.

This project reiterated the need to obtain high quality equipment with proven track records. There were no instances where equipment failed for reasons other than environmental hazards (e.g., lightning, salt corrosion). Salty environments take extra attention to maintenance and more frequent visits, hopefully at least once every 12-18 months. Rust can set in quickly on bolts, padlocks, connectors, and other exposed parts. In humid environments, mold and mildew begin to make thermometer housings less white, and can eventually permit greater heating of the radiation shield plates. Examples of exposure to the marine environment at Point Reyes are shown in Figures 34 through 37.

Figure 34. Point Reyes National Seashore RCA Building site. Radiation shield has been removed to reveal mildew and organic film covering portions of the support for the temperature and humidity sensors, which are located in the dark gray slotted area near the top of the photo.

Photo taken 13 March 2008 by Dave Simeral.

Figure 35. Point Reyes Lighthouse Rock station, showing corrosion of steel bolt after 18 months of exposure to salt. Site is 526 feet directly above the Pacific Ocean.

Photo 13 March 2008 by Dave Simeral.

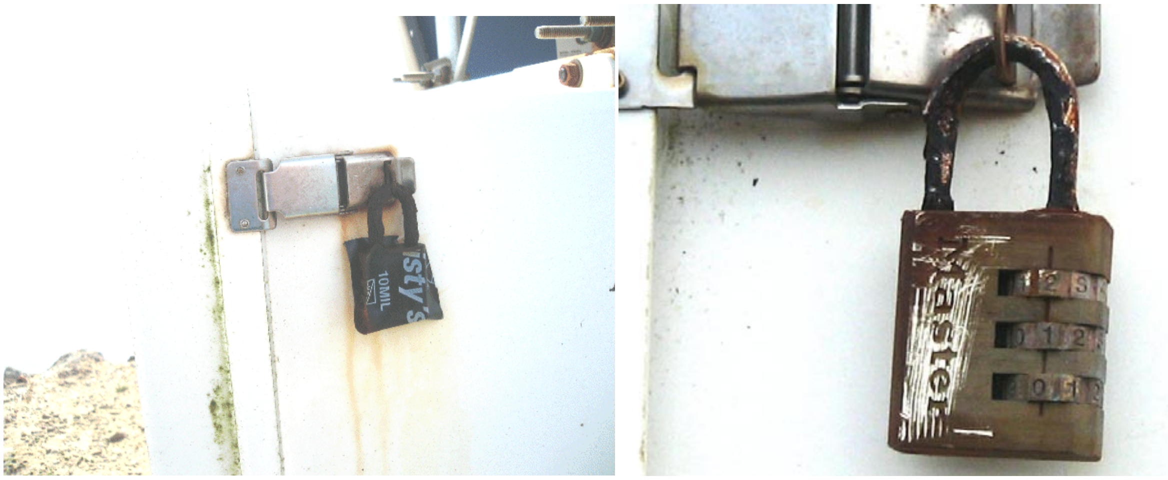


Figure 36. Padlocks on enclosure boxes showing level of rust and corrosion after 18 months exposure to salt environment. Left is at Point Reyes Lighthouse Rock, right is Point Reyes RCA Building. Locks had to be forcibly removed with saw.

Photo 13 March 2008 by Dave Simeral.

Figure 37. Thermometer shielding at Point Reyes RCA Building site, showing mildew and organic growth, 18 months after deployment. This causes extra heating on sunny days, and retains water for further growth. Material removed and cleaned.

Photo 13 March 2008 by Dave Simeral.

For long-term monitoring networks, station maintenance is a key issue, and was a consideration in this case from the start. During early stages of the project, prospects looked good that modest resources would be available to maintain the stations for at least several years after this project ended. In addition, sites and hosts that that might be able to assist with future maintenance were favored over others. The economic downturn of 2008 made the former possibility less likely. Attempts are under way to obtain support through other projects to maintain these stations. Except in marine environments, most of them can expect to be able to operate for a few years with routine service calls but without significant maintenance or sensor replacements. This entails some risk and is normally not the best practice, however. There are some possibilities that site hosts may be able to assist now that the sites have been deployed. Relationships with agencies that have operational monitoring responsibilities can pave the way for potential incorporation into those activities in future years.

The ability to pipe the data stream into an existing archival, summary, and dissemination infrastructure that specializes in this function has been a decided advantage. Such an approach is strongly encouraged in any future climate observing efforts. Such a linkage can also provide readily available avenues to provide the publicity and exposure needed to maintain a constituency supportive of continued maintenance.

Although recognized as a significant issue from the start, the project strongly reiterated the need to take the permitting process very seriously. This process can consume large amounts of people time, and often introduces lengthy delays into station deployment, from months to years. This activity has numerous idiosyncratic features, and can vary considerably from one individual to another, or from one management unit to another. At least one site was not deployed because the permit process eventually extended to beyond the project lifetime. Good cooperation with the site host can often help expedite permitting. All federal and most state lands will have permitting requirements. In particular, the California Coastal Commission closely scrutinizes all measurement activities, and in one case (Whale Point at Big Creek) a WMO-standard 10-meter tower had to be shortened to a 10-foot tripod to meet aesthetic and visibility requirements along the Coast Highway. Aesthetic considerations are likewise a significant factor with nearly all units of the National Park Service. Quite often these can be successfully negotiated without undue compromise to the integrity of the measurements, but at the expense of some delay. The re-occupation of a historic observing site instead of a new site, for example, can often be a deciding factor.

4.3. Benefits to California

A number of benefits to the state of California have been outlined in Section 3.0. Additional benefits are discussed here.

Global climate models have until recently operated at relatively coarse spatial resolution. The next generation that will be used by IPCC (the Intergovernmental Panel on Climate Change) will focus much more on regional and local climate. These models will need to better resolve small-scale processes that have larger-scale implications. For example, the southward-flowing California Current seen in summer, and associated upwelling, take place over a very limited distance off the coast, and require high spatial resolution in both models and in observational data sets. Similarly, in mountain settings, climate models must have embedded grids with the ability to "see" mountain ranges and large topographic features, for example, the various drainage basins of the Sierra Nevada, or the Tahoe Basin.

A variety of research efforts are under way within California that attempt to link ecological, water resources, energy, or public health issues to climate variations and trends. Sites deployed during this project have been intended to maximize the contribution of new information (over and above what is otherwise available).

This monitoring effort is distinct from, but related to, other efforts to measure, describe, and interpret California climate. An ongoing joint effort between WRCC and the CEC Scripps California Climate Change Center (CCCC) involves maintenance of additional Sierra Nevada monitoring stations at mid and higher elevations. These are all intended to better characterize and understand hydrologic processes and their relation to climate in mountain settings. A related activity, the California Climate Data Archive ("CalClim"), also joint with Scripps CCCC, is designed to make California climate data and monitoring information more accessible to the public. Another project has recently been initiated between WRCC and the California Department of Water Resources and its California Data Exchange Center (CDEC), to improve access to climate data and products by the California State Climatologist, and includes access to hourly data from California climate monitoring networks, and provision in standard form.

Another very dense high quality data network has recently become available to WRCC. The TREX (NSF and NOAA Terrain-induced Rotors Experiment) networks consists of 16 stations (originally, now 15) all about 1 mile apart, in three separate transects spanning the lowest 1000 feet of the Owens River Valley just south of Independence. These have 30-second and 10-minute data starting in Spring 2004 and extending through present, and both the stations themselves and the data set are maintained by WRCC and available via the web. These valley floor stations nicely complement the ridge stations atop the nearby White Mountains and are available for paired mountain-valley studies. The TREX stations can be outfitted with additional sensors if needed.

The publicity generated by the ECCM project has led to other monitoring efforts. One of these is a network of twelve stations on Santa Catalina Island, run for the Catalina Conservancy, and with both stations and data maintained by WRCC. As noted in Section 3.0, the ECCM project also resulted in a proposal to NSF to install climate stations in 20 additional units of the UC Natural Reserve System.

During the early stages of the ECCM project, the climate records from a number of stations were compared against each other by making use of a double mass technique (Arndt and Redmond, 2004). This method gives detailed information on the relationship between a single climate station and other stations selected for comparison, using daily data. The purpose is to identify changes in relationships between stations, indicative of changes at the comparison station under examination, referred to as data inhomogeneities. However, with the large number of stations in California, or even in one portion of California, the number of comparison permutations is very high. No obvious method presented itself to assimilate such a large amount of information, and another approach was desired. This motivated an effort by Kelly Redmond and John Abatzoglou to develop automated techniques to identify dates of non-climatic changes in relationships between stations, and then use best-correlated stations to adjust the records from the station under examination. About 200 stations scattered across the state were examined in this way (Table 2). An extensive pattern analysis procedure was then applied to both these 200 stations, separately and in combinations for maximum and minimum temperature and for precipitation. The same analysis was applied to a gridded time series of surface data from the PRISM data set (Daly et al., 2008). These two very extensive analyses were then used to develop a set of eleven coherent climate regions within California. These are likely the most extensive analyses of California monthly climate data that have ever been performed. Subsequently, techniques were developed to utilize recent climate data to update these monthly records a few days into each new month, and generate a set of graphics and data files. The resulting product is called the California Climate Tracker and can be accessed via the web at www.wrcc.dri.edu/monitor/cal-mon/index.html. Examples are shown in Figures 38-41.

Table 2. Stations used in California climate regionalization analysis.

NAME	COOPID	LAT	LON	ELEV (ft)
ALPINE	040136	32.83	-116.77	1730
ALTURAS RANGER STATION	040161	41.5	-120.55	4400
ANGWIN PAC UNION COL	040212	38.57	-122.43	1820
ANTIOCH PUMP PLANT 3	040232	37.98	-121.73	60
ASH MOUNTAIN	040343	36.48	-118.83	1710
AUBERRY 1 NW	040379	37.08	-119.5	2140
AUBURN	040383	38.92	-121.08	1290
BAKERSFIELD WSO ARPT	040442	35.42	-119.05	490
BERKELEY	040693	37.87	-122.25	350
BIG BEAR LAKE	040741	34.25	-116.88	6790
BISHOP WSO AIRPORT	040822	37.37	-118.37	4110
BLUE CANYON	040897	39.28	-120.7	5280
BLYTHE	040924	33.62	-114.6	270
BLYTHE CAA AIRPORT	040927	33.62	-114.72	390
BOCA	040931	39.38	-120.1	5580
BOWMAN DAM	041018	39.45	-120.65	5390
BRAWLEY 2 SW	041048	32.95	-115.55	-100
BRIDGEPORT	041072	38.25	-119.23	6470
BURBANK VALLEY PUMP PLA	041194	34.18	-118.35	660
BURNEY	041214	40.88	-121.67	3130
BUTTONWILLOW	041244	35.4	-119.47	270
CACHUMA LAKE	041253	34.58	-119.98	780
CALAVERAS BIG TREES	041277	38.28	-120.32	4700
CALLAHAN	041316	41.32	-122.8	3190
CAMPO	041424	32.62	-116.47	2630
CAMP PARDEE	041428	38.25	-120.85	660
CANOGA PARK PIERCE COLL	041484	34.18	-118.57	790
CANYON DAM	041497	40.17	-121.08	4560
CEDARVILLE	041614	41.53	-120.17	4670
CHERRY VALLEY DAM	041697	37.97	-119.92	4760
CHESTER	041700	40.3	-121.23	4520
CHICO EXPERIMENT STN	041715	39.7	-121.82	190
CHULA VISTA	041758	32.6	-117.1	60
CLEARLAKE 4 SE	041806	38.9	-122.6	1350
CLOVERDALE 3 S	041838	38.77	-122.98	320
COALINGA	041864	36.15	-120.35	670
COLFAX	041912	39.1	-120.95	2410
COLUSA 2 SSW	041948	39.2	-122.02	50

NAME	COOPID	LAT	LON	ELEV (ft)
CORCORAN IRRIG DIST	042012	36.1	-119.57	200
COVELO	042081	39.78	-123.25	1430
CRESCENT CITY 1 N	042147	41.77	-124.2	40
CULVER CITY	042214	34.02	-118.4	50
CUYAMACA	042239	32.98	-116.58	4640
DAGGETT FAA AIRPORT	042257	34.87	-116.78	1920
DAVIS 1 WSW	042294	38.53	-121.77	60
DEATH VALLEY	042319	36.47	-116.87	-190
DE SABLA	042402	39.87	-121.62	2710
DONNER MEMORIAL ST PK	042467	39.32	-120.23	5940
DOWNIEVILLE	042500	39.57	-120.83	2920
DOYLE 4 SSE	042506	39.97	-120.08	4390
EAGLE MOUNTAIN	042598	33.8	-115.45	970
EL CAPITAN DAM	042709	32.88	-116.82	600
EL CENTRO 2 SSW	042713	32.77	-115.57	-30
ELSINORE	042805	33.67	-117.33	1280
EUREKA WSO CITY	042910	40.8	-124.17	60
FAIRFIELD	042934	38.28	-122.07	40
FAIRMONT	042941	34.7	-118.43	3060
FORT BIDWELL	043157	41.85	-120.13	4500
FORT BRAGG 5 N	043161	39.5	-123.78	120
FORT ROSS	043191	38.52	-123.25	110
FRESNO WSO AP	043257	36.78	-119.72	340
FRIANT GOVERNMENT CAMP	043261	36.98	-119.72	410
GILROY	043417	37	-121.57	190
GLENNVILLE	043463	35.72	-118.7	3140
GRANT GROVE	043551	36.73	-118.97	6600
GRATON	043578	38.43	-122.87	200
HAIWEE	043710	36.13	-117.95	3830
HALF MOON BAY	043714	37.47	-122.45	40
HANFORD 1 S	043747	36.3	-119.65	250
HAT CREEK PH 1	043824	40.93	-121.55	3010
HAYFIELD RESERVOIR	043855	33.7	-115.63	1370
HEALDSBURG	043875	38.62	-122.87	100
HENSHAW DAM	043914	33.23	-116.77	2700
HETCH HETCHY	043939	37.95	-119.78	3870
HUNTINGTON LAKE	044176	37.23	-119.22	7020
IDYLLWILD FIRE DEPT	044211	33.75	-116.72	5380
IMPERIAL	044223	32.85	-115.57	-60
INDIO FIRE STATION	044259	33.73	-116.27	-20
INYOKERN	044278	35.65	-117.82	2440
IRON MOUNTAIN	044297	34.13	-115.13	920
JESS VALLEY	044374	41.27	-120.3	5300

NAME	COOPID	LAT	LON	ELEV (ft)
KENTFIELD	044500	37.95	-122.55	130
KING CITY	044555	36.2	-121.13	320
LAGUNA BEACH	044647	33.55	-117.78	40
LAKE ARROWHEAD	044671	34.25	-117.18	5200
LA MESA	044735	32.77	-117.02	530
LEMON COVE	044890	36.38	-119.03	510
LINDSAY	044957	36.2	-119.05	420
LIVERMORE	044997	37.67	-121.77	480
LODI	045032	38.12	-121.28	40
LOMPOC	045064	34.65	-120.45	90
LONG BEACH WSCMO	045085	33.82	-118.15	20
LOS ANGELES WSO ARPT	045114	33.93	-118.4	100
LOS ANGELES CIVIC CENTE	045115	34.05	-118.23	270
LOS BANOS	045118	37.05	-120.87	120
LOS GATOS	045123	37.23	-121.97	370
MADERA	045233	36.95	-120.03	270
MANZANITA LAKE	045311	40.53	-121.57	5750
MARYSVILLE	045385	39.15	-121.6	60
MC CLOUD	045449	41.25	-122.13	3280
MECCA 2 SE	045502	33.57	-116.07	-180
MERCED MUNICIPAL ARPT	045532	37.28	-120.52	150
MINERAL	045679	40.35	-121.6	4880
MITCHELL CAVERNS	045721	34.93	-115.53	4350
MODESTO	045738	37.65	-121	90
MONTEREY	045795	36.6	-121.9	380
MORRO BAY FIRE DEPT	045866	35.37	-120.85	120
MOUNT DIABLO JUNCTION	045915	37.87	-121.93	2170
MOUNT HAMILTON	045933	37.33	-121.65	4210
MOUNT SHASTA	045983	41.32	-122.32	3590
MT WILSON NO 2	046006	34.23	-118.07	5710
NAPA STATE HOSPITAL	046074	38.28	-122.27	40
NEEDLES FAA AIRPORT	046118	34.77	-114.62	910
NEVADA CITY	046136	39.25	-121.02	2780
NEWARK	046144	37.52	-122.03	10
NEWMAN	046168	37.3	-121.03	90
NEWPORT BEACH HARBOR	046175	33.6	-117.88	10
OCEANSIDE MARINA	046377	33.22	-117.4	10
OJAI	046399	34.45	-119.23	750
ORLAND	046506	39.75	-122.2	250
ORLEANS	046508	41.3	-123.53	410
PALMDALE	046624	34.58	-118.1	2600
PALM SPRINGS	046635	33.83	-116.5	420
PALO ALTO	046646	37.45	-122.13	20

NAME	COOPID	LAT	LON	ELEV (ft)
PALOMAR MOUNTAIN OBSERV	046657	33.35	-116.87	5550
PARADISE	046685	39.75	-121.62	1750
PARKER RESERVOIR	046699	34.28	-114.17	740
PASADENA	046719	34.15	-118.15	860
PASO ROBLES	046730	35.63	-120.68	700
PASO ROBLES FAA ARPT	046742	35.67	-120.63	800
PETALUMA FIRE STN 3	046826	38.23	-122.63	30
PINNACLES NM	046926	36.48	-121.18	1310
PLACERVILLE	046960	38.72	-120.82	1850
POMONA FAIRPLEX	047050	34.07	-117.82	740
PORTOLA	047085	39.8	-120.47	4850
POTTER VALLEY P H	047109	39.37	-123.13	1020
RANDSBURG	047253	35.37	-117.65	3570
RED BLUFF FSS	047292	40.15	-122.25	350
REDLANDS	047306	34.05	-117.18	1320
REDWOOD CITY	047339	37.48	-122.23	30
RIVERSIDE FIRE STN 3	047470	33.95	-117.38	840
RIVERSIDE CITRUS EXP ST	047473	33.97	-117.35	990
SACRAMENTO FAA ARPT	047630	38.52	-121.5	20
SACRAMENTO 5 ESE	047633	38.58	-121.5	20
SAINT HELENA	047643	38.5	-122.47	230
SALINAS 2 E	047668	36.67	-121.6	80
SALINAS FAA AIRPORT	047669	36.67	-121.6	70
SANDBERG WSMO	047735	34.75	-118.73	4520
SAN DIEGO WSO AIRPORT	047740	32.73	-117.17	10
SAN FRANCISCO WSO AP	047769	37.62	-122.38	10
SAN FRAN MISSION DOLORE	047772	37.77	-122.43	80
SAN GABRIEL FIRE DEPT	047785	34.1	-118.1	450
SAN GREGORIO 2 SE	047807	37.3	-122.37	270
SAN JOSE	047821	37.35	-121.9	70
SAN RAFAEL CIVIC CENTER	047880	38	-122.52	120
SANTA ANA FIRE STN	047888	33.75	-117.87	130
SANTA BARBARA	047902	34.42	-119.68	0
SANTA BARBARA FAA ARPT	047905	34.43	-119.83	10
SANTA CRUZ	047916	36.98	-122.02	130
SANTA MARIA WSO ARPT	047946	34.9	-120.45	250
SANTA PAULA	047957	34.32	-119.15	240
SANTA ROSA	047965	38.45	-122.7	170
SCOTIA	048045	40.48	-124.1	140
SHASTA DAM	048135	40.72	-122.42	1070
SONOMA	048351	38.3	-122.47	100
SONORA RS	048353	37.98	-120.38	1750
SOUTH ENTR YOSEMITE NP	048380	37.5	-119.63	5120

NAME	COOPID	LAT	LON	ELEV (ft)
STOCKTON WSO	048558	37.9	-121.25	20
STOCKTON FIRE STN # 4	048560	38	-121.32	10
STONY GORGE RESERVOIR	048587	39.58	-122.53	800
STRAWBERRY VALLEY	048606	39.57	-121.1	3810
SUSANVILLE ARPT	048702	40.38	-120.57	4150
TAHOE	048758	39.17	-120.13	6230
TEJON RANCHO	048839	35.03	-118.75	1420
TORRANCE	048973	33.8	-118.33	110
TRACY CARBONA	048999	37.7	-121.42	140
TRACY PUMPING PLANT	049001	37.8	-121.58	60
TRONA	049035	35.77	-117.38	1690
TRUCKEE RANGER STN	049043	39.33	-120.18	6020
TULELAKE	049053	41.97	-121.47	4040
TWENTYNINE PALMS	049099	34.13	-116.03	1980
UKIAH	049122	39.15	-123.2	630
U C L A	049152	34.07	-118.45	430
VACAVILLE	049200	38.4	-121.95	110
VICTORVILLE	049325	34.53	-117.3	2860
VISALIA	049367	36.33	-119.3	330
WASCO	049452	35.6	-119.33	350
WATSONVILLE WATERWORKS	049473	36.93	-121.77	90
WEAVERVILLE RANGER STN	049490	40.73	-122.93	2050
WILLITS 1 NE	049684	39.42	-123.33	1350
WILLOWS 6 W	049699	39.52	-122.3	230
WINTERS	049742	38.53	-121.97	130
WOODLAND 1 WNW	049781	38.68	-121.8	70
YOSEMITE PARK HDQTRS	049855	37.75	-119.58	3970
YREKA	049866	41.72	-122.63	2630

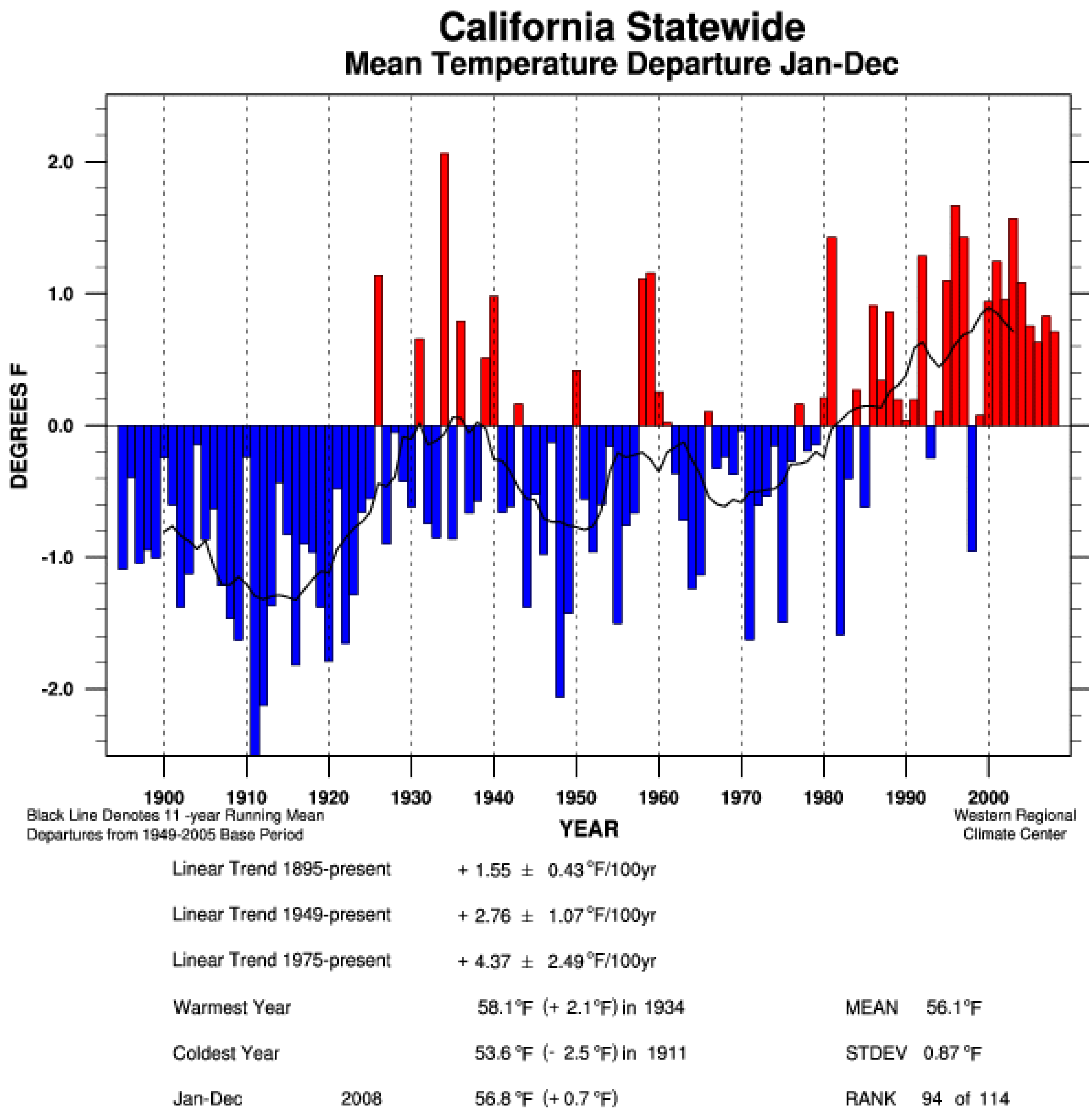
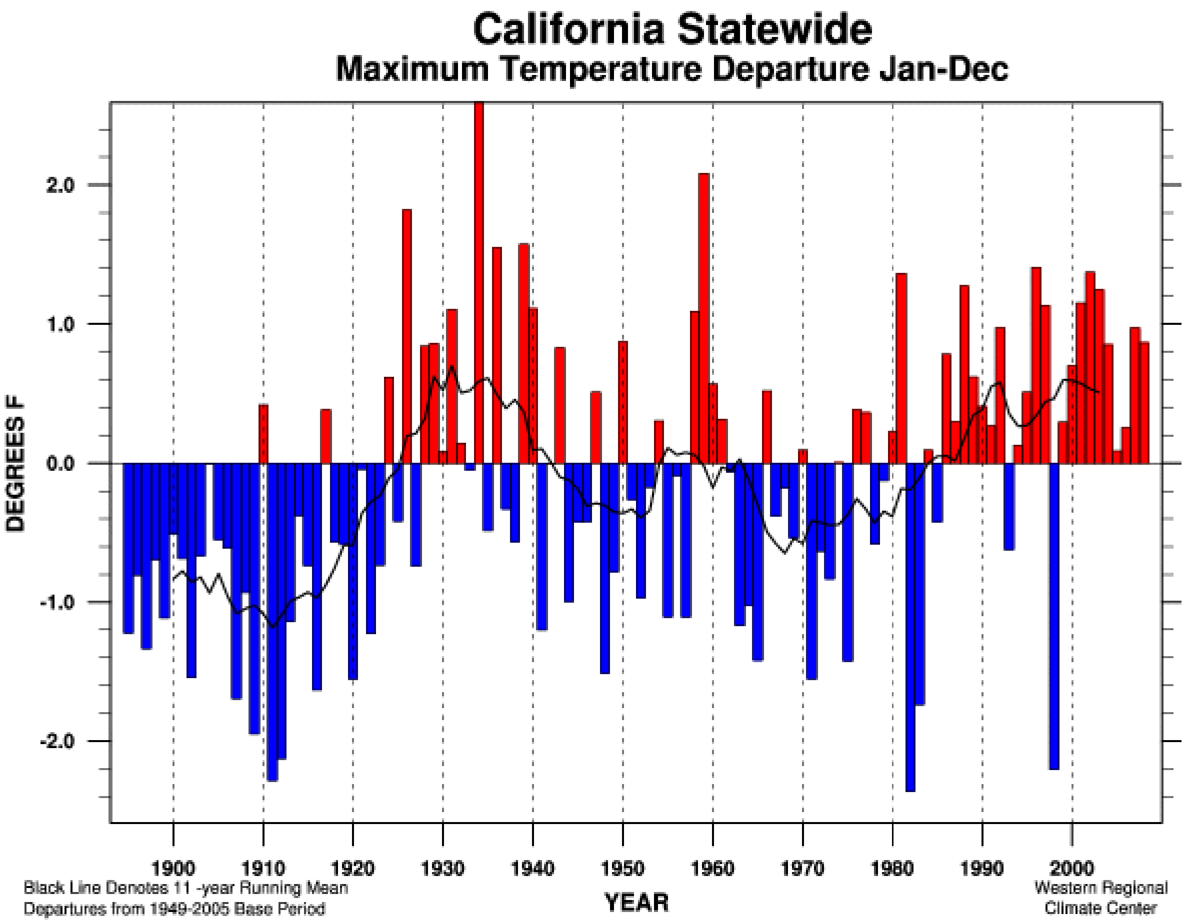


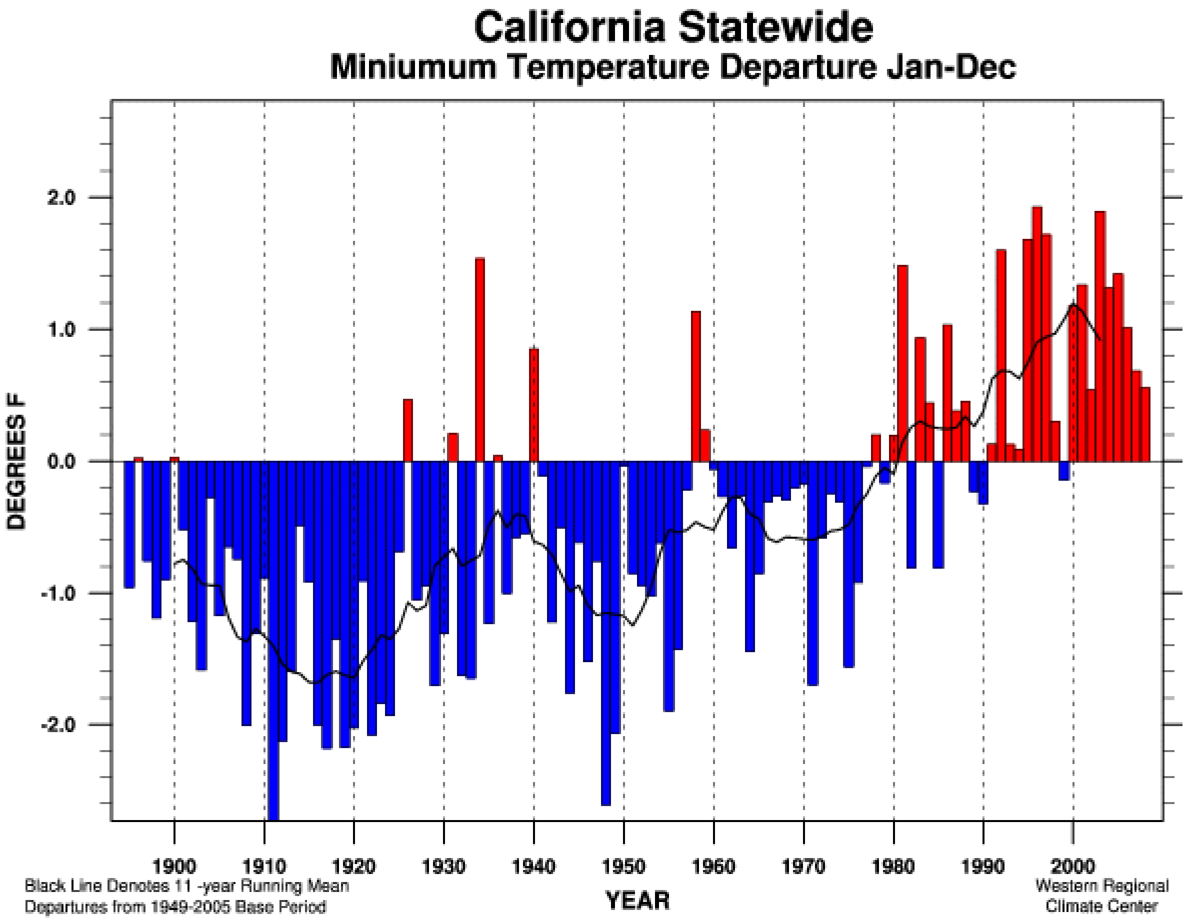
Figure 38. California statewide annual mean temperature from California Climate Tracker. Various statistics covering different periods are computed and presented below the graph. **Calculations performed by John Abatzoglou.**



Linear Trend 1895-present		+ 1.09 ± 0.53 °F/100yr		
Linear Trend 1949-present		+ 1.74 ± 1.35 °F/100yr		
Linear Trend 1975-present		+ 3.80 ± 3.26 °F/100yr		
Warmest Year		71.6 °F (+ 2.6 °F) in 1934	MEAN	69.0 °F
Coldest Year		66.6 °F (- 2.4 °F) in 1982	STDEV	0.95 °F
Jan-Dec	2008	69.9 °F (+ 0.9 °F)	RANK	96 of 114

Figure 39. California statewide annual mean maximum (daytime) temperature from California Climate Tracker. Various statistics covering different periods are computed and presented below the graph.

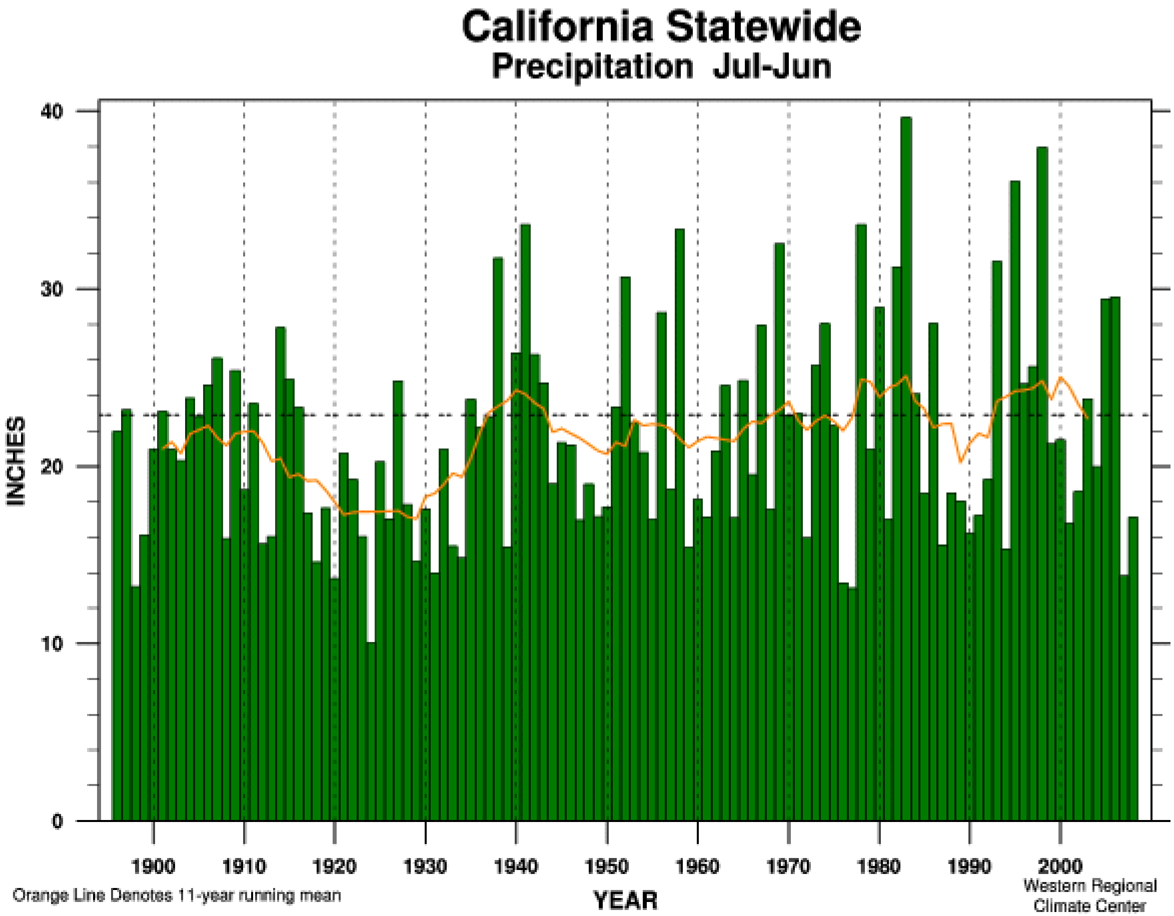
Calculations performed by John Abatzoglou.



Linear Trend 1895-present		+ 2.02 ± 0.47 °F/100yr		
Linear Trend 1949-present		+ 3.79 ± 1.06 °F/100yr		
Linear Trend 1975-present		+ 4.95 ± 2.60 °F/100yr		
Warmest Year		45.1°F (+ 1.9 °F) in 1996	MEAN	43.1°F
Coldest Year		40.4 °F (- 2.7 °F) in 1911	STDEV	0.98 °F
Jan-Dec	2008	43.7 °F (+ 0.6 °F)	RANK	97 of 114

Figure 40. California statewide annual mean minimum (nighttime) temperature from California Climate Tracker. Various statistics covering different periods are computed and presented below the graph.

Calculations performed by John Abatzoglou.



Linear Trend 1895-present	+ 3.53 ± 3.28 in.	(+ 15 ± 14%) per 100 yr		
Linear Trend 1949-present	+ 1.20 ± 10.03 in.	(+ 5 ± 43%) per 100 yr		
Linear Trend 1975-present	- 1.42 ± 28.11 in.	(- 6 ± 122%) per 100 yr		
Wettest Year	39.63 in. (173%)	in 1983	MEAN	22.89 in.
Driest Year	10.03 in. (43%)	in 1924	STDEV	6.46 in.
Jul-Jun 2008	17.14 in. (74%)		RANK	29 of 113

Figure 41. California statewide winter-centered 12-month July-June precipitation from California Climate Tracker. Various statistics covering different periods are computed and presented below the graph.

Calculations performed by John Abatzoglou.

The California Climate Tracker was entirely motivated by CEC activities though Scripps CCCC and the ECCM project. A paper describing the analysis (Abatzoglou et al., 2009) is in press at this writing. Despite the large amount of attention that climate change receives in the state of California, there seemed to be no definitive source of accessible and understandable updated information to track the progress of climate within the state. The audience for this product is intended to be government agencies, the press, resource managers, the research community, and above all the public. This product is coming into increasingly wide use, and is incorporated into the annual state report on Indicators of Climate Change in California (OEHHA, 2009).

The various components of the Enhanced California Monitoring Program have been presented in oral and poster form at several annual California Climate Change Conferences, at CalFed science meetings, the American Geophysical Union fall meeting in San Francisco, the Pacific Climate Workshop, the Mountain Climate Workshop, and other climate research meetings. This project has been discussed during presentations to a number of groups around the state in sectors as varied as water management, air quality, natural resource management, fire, entomology, ecology, the legal profession, the National Park Service, drought management and drought monitoring forums, range managers, the skiing industry, and others. The varied and picturesque settings have led to many requests from the print and broadcast press to accompany during field visits, and stories in various media afterwards.

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6.0 Glossary

BMP	Best Management Practices
CalClim	California Climate Data Archive (WRCC)
CARB	California Air Resources Board
CCCC	California Climate Change Center (Scripps)
CCDA	California Climate Data Archive (WRCC)
CCSS	California Cooperative Snow Survey (CDWR)
CDEC	California Data Exchange Center (CDWR)
CDWR	California Department of Water Resources
CEC	California Energy Commission
CeNCOOS	Central and Northern Coastal Ocean Observing System
CIRMOUNT	Consortium for Integrated Climate Research in Western Mountains
CRN	Climate Reference Network (NOAA)
CSSL	Central Sierra Snow Lab
ECCM	Enhanced California Climate Monitoring Project (CEC)
DRI	Desert Research Institute
GLORIA	Global Observation Research Initiative in Alpine Environments
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
GR	Global Reanalysis (NCEP/NCAR)
HCNM	Historical Climate Network - Modernized
HMT	Hydrometeorological Test Bed (NOAA, North Fork American River)
IPCC	Intergovernmental Panel on Climate Change
NARR	North American Regional Reanalysis
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration

NPS	National Park Service
NRS	Natural Reserve System (University of California)
NWS	National Weather Service (NOAA)
NSF	National Science Foundation
OEHHA	Office of Environmental Health Hazard Assessment (State of California)
PRISM	Parameter Regression on Independent Slopes Method
TMDL	Total Maximum Daily Load
TREX	Terrain-Induced Rotors Experiment
UC	University of California
USDA	US Department of Agriculture
USFS	US Forest Service (USDA)
WMO	World Meteorological Organization
WRCC	Western Regional Climate Center (NOAA / DRI)