National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Climate Assessment for the Sierra Nevada Network Parks

Natural Resource Report NPS/2011/NRR—2011/482

ON THE COVER
Low clouds in Yosemite Valley as viewed from Olmsted Point, October 2005.
Photograph by: Laura Edwards, Western Regional Climate Center.

Climate Assessment for the Sierra Nevada Network Parks

Natural Resource Report NPS/2011/NRR—2011/482

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Executive Summary

The National Park Service (NPS) Inventory & Monitoring (I&M) Program was established in 2000 as part of the Natural Resource Challenge, a long-term strategy to improve park management by increasing access to and reliance on high-quality scientific information. The Sierra Nevada Network (SIEN) is one of 32 I&M networks that will develop and provide scientifically credible information on the status and long-term trends in selected vital signs, or indicators of ecosystem condition. The SIEN comprises four units: Devils Postpile National Monument (DEPO), Sequoia & Kings Canyon National Park (jointly administered units referred to as SEKI, or individually as SEQU & KICA), and Yosemite National Park (YOSE).

Weather and climate data and information have applications spanning a range that encompasses park operations, safety and maintenance, protection and improved understanding of park ecosystems, long-term monitoring, visitor usage and travel planning, a variety of research programs, and public interpretation. In 2007, the Western Regional Climate Center (WRCC) completed an inventory of existing weather and climate stations for each of the I&M networks. This document expands upon that knowledge base by discussing in-depth climate analyses, trends, and projections, and providing recommendations on how the SIEN can best allocate its resources to enhance current climate monitoring efforts.

The SIEN requested that the WRCC perform an assessment of past and current climate data and information in the parks and of potential needs to inform development of a climate monitoring protocol. In so doing, we have considered existing literature, ongoing projects and programs, tools for accessing and manipulating data and information, and existing climate summaries. We have also performed a necessarily limited amount of new analyses to further develop and augment presently available information, specifically oriented toward the needs of the SIEN park units, and to fill gaps in our understanding of climate processes at work in this region. Here we summarize our findings and recommendations for the SIEN.

Our data analyses have revealed a number of findings that are relevant to park management. Correlation analysis shows moderate east and west slope linkages, and also good north-south connections. Further, there are differences from month to month in how station temperature and precipitation relate across space, and these differences are elevation dependent. Important elevation bands where behaviors change include those below which the winter Central Valley inversion is found (below about 3000-4000 ft (914-1219 m)), the transition zone to nearly continuous winter snow (approximately 6000 ft (1829 m)), another zone above and below which melting and other snow processes behave differently from year to year (9000-10000 ft (2743-3048 m)), and the uppermost elevations (12000-14000 ft (3657-4267 m)). The analyses revealed that mean temperature and precipitation on the west slopes and east slopes of the SIEN park units are at least moderately well correlated. There is good correspondence between east-slope and west-slope temperatures in most months, but not enough that one set of stations can freely substitute for the other.

The correlation analysis of Remote Automated Weather Stations (RAWS) showed that these stations have performed well and, for the most part, are generating good quality data. Regular maintenance of the stations and their environments is crucial to retain their value for climate monitoring and assessment, as well as making them valuable for other uses such as fire weather.

RAWS and other automated stations are particularly useful because they provide information on elements not measured manually: humidity, solar radiation, wind speed and direction, sometimes pressure, and occasionally other assorted climate elements, and at hourly or better time resolution.

Another analysis based on assimilated upper air data showed that SIEN temperatures have been slowly warming in the past 30-35 years, that freezing levels have been rising in altitude (in seasons other than winter), and there are suggestions that high elevation trends may be slightly greater than those at lower elevations. Greatly needed are surface stations at a range of elevations to use as ground truth for comparison with the gridded global and regional reanalysis data.

The length and quality of climate records in the SIEN vary, though there are climate records of a century or more in or near all SIEN park units. In general, it is very difficult to find daily stations that have well-documented, consistent, and complete data records for periods of 6-10 decades, or more, from well-maintained sites. Our strongest recommendation is that at least a few such stations be given high priority for quality observations. Of greatest concern is the Yosemite Headquarters Cooperative Station (COOP). This station, established in 1905, has the longest record in the SIEN, and should be considered the most important site in YOSE.

Next, better high-altitude monitoring is needed. The environment in the SIEN park units is affected by multiple stressors. Of these, climate change has considerable potential to alter hydrologic and ecological functions and behavior throughout the area, and to take these systems outside of measured or recent proxy experience. The greatest concerns are with the effects on snow and snowpack. The longest climate records tend to be at lower elevations. However, with a warming climate, climate zones in the SIEN region are expected to migrate northward, and also higher in altitude. Baseline measurements should be in place at higher elevations in order to capture an expected upward wave of plant and animal migration during a future warming climate. A few more high elevation stations are needed so that the 10000-14000 ft (3048-4267 m) band is adequately represented and bracketed.

We recommend that each park unit identifies several benchmark stations that measure temperature and precipitation (including snow) and are maintained for high quality records in perpetuity. Specific locations for high altitude stations and benchmark stations are listed in the body of this report. It is important to maintain manual precipitation measurements, even as automated equipment is increasingly deployed. The best manual snow measurements are much better than typical automated measurements. Manual snow course data were not analyzed due to resource limitations, but these measurements are among the few higher elevation observations that extend back to the middle 20th century. They are very useful, even though data points are added slowly and only in certain (winter and spring) months. Automated snow survey stations (snow pillows) are useful, partly because they take precipitation measurements. However, the manual measurements should not be discontinued solely because of installation of automated sensors.

Park personnel have expressed a desire and need for relatively painless access to the basic data and for tools to efficiently manipulate and summarize these data. This can be accomplished with specialized web pages and by making use of tools and procedures that are supported by other NPS and non-NPS efforts at WRCC.

Acknowledgments

The authors would like to thank David Simeral at the Western Regional Climate Center (WRCC), and John Abatzoglou (at WRCC, San Jose State University, and now University of Idaho) for figure preparation. Greg McCurdy and Grant Kelly of WRCC also assisted with many questions about station records, and analysis software. Mike Anderson and Frank Gehrke at the California Department of Water Resources also contributed useful information for this report. Jessica Lundquist of the University of Washington provided her Tuolumne Meadows research data set, and Michael Collee and colleagues at UC Santa Barbara generously shared their Sierra Nevada database. Paul Jones of the National Weather Service in Hanford, CA provided much valuable information about their observational program. We would also like to thank staff of the National Park Service, and particularly those in the Sierra Nevada Network (SIEN) Inventory & Monitoring program who funded this report. Especially invaluable was the assistance provided by SIEN Physical Scientist Andi Heard, who coordinated an initial meeting to identify weather and climate data needs in the parks, and provided information, contacts, and helpful reviews of earlier drafts of this report. Other NPS and USGS staff participated in identifying their needs for weather and climate data, helping acquire some of the data used in these analyses, and reconstructing historical knowledge scattered among many individuals with deep knowledge of these parks. This report was funded by the Sierra Nevada Network through task agreement J8R07060018 with the Desert Research Institute at the University of Nevada, Reno. It was initially submitted by the Western Regional Climate Center as report WRCC-08-01.

List of Acronyms

BLM	Bureau of Land Management
CDEC	California Data Exchange Center
CDWR	California Department of Water Resources
CEC	California Energy Commission
COOP	Cooperative Observer Program
CRN	NOAA US Climate Reference Network
CRS	Cotton Region Shelter
CSC	US Department of Interior Climate Science Center
DEPO	Devils Postpile National Monument
DOI	US Department of Interior
DRI	Desert Research Institute
ENSO	El Nino—Southern Oscillation
GCM	Global Circulation Model
GOES	Geostationary Operational Environmental Satellite
HPD	Hourly Precipitation Data
I&M	Inventory and Monitoring Program
IPCC	Intergovernmental Panel on Climate Change
KICA	Kings Canyon National Park
LIG	NOAA Liquid-in-Glass thermometer
MJO	Madden-Julian Oscillation
MMTS	Maximum / Minimum Temperature System
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NCEP	National Centers for Environmental Prediction
NIFC	National Interagency Fire Center
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NWS	National Weather Service
PDO	Pacific Decadal Oscillation
PRISM	Precipitation-Elevation Regressions on Independent Slopes Model
RAWS	Remote Automated Weather Station
SEKI	Sequoia and Kings Canyon National Parks
SEQU	Sequoia National Park
SIEN	Sierra Nevada Inventory and Monitoring Network
SNARL	Sierra Nevada Aquatic Research Laboratory
SRES	Special Report on Emissions Scenarios
SRG	standard rain gauge
SST	sea surface temperature
USFS	United States Forest Service
WRCC	Western Regional Climate Center
YOSE	Yosemite National Park

I. State of Knowledge of Climate in the Sierra Nevada

The National Park Service (NPS) Inventory & Monitoring (I&M) Program was established in 2000 as part of the Natural Resource Challenge, a long-term strategy to improve park management by increasing access to and reliance on high-quality scientific information. The Sierra Nevada Network (SIEN) is one of 32 I&M networks that will develop and provide scientifically credible information on the status and long-term trends in selected Vital Signs, or indicators of ecosystem condition. The SIEN is comprised of four units: Devils Postpile National Monument (DEPO), Sequoia & Kings Canyon National Park (jointly administered units that are referred to as SEKI, or individually as SEQU & KICA), and Yosemite National Park (YOSE) (Figure 1).

The unique terrain of the Sierra Nevada attracts many visitors to the SIEN parks. A high percentage of SIEN park lands are designated Wilderness, and the remote lakes, meadows, forests, and high granite peaks attract hikers from all over the world. The more accessible areas of the parks such as the Devils Postpile formation, Yosemite Valley, and the Giant Forest sequoia grove are also popular destinations and in 2009, the four park units together had over 5 million visitors (Table 1). Climate plays an integral role in the tourist appeal of the SIEN park units. Relatively cooler temperatures in the summer season draw tourists from other much warmer regions of California and beyond, and abundant winter snow brings snow enthusiasts. At all times the wildlife, unique ecology, and majestic glaciated valleys are an attraction. Several of the rivers in this region of the Sierra Nevada have been designated as Wild and Scenic, including Tuolumne and Merced Rivers in YOSE, and Kings and Kern Rivers in SEKI. In addition to the scenic beauty of the region, these rivers are an integral component of both the ecological viability of the region and the water supply system in California.

Table 1. General statistics for Sierra Nevada Network parks as of 2009 (National Park Service 2010).

	DEPO	**SEKI**	**YOSE**
Size (ha)	324	349,581	308,075
Percent Wilderness (%)	75	93	94
Elevation Range (m)	2200-2500	400-4417	610-3998
Number of Visitors (2009)	110,212	965,710 (SEQU) 609,296 (KICA)	3,737,472

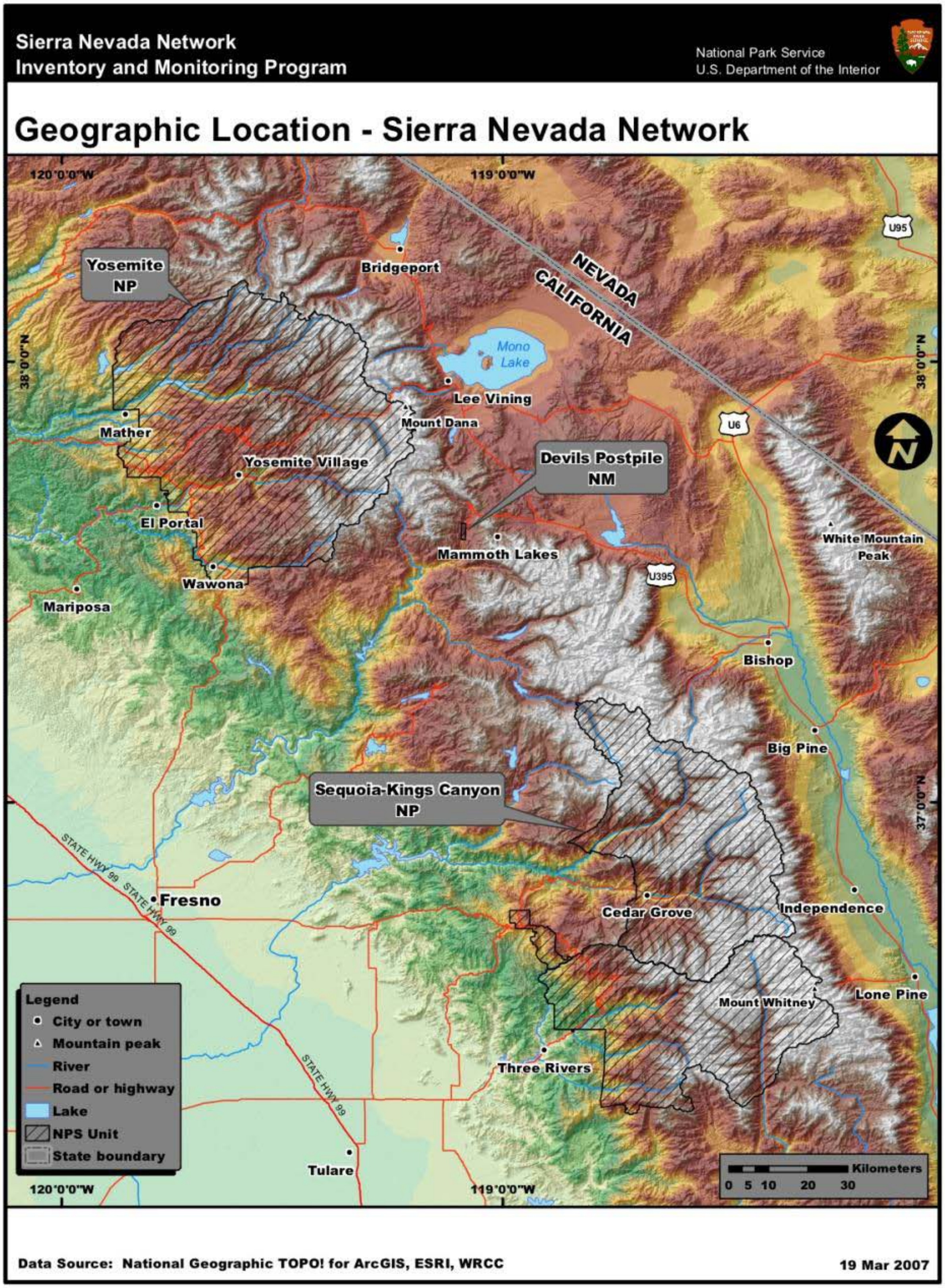

Figure 1. Geographic setting of the Sierra Nevada Network. *Prepared by David Simeral*.

Climatic forces are a major driver of Sierra Nevada ecosystems. Current patterns of vegetation, water dynamics, and animal distribution in the Sierra Nevada are determined largely by cumulative effects of past and present climates, in concert with geologic factors. Anthropogenic climate change is the stressor that is predicted to have the most pronounced effects on Sierra Nevada ecosystems. The importance of weather and climate monitoring was recognized by the SIEN and identified as a high priority for long-term monitoring. SIEN parks have substantial climate monitoring infrastructure that is maintained by multiple agencies and universities. There is already an existing weather and climate monitoring network in and around these parks; thus, the SIEN strategy is to augment, enhance, and extend these efforts. One purpose of this report is to assess the adequacy of the current climate monitoring network, undertake limited original analyses, and make recommendations on how the SIEN can best allocate its resources to enhance weather and climate monitoring.

Understanding the climate and weather in the parks is essential to management of SIEN's natural resources. Weather and climate was selected as one of 12 high-priority vital signs in the network, because climate is a major driver of SIEN ecosystem processes, including fire regimes, hydrologic regimes, vegetation type and distribution, and animal populations (Mutch et al. 2008). Changes in climate may lead to changes in habitat, migration of vegetative and animal species, altered hydrology, and other repercussions. An investigation of the historical climate of SIEN's region is necessary to establish a foundation for understanding how natural changes impact the ecosystems in the parks. Following such an investigation, projections of future climate changes can be taken into account and analyzed for the change in impact on the region's ecosystem and natural resources.

This project was initiated with a meeting between the Western Regional Climate Center (WRCC), the SIEN, park staff, and local US Geological Survey staff members in October 2006 at Yosemite National Park. Gaps in knowledge, monitoring, research, and operational needs, and project objectives were discussed and prioritized. The minutes from this meeting can be found in Appendix A. The top priorities as determined at that meeting included:

- Deliver historical and current climate data online in an easy-to-use interface
- Identify core climate parameters to be measured in the parks
- Ensure adequate climate monitoring at high elevation sites
- Improve access to high resolution climate maps (e.g. Parameter-elevation Regressions on Independent-Slopes Model , or PRISM)
- Inform ecological concerns with climate information
- Determine the degree to which SEKI and YOSE can serve as surrogates for each other. What can the climate in one park region tell us about the others; what are the relationships among the climates of the three management units? Where is climate changing faster and slower in these parks?
- Address the need for more or better precipitation measurements, especially snow

- Maintain metadata standards
- Identify micro-site biases in the climate record.

Resource limitations necessarily limit the scope of this report, the number of climatic factors that can be treated in any detail, and the number of stations whose data can be ingested and made available for analysis. The report does address the following:

- Core climate measurements that should be routinely made
- Middle and upper elevation climate needs
- Access to point (in situ) and gridded climate data
- Spatial structure (fields) of temporal correlation
- Representativeness of observed data for temporal and spatial applications
- Maintenance and data quality
- Global and regional climate change projections and observations
- Present and future observing priorities
- Gaps in coverage
- Recommendations with allowance for budgetary and geographical constraints

The report does not address the following:

- Quality of data from air quality sites (NPS, CastNet,etc.)
- Quality control mechanisms for use on daily data
- Quality assessments of measurements made by the California Dept of Water Resources
- Information that is overly repetitious with that found in the SIEN Inventory and Monitoring Climate Report (Davey et al. 2007)
- Detailed analyses of wind, humidity, solar radiation, and snow

Historical Climate

The SIEN is generally characterized as having a Mediterranean climate, with warm, dry summers and wet, cool winters at lower elevations, and a boreal climate zone with cold winters at higher elevations. Most of the precipitation occurs in the winter season, with snow possible at all elevations of the park units. Figures 2-4 depict mean annual precipitation, snowfall and temperature in the region.

Mean annual precipitation in California decreases from north to south, and this is true in the Sierra Nevada as well. SEKI is generally considerably drier than YOSE, with the wetter parts of SEKI being somewhat drier than the average conditions found in YOSE (Figure 2). The wetter parts of SEKI tend to be in the lower west-side elevations, whereas the wetter parts of YOSE tend to be in the middle of that park. The wettest part of YOSE is in its northern section and at middle and higher elevations, and considerably wetter than the wettest parts of SEKI. The extended High Sierra in eastern SEKI generally receives less than the lower area to its west, and the highest peaks are drier than the wettest areas at lower elevations.

By virtue of its elevation, the High Sierra of SEKI is cold enough that more of its precipitation falls in frozen form, so that snowfall in SEKI, especially the eastern half, is considerably more than in YOSE (Figure 3). Only modest amounts of snow (3-6 ft, 1-2 m) fall in the western lower elevations of YOSE and SEKI, and much precipitation in these areas falls as rain. Snow tends to become much more prevalent above about 5000 feet (1600 m) in YOSE and a somewhat higher elevation in SEKI.

Although mean annual temperature at a given elevation generally increases from north to south, elevation rises so quickly from north to south that much of SEKI is colder than YOSE, and by several degrees (Figure 4). Significant portions of SEKI have mean annual temperatures below freezing, a feature seen in only a small portion of YOSE.

The climate at DEPO is characterized as boreal (also called microthermal), with cold, snowy winters and warm, mostly dry summers. Winter temperatures are cold with many days never rising above freezing. Summer days are warm but nights are cool, so daily temperature ranges are large. Summer skies are usually clear and the humidity is usually low, helping to promote this nighttime cooling. Local winds tend to be directed along the axis of the San Joaquin River canyon, either from the south or north.

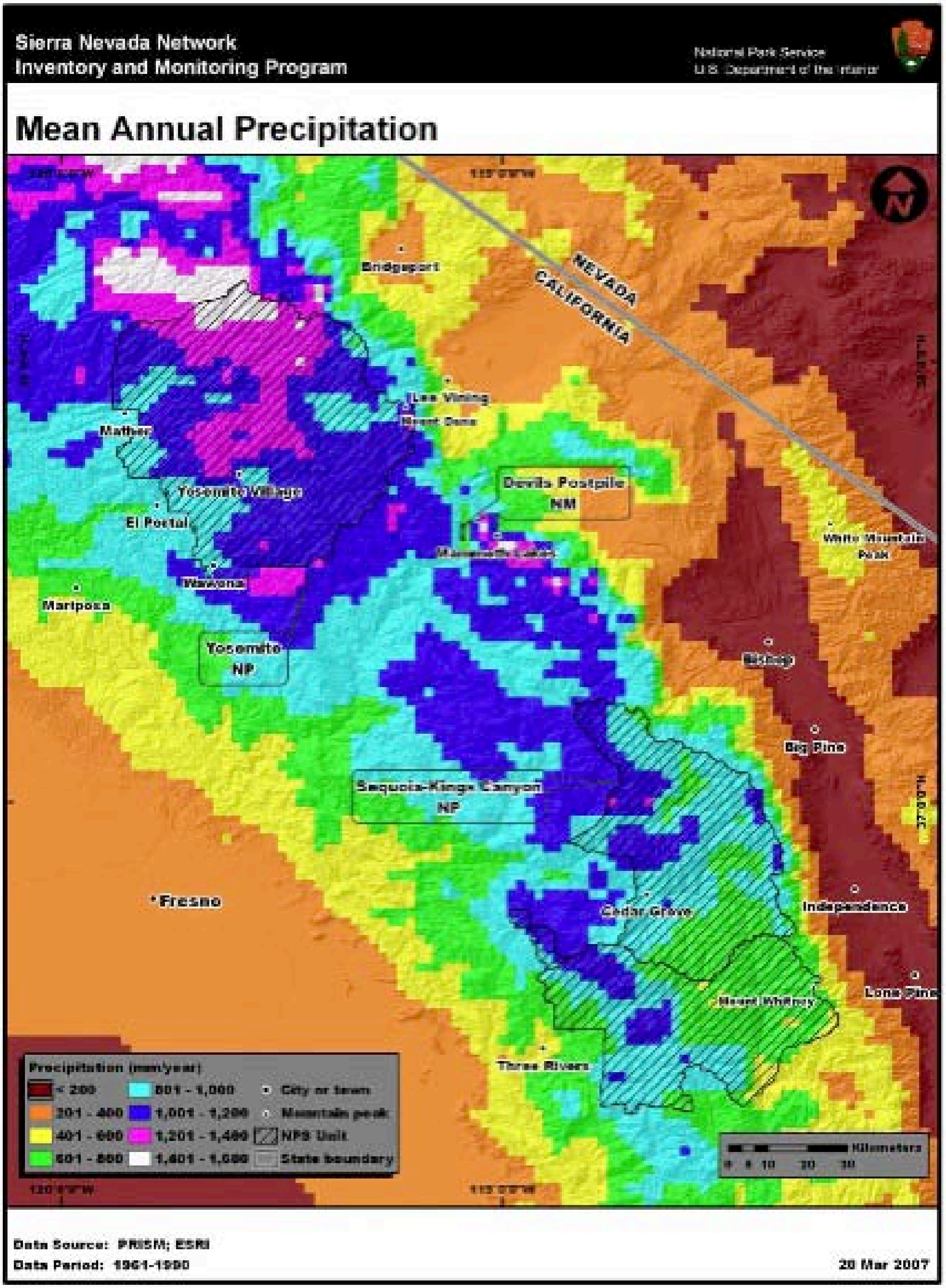

Figure 2. Sierra Nevada Network area mean annual precipitation, 1961-1990, from PRISM. *Prepared by David Simeral.*

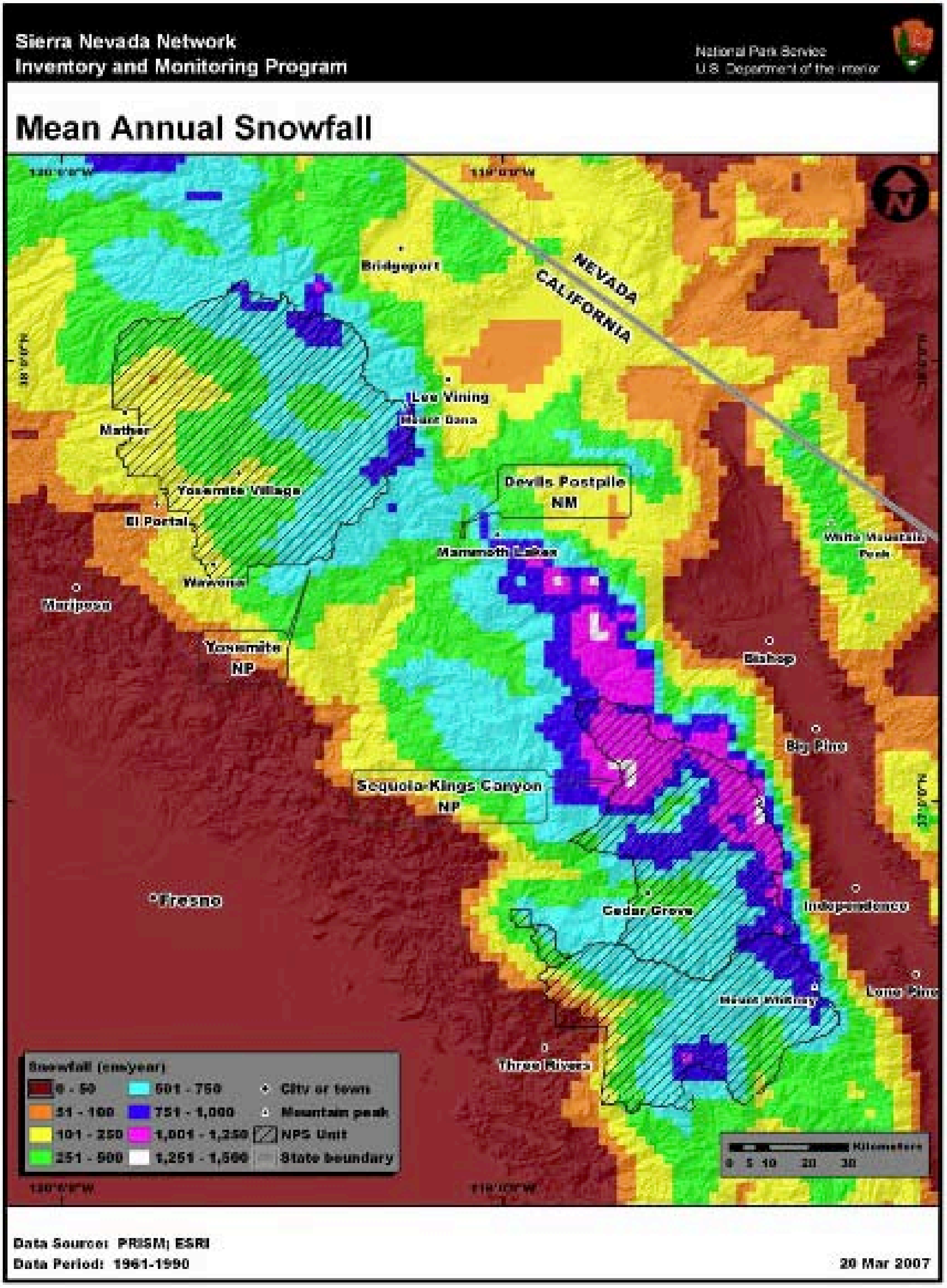

Figure 3. Sierra Nevada Network area mean annual snowfall, 1961-1990, from PRISM. *Prepared by David Simeral.*

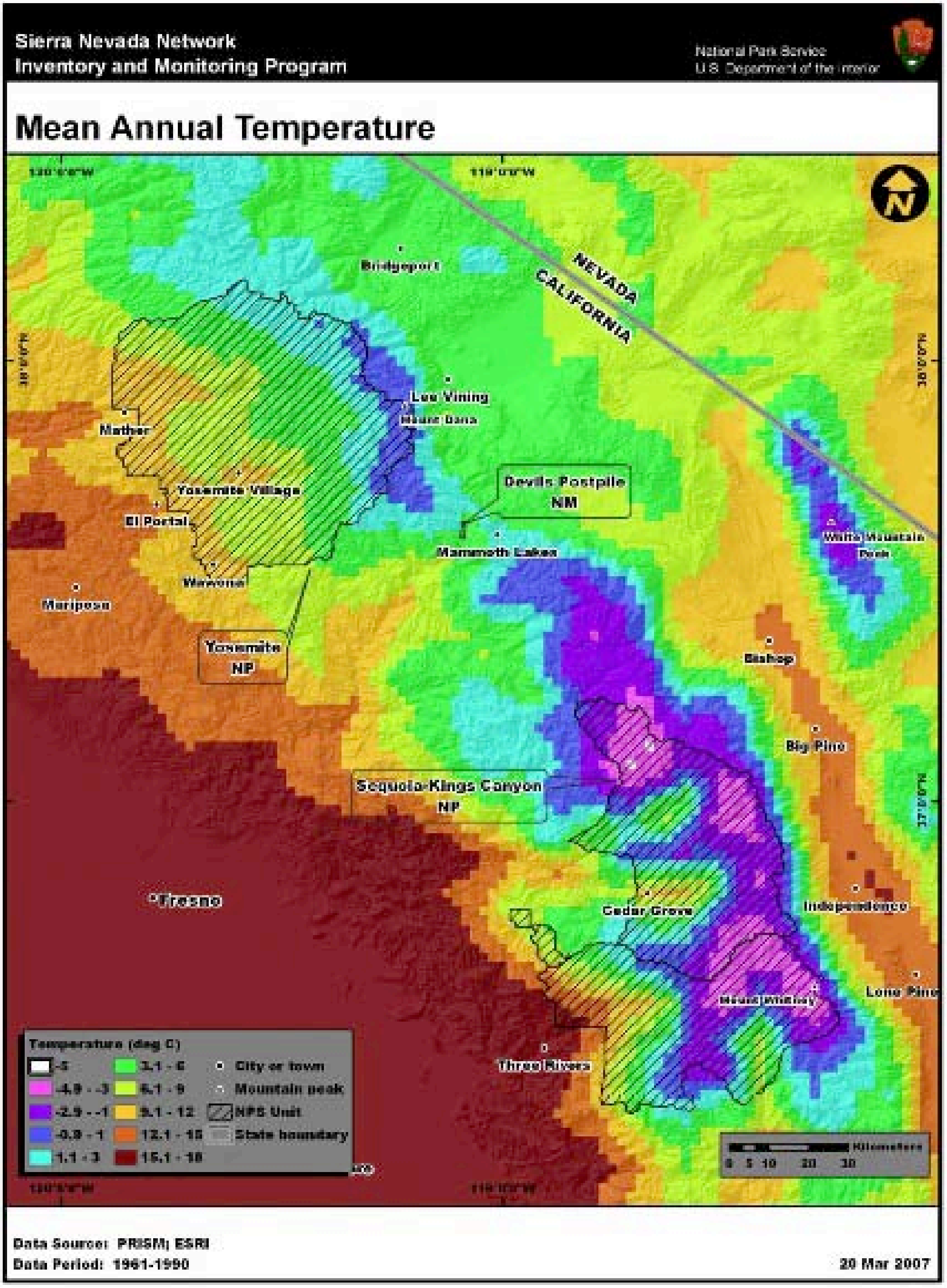

Figure 4. Sierra Nevada Network mean annual temperature,1961-1990, from PRISM. *Prepared by David Simeral*.

Figures 5-10 show histories of annual temperature and winter-centered precipitation for the five counties encompassing the SIEN area, arranged from south to north. Southern counties receive less precipitation; the southernmost counties are cooler only by virtue of their higher elevation. Tulare County has the largest portion of its area in the High Sierra. There is large temporal variability in precipitation in all counties, and many of the more extreme years can be linked to ENSO phase (see later in this section). In all cases, mean temperature has been increasing since the mid-1970s. In the instrumental record since 1895 there have been variations, with periods of warming and cooling. Average temperature over the last decade approaches or exceeds that of any other 10-year period on record. These plots are created through the Westmap project (http://www.cefa.dri.edu/Westmap/), using gridded climate data provided by PRISM (Precipitation-elevation Regressions on Independent Slopes Model; Daly 1994, 2008) at Oregon State University. For each of these figures, red indicates the calendar year precipitation in the first image and the winter-centered precipitation (July-June year) in the second image; blue indicates the 10-year running mean, and green indicates the period of record mean.

Figure 10 shows the time history of mean annual maximum and minimum temperature for Madera County, the middle among the five counties that the SIEN is in. The histories are similar for all five counties and show that maximum temperatures have risen a small amount in the past 75 years, but that the minimum (nighttime) temperatures have risen fairly dramatically. This behavior is seen elsewhere in California and throughout much of the western United States. Mean temperatures have been and continue to be on the rise primarily because minimum temperatures are increasing; though in recent years maximum temperatures show some small increases as well. The reason that minimums are rising much more than maximums is not known. One hypothesis is that the rise in irrigation has kept maximum temperatures from rising (evaporative cooling), but this mechanism would be at work only in summer and only in the lowest, irrigated parts of these counties. There are physical reasons to think that warming from greenhouse gases will be seen more clearly at night.

The Remote Automated Weather Stations (RAWS) network has sufficiently long records to allow the depiction of typical wind regimes in mountainous terrain such as SIEN. Examples of “wind roses” are shown in Figure 11, one for each month, for the Crestview RAWS station. This station is located at 7600 ft (2316 m) just west of Deadman Summit, on US 395 near Obsidian Dome, north of Mammoth. The short rectangular segments represent the percent of time that the wind blows from the indicated direction and within the indicated speed range. Radial rings are labeled in percentages. The colors (and width) indicate the wind speed interval, and the length of each bar is a percentage, with all segments plus calm totaling 100%. This station was selected due to its long and fairly complete period of record. The graphs show that southwest winds are prominent all year, and that calm conditions are common in winter, with mean hourly speeds below 1.3 mph about half the hours in those months. These graphics can be generated by anyone at no cost on the WRCC web pages.

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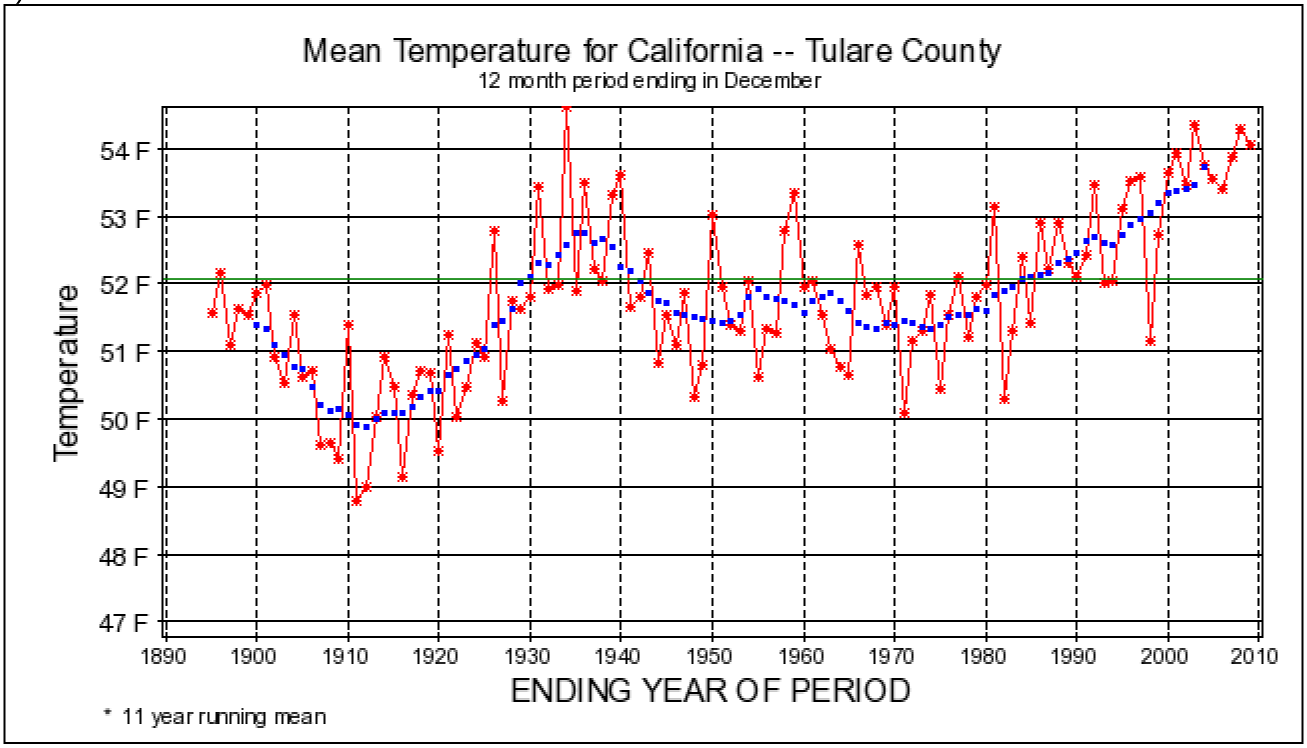

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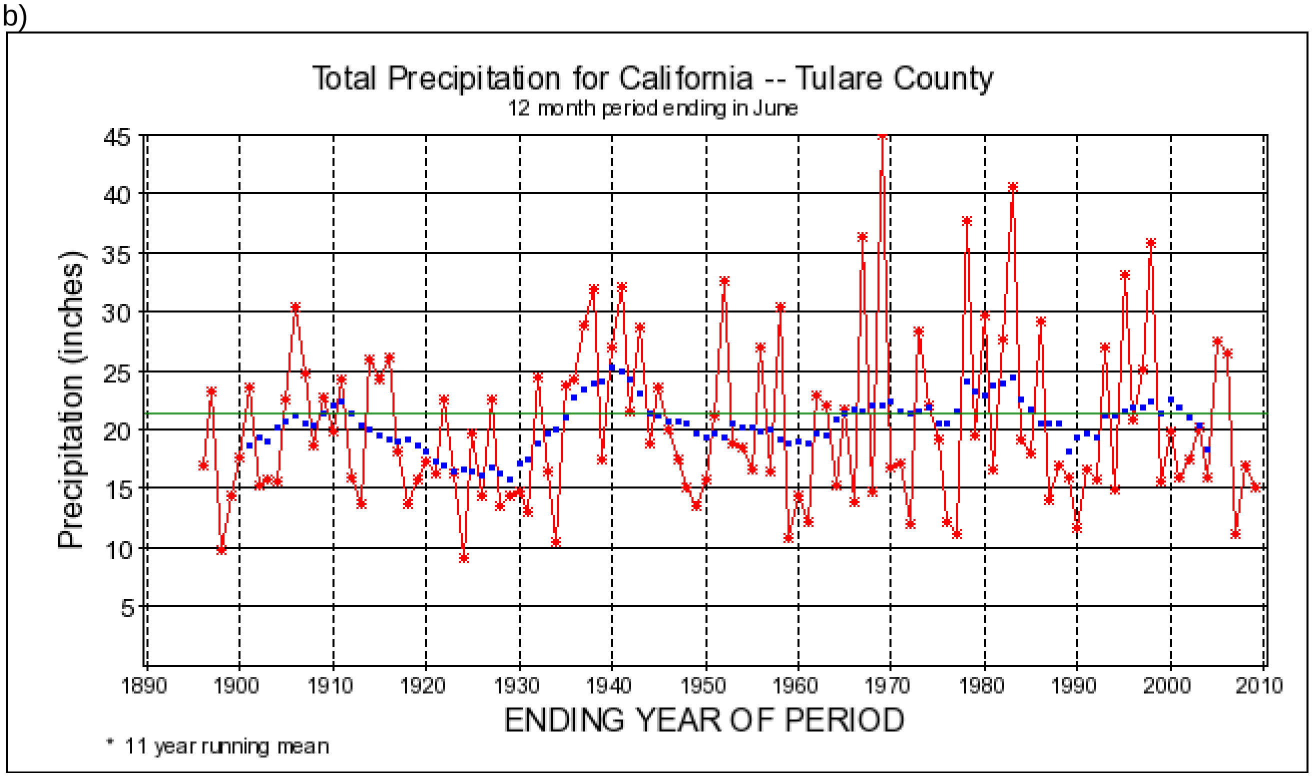

Figure 5. Tulare County (SEQU area) temperature and precipitation time series. a) Mean calendar year temperature (1895-2009) and b) winter-centered total precipitation. Blue: 11-month running mean. Green: 1971-2000 mean. Data from PRISM. *Source: Interactive plots, WRCC/UArizona Westmap.*

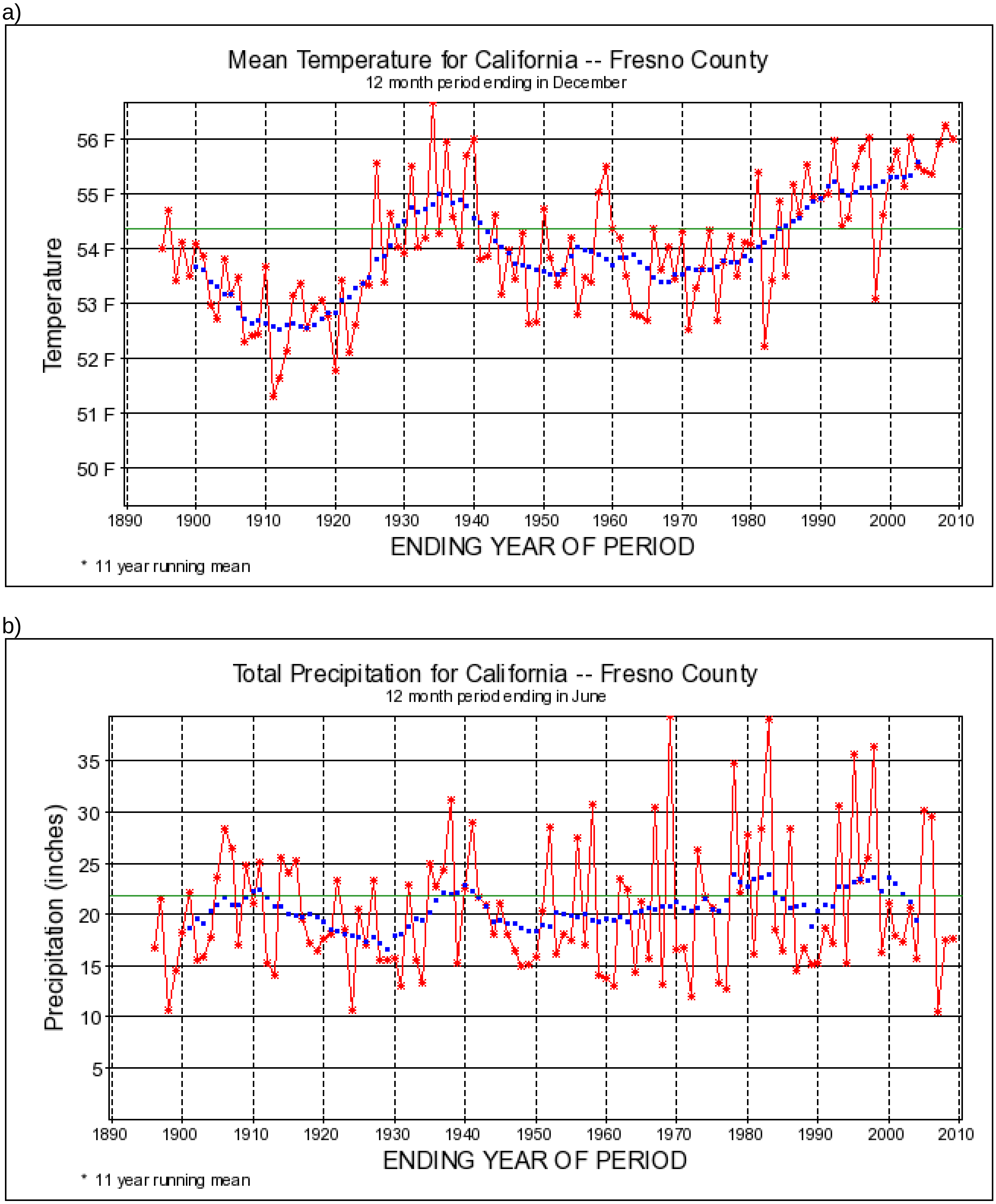

Figure 6. Fresno County (KICA area) temperature and precipitation time series. a) Mean calendar year temperature (1895-2009) and b) total winter-centered precipitation (1895/96-2008/09). Blue:11-year running mean. Green: 1971-2000 mean. Data from PRISM. *Source: Interactive plots, WRCC/UArizona Westmap.*

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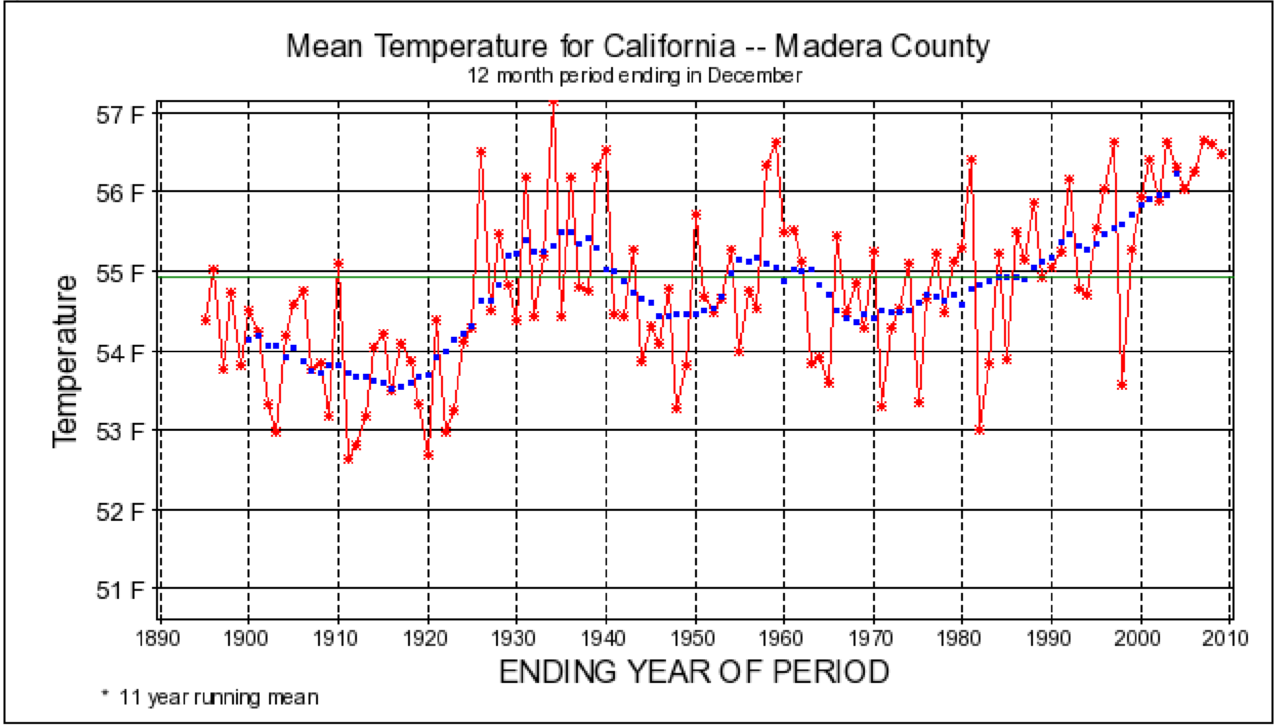

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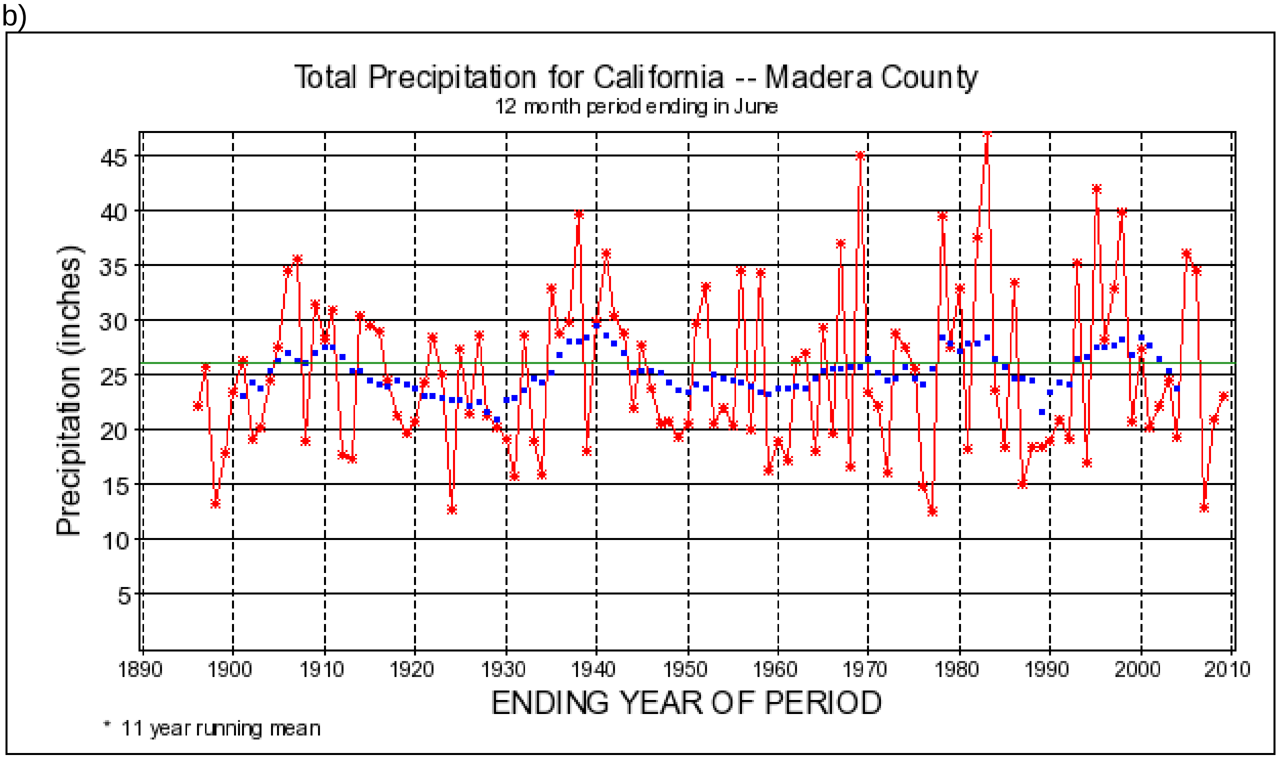

Figure 7. Madera County (DEPO, YOSE SE area) temperature and precipitation time series. a) Mean calendar year temperature (1895-2009) and total winter-centered precipitation (1895/96-2008/09). Blue: 11-year running mean. Green: 1971-2000 mean. Data from PRISM. *Source: Interactive plots, WRCC/UArizona Westmap.*

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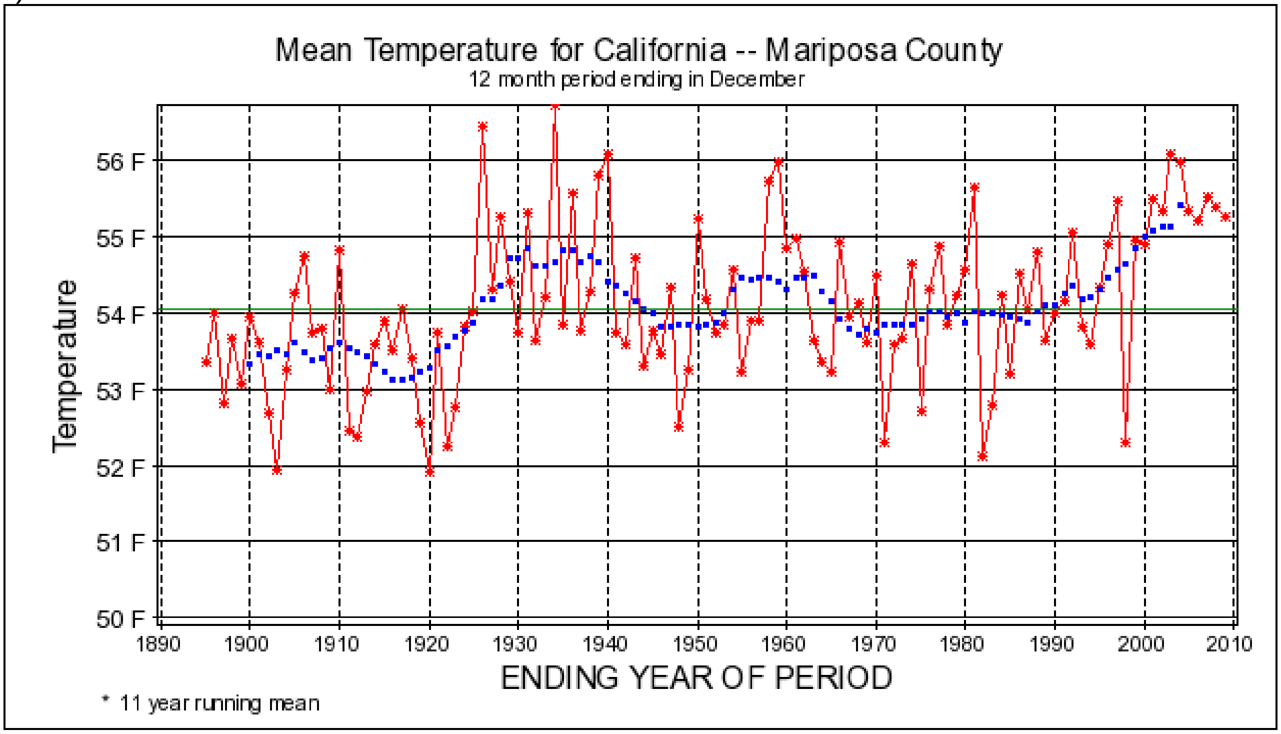

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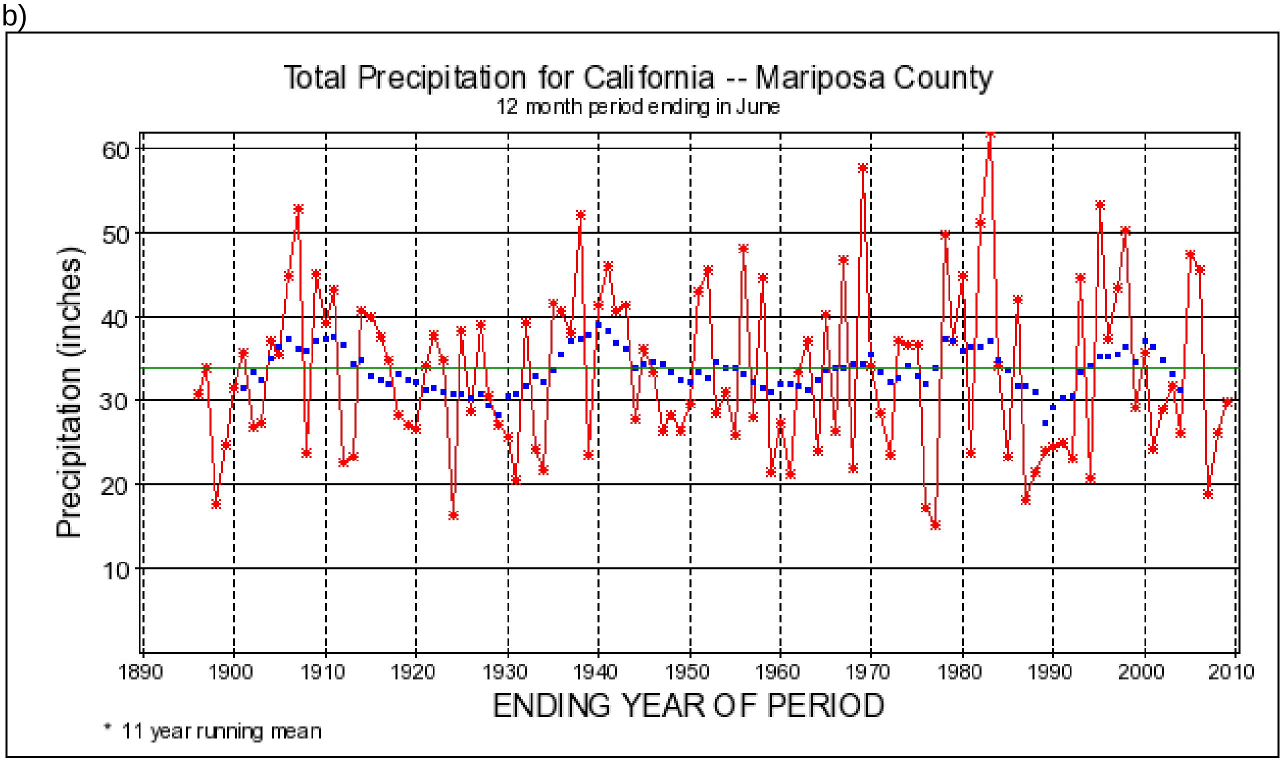

Figure 8. Mariposa County (YOSE Cent/SW area) temperature and precipitation time series. a) Mean calendar year temperature (1895-2009) and b) total precipitation (1895/96-2008/09). Blue: 11-year running mean. Green: 1971-2000 mean. Data from PRISM. *Source: Interactive plots, WRCC/UArizona Westmap.*

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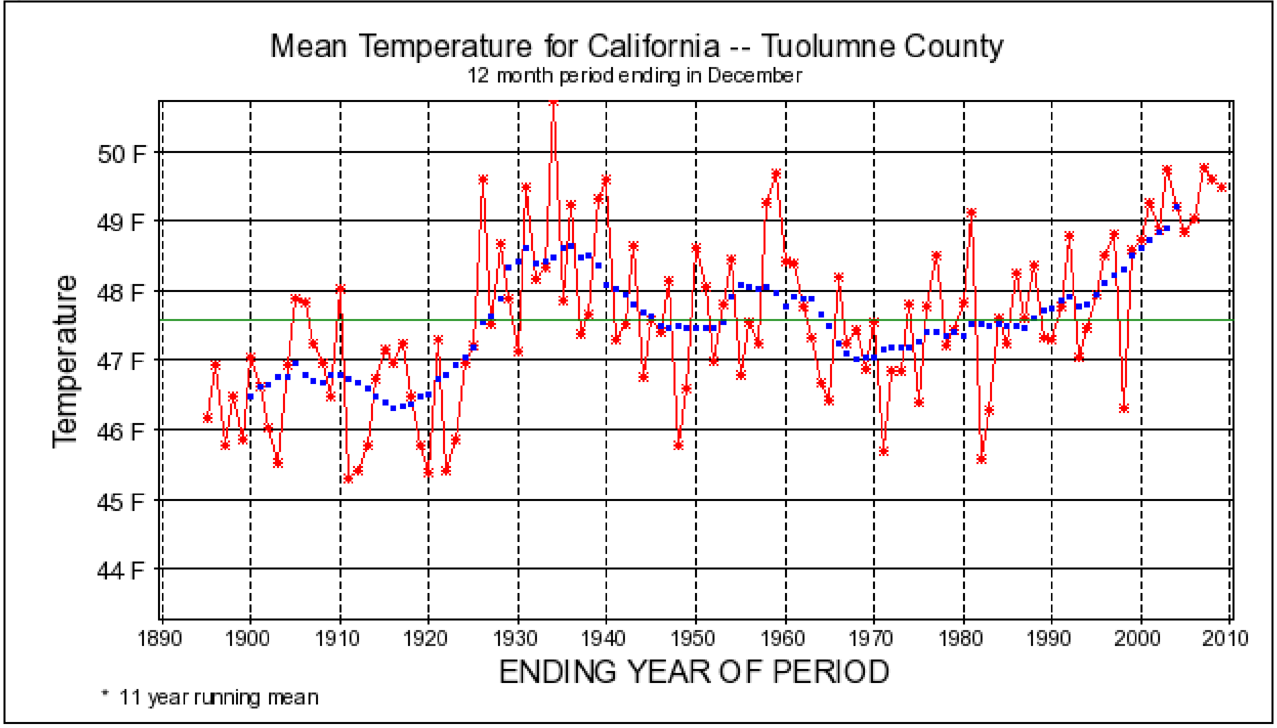

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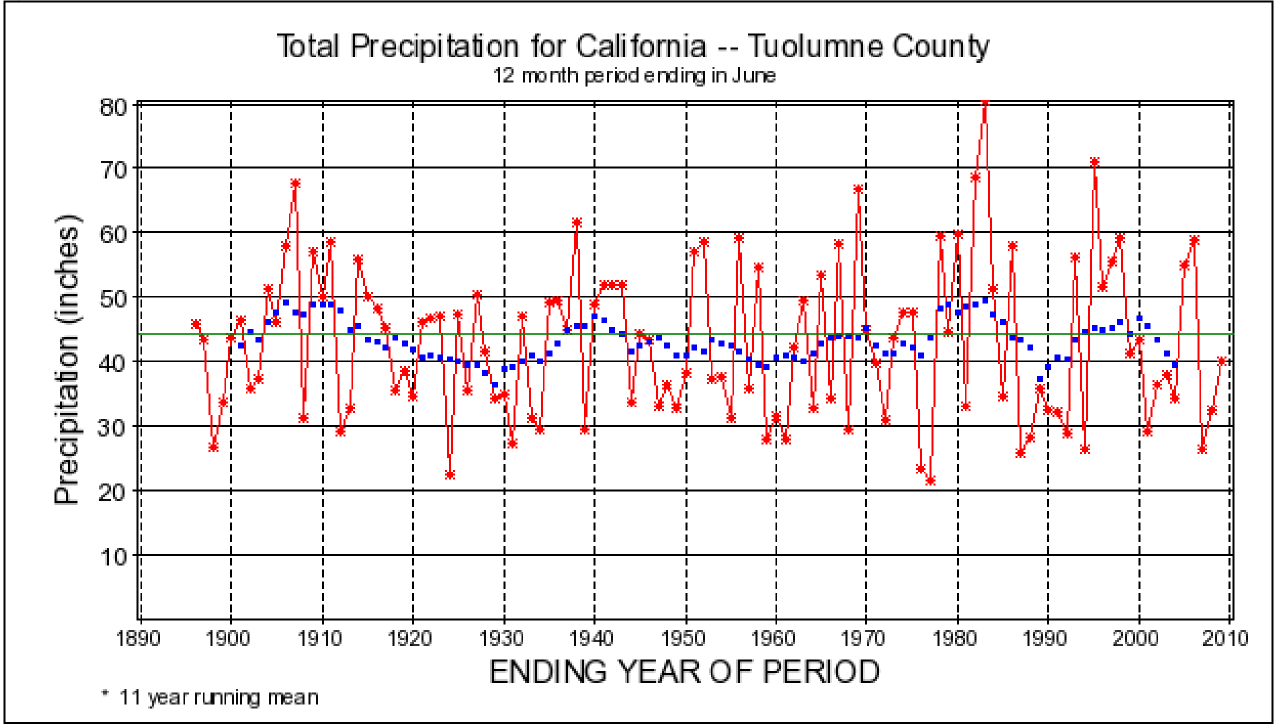

Figure 9. Tuolumne County (YOSE area) temperature and precipitation time series. a) Mean calendar year temperature (1895-2009) and b) total winter-centered precipitation (1895/96-2008/09). Blue: 11-year running mean. Green: 1971-2000 mean. Data from PRISM. *Source: Interactive plots, WRCC/UArizona Westmap.*

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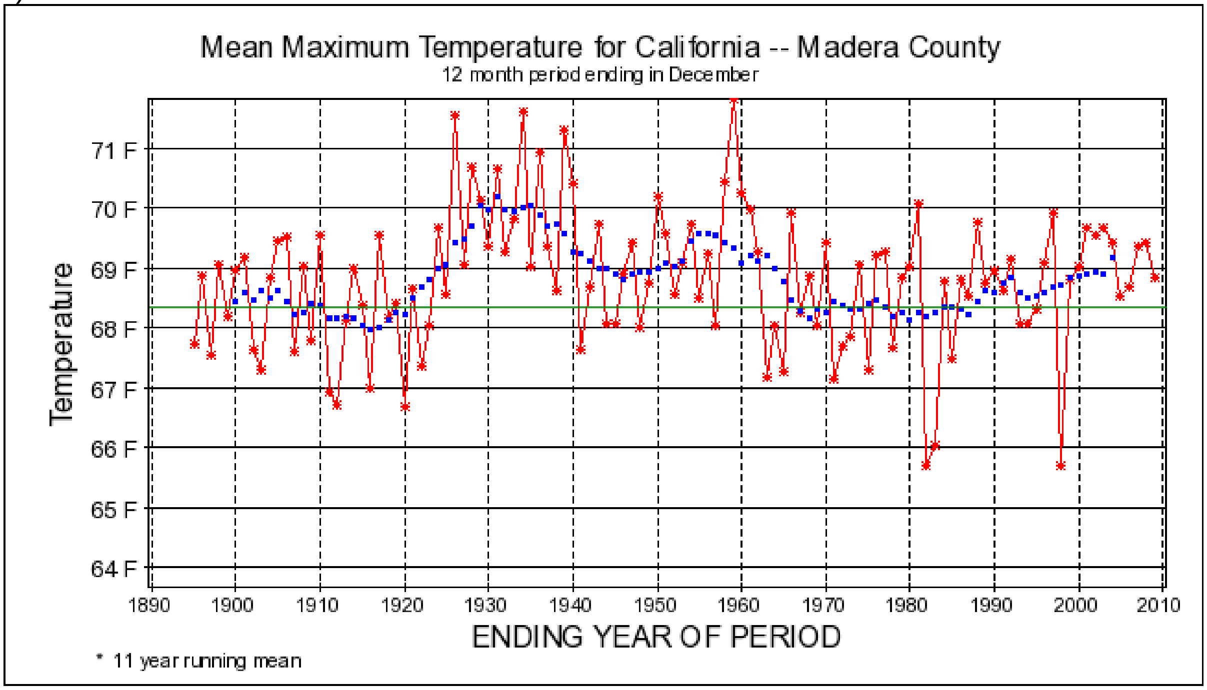

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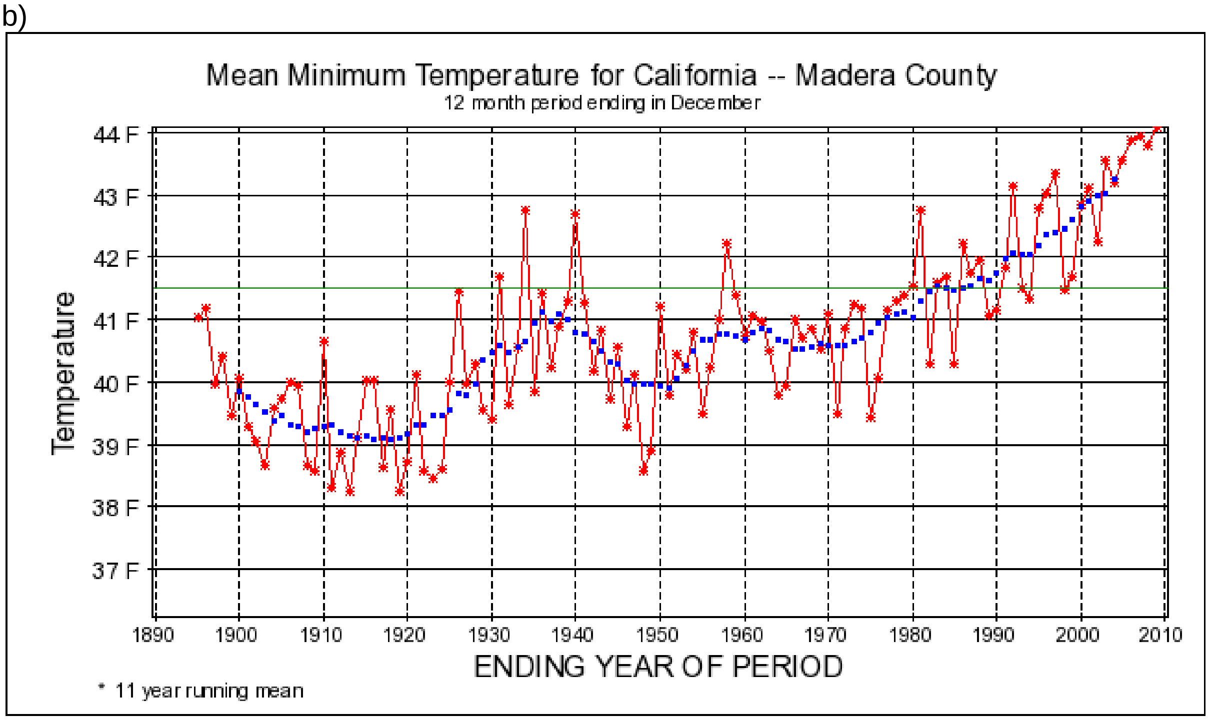


Figure 10. Madera County maximum and minimum temperature time series**.** a) Mean calendar year maximum and b) minimum temperature. (1895-2009), Red: individual years. Blue: 11-year running mean. Green: 1971-2000 mean. Data from PRISM. *Source: Interactive plots, WRCC/UArizona Westmap.*

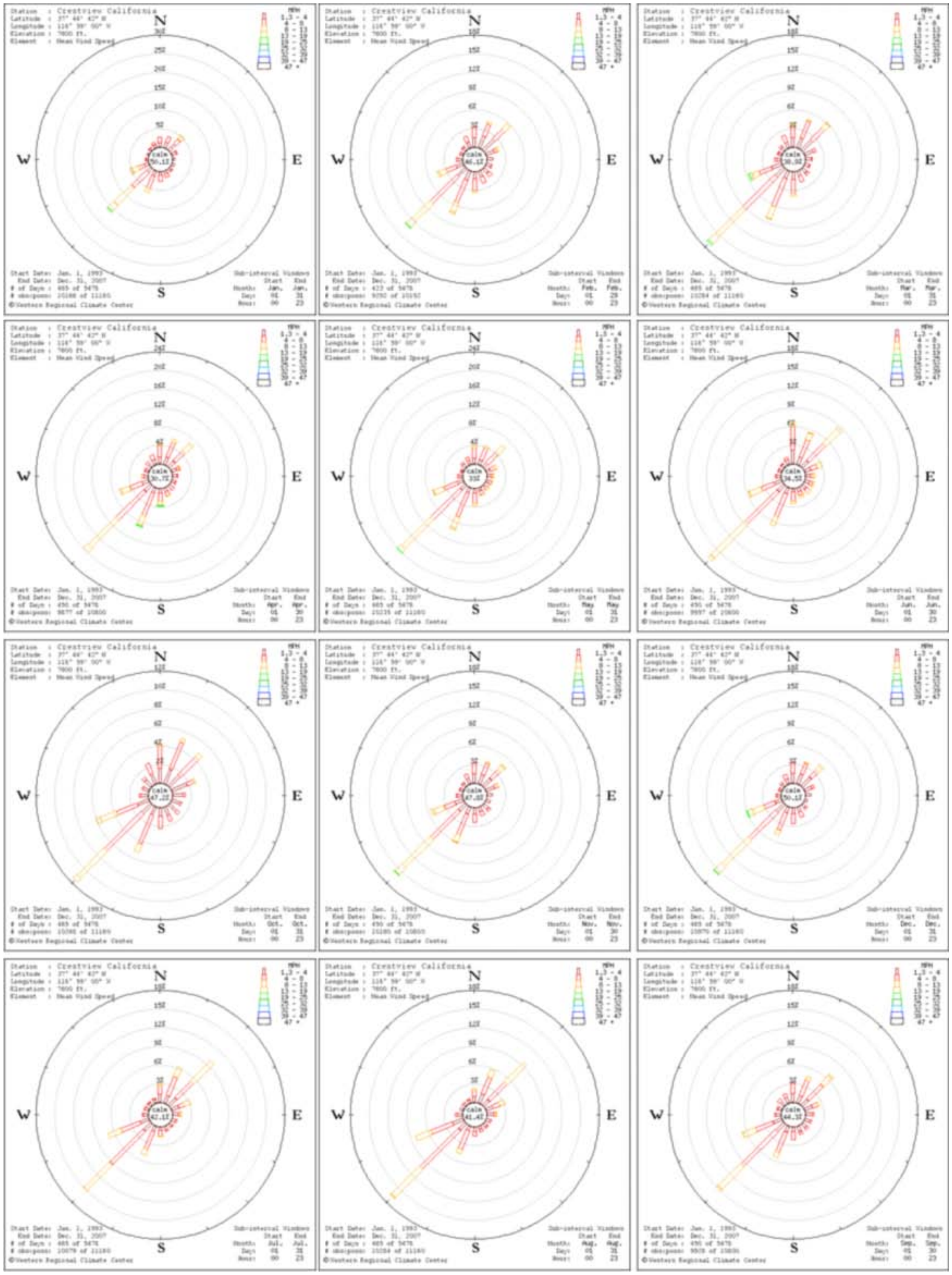


Figure 11. Monthly wind roses, all months of the year and all hours,for Crestview RAWS station, based on data from January 1993 through December 2007. Arranged by row from top to bottom, Jan-Mar, Apr-Jun, Jul-Sep, and Oct-Nov. *Source: WRCC RAWS interactive applications.*

Large Scale Influences on Climatic Variability

The geographic location of SIEN in the central and southern Sierra Nevada is such that it can be influenced on intra-seasonal to inter-decadal time scales by large-scale circulation patterns over the Pacific Ocean, that include (from fastest to slowest): the Madden Julian Oscillation (MJO), El Niño-Southern Oscillation (ENSO), and the Pacific Decadal Oscillation (PDO).

The pattern with the longest time scale, but seemingly the least (or least clear) influence on SIEN, is the PDO (Mantua et al. 1997). This pattern emerges from a principal components analysis (PCA) of simultaneous sea surface temperature (SST), sea level pressure (SLP) and wind stress on the ocean's surface in the north Pacific Ocean, as shown in Figure 12. An index of its status can be calculated from the projection of the anomalous SST and SLP patterns for a given month onto the pattern that defines the PDO, with a sign convention such that a positive PDO is associated with warm water just off the west coast of Canada. The monthly time series (not shown) of the PDO magnitude over the past century shows that the "decadal" index actually takes closer to 50 years to complete a full warm-cool-warm fluctuation. A major and sudden shift from cool to warm took place in 1976 (Ebbesmeyer et al. 1991), the first major shift since about 1947, and the completion of an apparent oscillation that started with another transition from cool to warm in 1924. Conditions over the north Pacific Ocean influence temperature and snowpack in North America, particularly the Pacific Northwest. The pattern was uncovered during investigations of climate influences on Northwest and Alaska salmon (Mantua et al. 1997). Farther south, PDO effects in California are rather ambiguous, including in the SIEN region (Table 2). The mechanisms that drive the PDO are at this time not well understood (Newman et al. 2003), and it is not certain that the PDO should be called an "oscillation." Changes in phase are hard to predict, and may not be recognized until some years afterward. As a result, the PDO appears to have more diagnostic than prognostic value. Because of its multi-year duration, however, PDO changes and climate changes can be intermingled and possibly confused with each other.

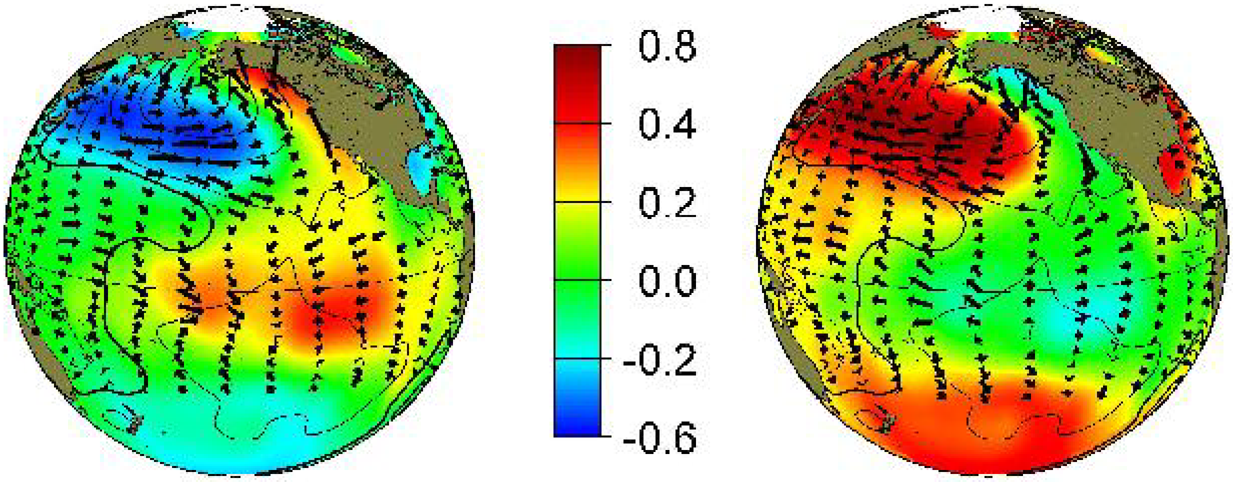


Figure 12. Pacific Decadal Oscillation spatial pattern, warm and cool phases. Characteristic sea surface temperature anomaly and wind stress for warm phase (left) and cool phase (right). Temperature anomalies are in degrees C. After Mantua et al.1997. *From http://jisao.washington.edu/pdo/*

Table 2. PDO phase and impact on regional climate in North America. *From Mantua, 2002 www.atmos.washington.edu/~mantua/REPORTS/PDO/PDO_egec.htm).*

Climate anomaly	Warm PDO Phase	Cool PDO Phase
SST in northeastern and tropical Pacific Ocean	Above average	Below average
Oct-Mar northwestern North America air temperature	Above average	Below average
Oct-Mar southern US/northern Mexico precipitation	Above average	Below average
Oct-Mar northwestern North America precipitation	Below average	Above average
Northwestern North American spring snowpack and water year (Oct-Sep) streamflow	Below average	Above average
Winter and spring flood risk in Pacific Northwest	Below average	Above average

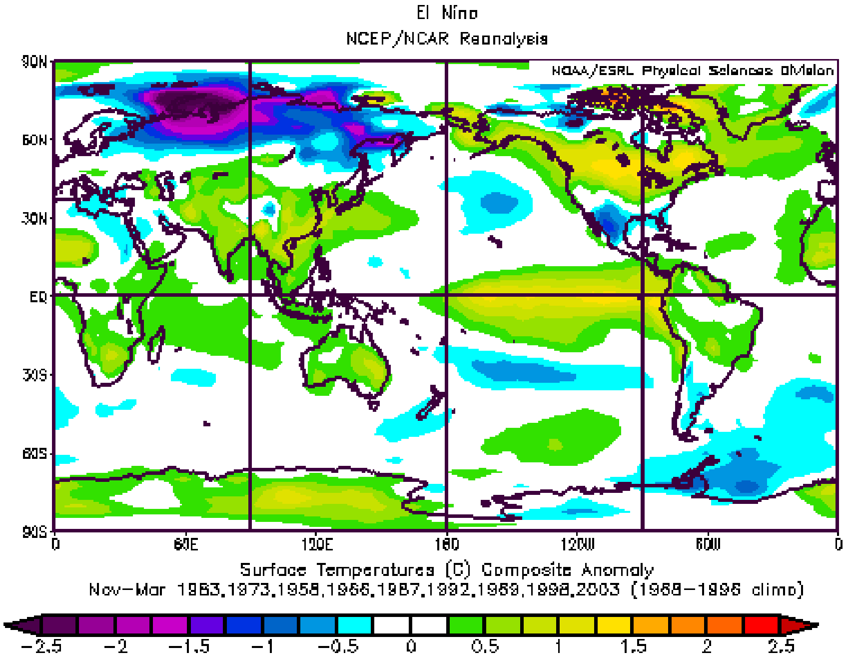
The El Niño-Southern Oscillation (ENSO) is the result of air-sea interaction in the equatorial Pacific Ocean, and thus has an atmospheric component and an ocean component. Its two phases have separate names, El Niño (warm phase) and La Niña (cool phase). The main defining feature is the ocean temperature within a few degrees latitude of the equator, between Peru and the Date Line. A concurrent phenomenon is seen in the overlying atmosphere, with barometric pressure over the equatorial Pacific exhibiting an out-of-phase relationship with pressure over large parts of the Southern Hemisphere, including Australia. This correlation pattern was identified in the 1920s and is called the Southern Oscillation. El Niño occurs in an irregular manner typically once in 2-7 years (inter-annually), averaging around 4 years. From start to finish a typical warm or cool phase lasts 6-18 months, but both El Niño and La Niña have on occasion lasted two and even three years.

It is perhaps more instructive and accurate to consider the El Niño - La Niña interplay to be the norm, and for "average" conditions to simply be transitions between these two extreme states (Philander 2004). The air temperature patterns associated with El Niño and La Niña are shown in Figure 13. The air over the ocean typically shows the same sign of anomaly as does the ocean surface temperature. The patterns of ENSO and PDO do look quite similar to the eye, but Mantua et al. (1997) showed that their time histories are poorly correlated.

Studies in the wake of the major El Niño of 1982-83 showed the then-surprising conclusion that ocean temperature and pressure variations in the eastern equatorial Pacific were significantly correlated with precipitation in western North America (these links are sometimes called "teleconnections"). These correlations are strongest in the cool half of the year (October through March), and almost non-existent in the warm half of the year (April through September). In southern California, La Niña is reliably associated with dry winters, and El Niño is less reliably associated with wet winters (Redmond and Koch 1991 and updated on the WRCC website www.wrcc.dri.edu; Figures 14, 15). In the Sierra Nevada this association is strongest in the south, and nearly disappears at about the latitude of Lake Tahoe. Thus, SEQU shows a somewhat stronger and more definitive relation to El Niño and La Niña than does YOSE (Redmond and Koch 1991). In the SIEN region, El Niño winters tend to bring more wet days, more precipitation per wet day, cooler temperatures, more snow, and more persistent (longer duration) precipitation events. La Niña tends to bring the opposite: dry winters, fewer precipitation days, less precipitation per wet day, and warmer temperatures. The effects of El Niño and La Niña on winter precipitation along the West Coast are approximately but not exactly opposite of each other.

Somewhat paradoxically, La Niña tends to bring a moderately higher likelihood of major flooding, associated with "atmospheric rivers" of very moist air from the Pacific Ocean at the latitude of Hawaii or southward, conditions sometimes referred to as the "pineapple express." El Niño can bring wet winters, but does not seem to be associated with the largest Sierra Nevada winter floods, the most damaging floods that California experiences. YOSE in particular has experienced major flooding from these situations, most notably during the 1996-97 New Year's Day flood. Another recent notable flood occurred in a rather unusual month, May 2005, not associated with either phase of ENSO.

On the shortest scale usually associated with climate (a few weeks) we find the Madden-Julian Oscillation (MJO). This operates within the seasonal time frame, with a typical period of 40-70 days. The MJO is characterized by the slow propagation of convective activity (often paired with an adjoining area lacking convection) from the eastern Indian Ocean eastward across Indonesia almost to the Date Line. Sometimes these pairs are very evident ("active" periods), and at other times they are nearly absent. The atmospheric heating associated with the release of precipitation in very deep thunderstorms interacts with the jet stream to the north that is flowing eastward off the Asian continent. This in turn can set up a wave train of disturbances that propagate across the entire Pacific to reach the West Coast and produce multi-day episodes of precipitation. Active MJO periods can sometimes lead to extended wet episodes to California. The MJO occurs mostly independently of El Niño and La Niña, but these phenomena can interact to enhance or diminish California precipitation. Jones (2000) found that the most extreme MJO-driven precipitation events in central and southern California occurred during El Niño phases. An active MJO pattern that can bring heavy precipitation to the Sierra Nevada is also sometimes identified as the Pineapple Express, as referred to earlier. Typically these are warmer storms with more intense precipitation and high freezing levels, resulting in rain at high elevations, flooding from rapid runoff, and at times added contributions from rapidly melting snow. Current research is focusing on the interplay between El Niño / La Niña, the MJO, "atmospheric rivers" of concentrated moist flow, and flooding in the Coast Range and Sierra Nevada (Ralph et al. 2006; Neiman et al. 2008, Dettinger et al. 2011).



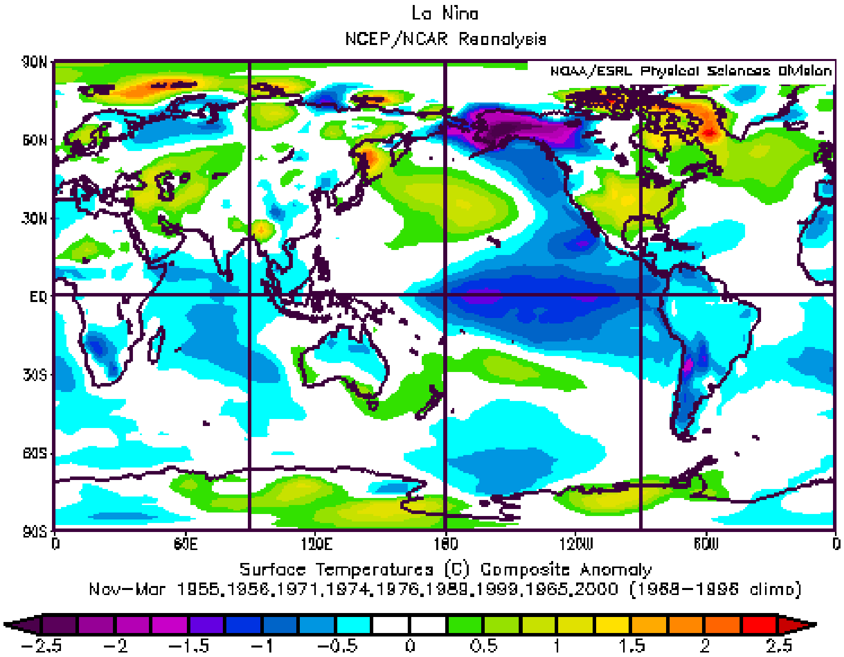


Figure 13. Composite global El Niño and La Niña winter temperature anomalies. Surface temperature departures from average (degrees C) for November through March. *From ESRL/PSD, www.cdc.noaa.gov.*

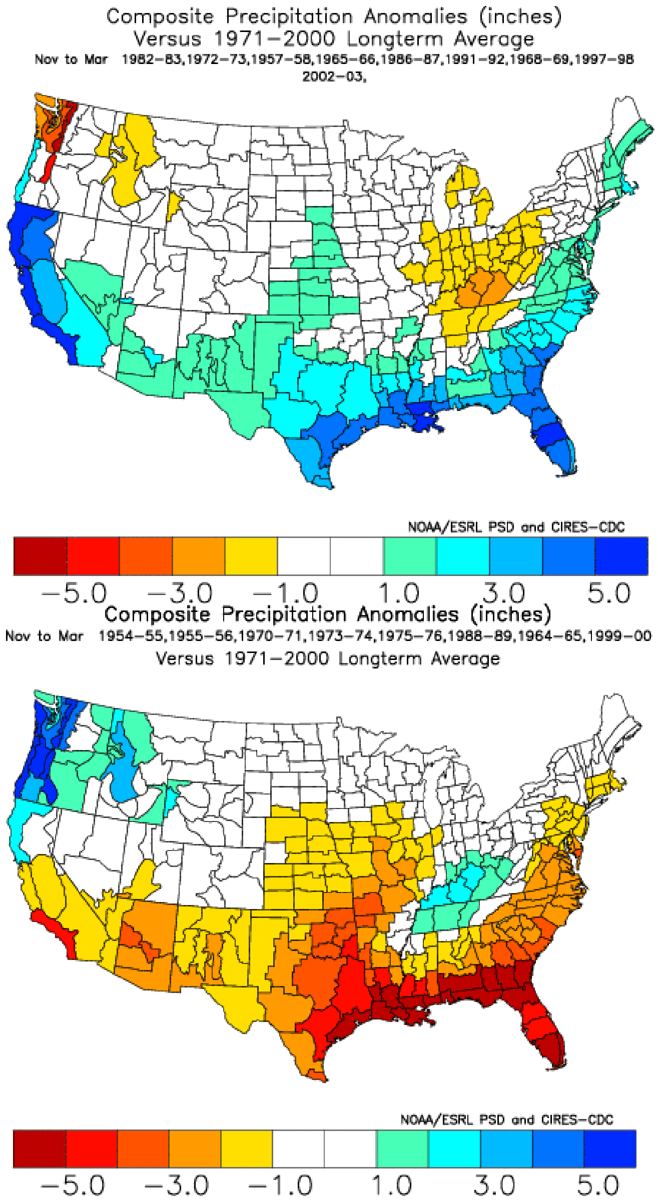


Figure 14. Characteristic winter precipitation anomalies for El Niño and La Niña. El Niño (above) and La Niña (below) composite precipitation anomalies for November-March by climate division. *From NOAA's ESRL/PSD Climate Analysis Branch, http://www.cdc.noaa.gov/.*

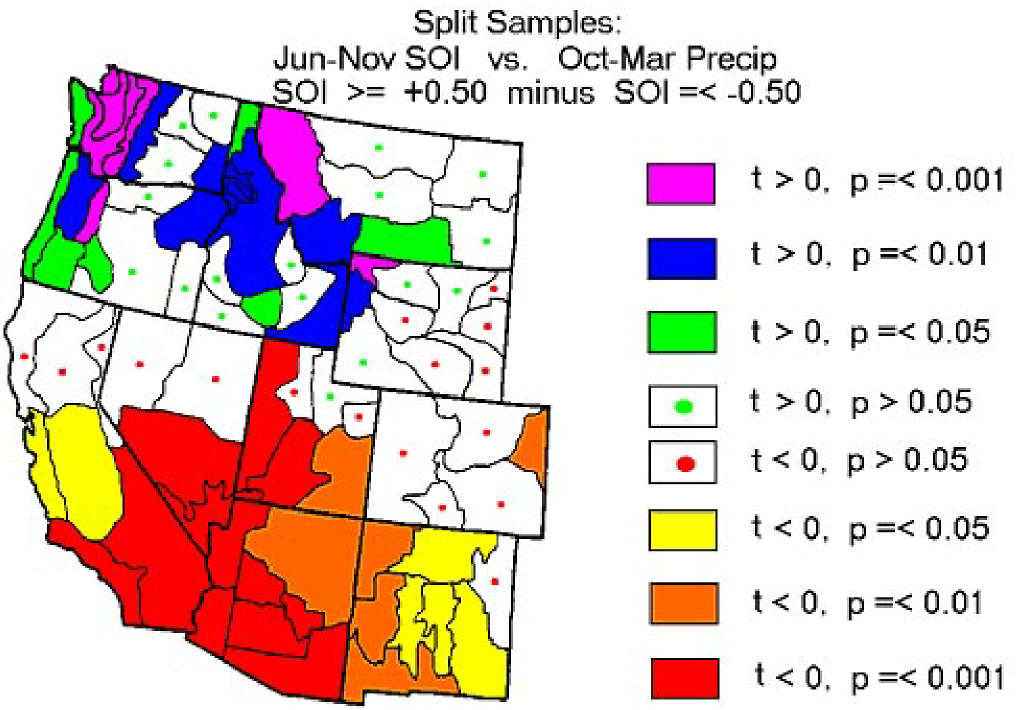


Figure 15. Precipitation differences between high and low Southern Oscillation Index. Significant tests of difference in October-March precipitation, for sets of years with mean prior summer-autumn (June-November) Southern Oscillation Index (SOI) greater than +0.50 minus those years with SOI less than -0.50. Positive SOI indicates La Nina, negative SOI indicates El Nino. Updated from Redmond and Koch, 1991. *Source: WRCC, http://www.wrcc.dri.edu/enso/map2b.gif.*

Seasonally, the southwestern U.S. summer monsoon can also affect this area. The eastern slope of the Sierra Nevada experiences more impact from the monsoon than the western slope. The monsoon can bring thunderstorm and shower activity to the eastern slope region in the summer months, usually from late June to mid-September. As an example, an extremely intense storm occurred July 12, 2008 over Oak Creek, west of Independence, with reports of up to 7 inches of rain in just a few hours. A significant flood damaged or destroyed 50 homes as the water and mud from the steep mountains traveled toward the Owens River. Lightning and high winds that often accompany these storms are also of concern during this typically dry season because of possible wildland fire ignitions.

More thunderstorms occur east of the Sierra Nevada (Bishop averages 12 per year) but are concentrated in the warm months. West slope thunderstorms are less frequent (Fresno averages about 5) but can occur in any month. Warm season thunderstorms show a strong diurnal cycle, with peak frequency in afternoon from daytime heating, whereas cool season thunderstorms, occurring as embedded convection in large scale storms, do not show such strong preference for time of day. Once formed, thunderstorms tend to drift toward the east or north, carried by prevailing flow.

Spatially, convective warm season storms produce very spotty and localized precipitation. It is not uncommon for places less than a mile apart to witness no rain in one area, and several tenths an inch in the next. Precipitation from cool season cyclonic storm systems tends to be more uniform, though typically increasing with elevation (see below). However, embedded convective updraft cells can produce intense localized increases of precipitation intensity in winter storms.

The simplified asymmetric west-east profile of the Sierra Nevada consists of a long moderately-inclined ramp on the west side from nearly sea level to the High Sierra crest, and then a steep drop on the east side. This topography can enhance precipitation by the process of "orographic lifting." Flow associated with winter storms typically ascends at some angle to the maximum elevation gradient, causing the usually moist air to cool, and the water vapor to condense into liquid form as clouds. This uplift can either enhance precipitation that was already going to occur, or lead to precipitation where none at all would have occurred over flat land. The mountains experience precipitation more frequently, and typically in greater amounts per wet day than valleys. As the air rises and cools, there is usually an elevation zone where precipitation rates are greatest, at about 5000-8000 feet (1600-2400 m), and above which the precipitation rate decreases (Figure 16).

The eastern slope of the Sierra Nevada is drier than the western slope. Clouds descending the abrupt sharp east face rapidly evaporate and little precipitation reaches the ground, creating a "rain shadow." This is one of the sharpest annual precipitation gradients in the United States. From satellite or radar images, the movement of cloud elements gives the appearance of a precipitation about to move over the crest and beyond. But, the clouds and their orographic precipitation are actually locked to topography and from an east-side vantage stubbornly refuse to translate any farther to the east.

Another source of climatic variability is anthropogenic effects of humans on global and regional climate. This is discussed in more detail in a separate section below. Each of the pre-existing factors of climatic variability described here will continue to contribute to the climate of the SIEN park units into the foreseeable future, even if climate change from human sources does occur. Climate change may lead to modifications in the way in which the effects of the above phenomena (and others) are expressed as weather and climate events. Current climate models are rather poor in their ability to represent the various oscillations, especially the PDO and MJO, but even ENSO. Thus, we are presently unable to make definitive statements about how these features might change, and therefore change the measured climate of the SIEN park units.

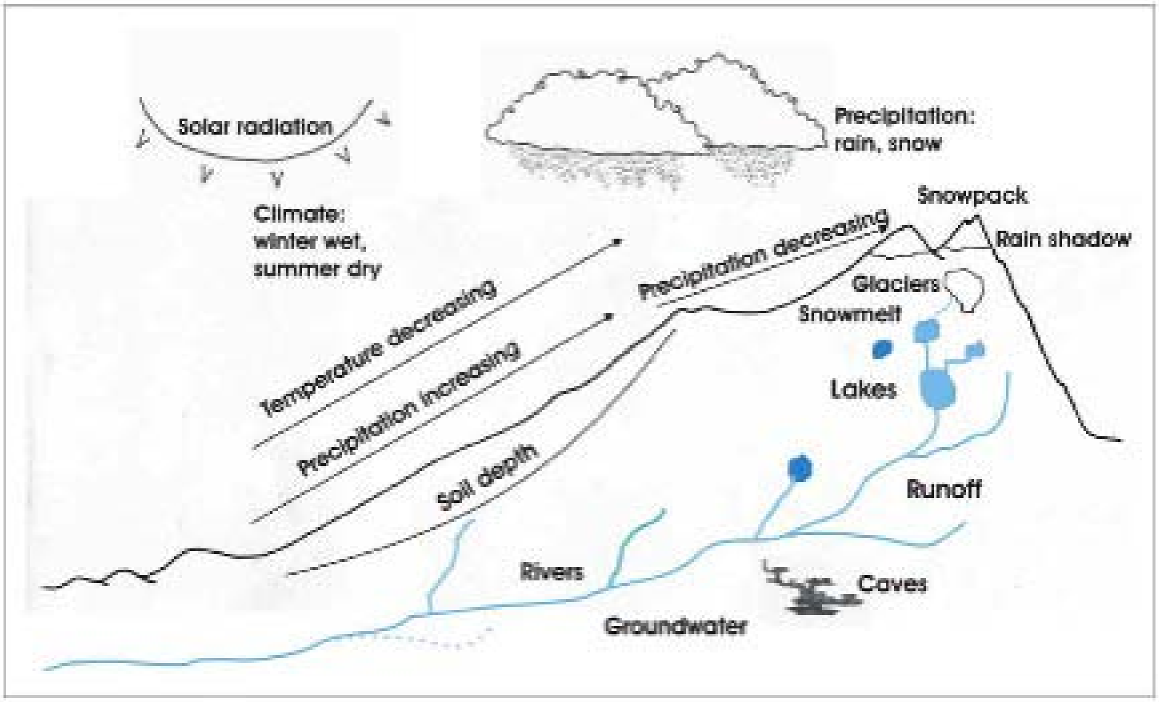


Figure 16. Graphical description of orographic precipitation effects in the Sierra Nevada. Orographically forced precipitation and cooling temperature effects, by elevation, in the Sierra Nevada. *From Mutch et al. 2008.*

Drought

Most precipitation in the southern Sierra Nevada occurs in the cool half of the year, with a lengthy dry season of little or no precipitation in the summer months. As a recurrent climatological feature, the term “drought” is usually not applied to this circumstance. The most important droughts are those that affect the season(s) of primary precipitation. Inter-annual winter precipitation is highly variable; a single winter with deficient precipitation can be sufficient to produce severe drought. Once the winter season is “lost” there is essentially no opportunity for recovery until the following winter. Consecutive dry winters will exacerbate drought conditions.

Drought in the Sierra Nevada is not the classic Dust Bowl drought vividly depicted in the images of Arthur Rothstein or Dorothea Lange. Winter drought is not always apparent to direct observation, because precipitation generally still occurs and the landscape can appear wet. The most visible manifestation is reduced snowpack. Drought becomes more apparent in spring when the high country melts out earlier than usual, rocks appear through snow fields, and the spring pulse of streamflow from melting snow is subdued, earlier than usual, and at times not very apparent.

Drought has both practical and ecological consequences. The high mountains of the SIEN parks are source regions for rivers later harnessed by agricultural, municipal and recreational interests at lower elevations. These interests are utterly dependent on this water, and monitor the development of winter snowpack with great attention. In YOSE, Hetch Hetchy is the main water source for the city of San Francisco. Park visitation can be both helped and hurt by drought. The

Wawona area in YOSE nearly ran out of water for the hotel in the summer of 2007 after a very dry winter reduced flow in the South Fork of the Merced to a little over one cubic foot per second. Increased wildfire activity due to dry vegetation may also affect visitation and because of smoke, the quality of the visitor experience.The opening date of YOSE's Tioga Pass is an important tourism milestone each year. Rafting is a major seasonal business downstream of each of these park units. Snow-plowing budgets are based on expectations of average winters and can fluctuate depending on winter conditions. The waterfalls of YOSE, notably, and the other units of SIEN are a significant scenic attraction and reach low flows or dry up on different dates in most summers. Bears and other animals in search of water or food are more apt to interact with visitors or enter dwellings in or near park lands when drought reduces food sources and forces them to take more chances.

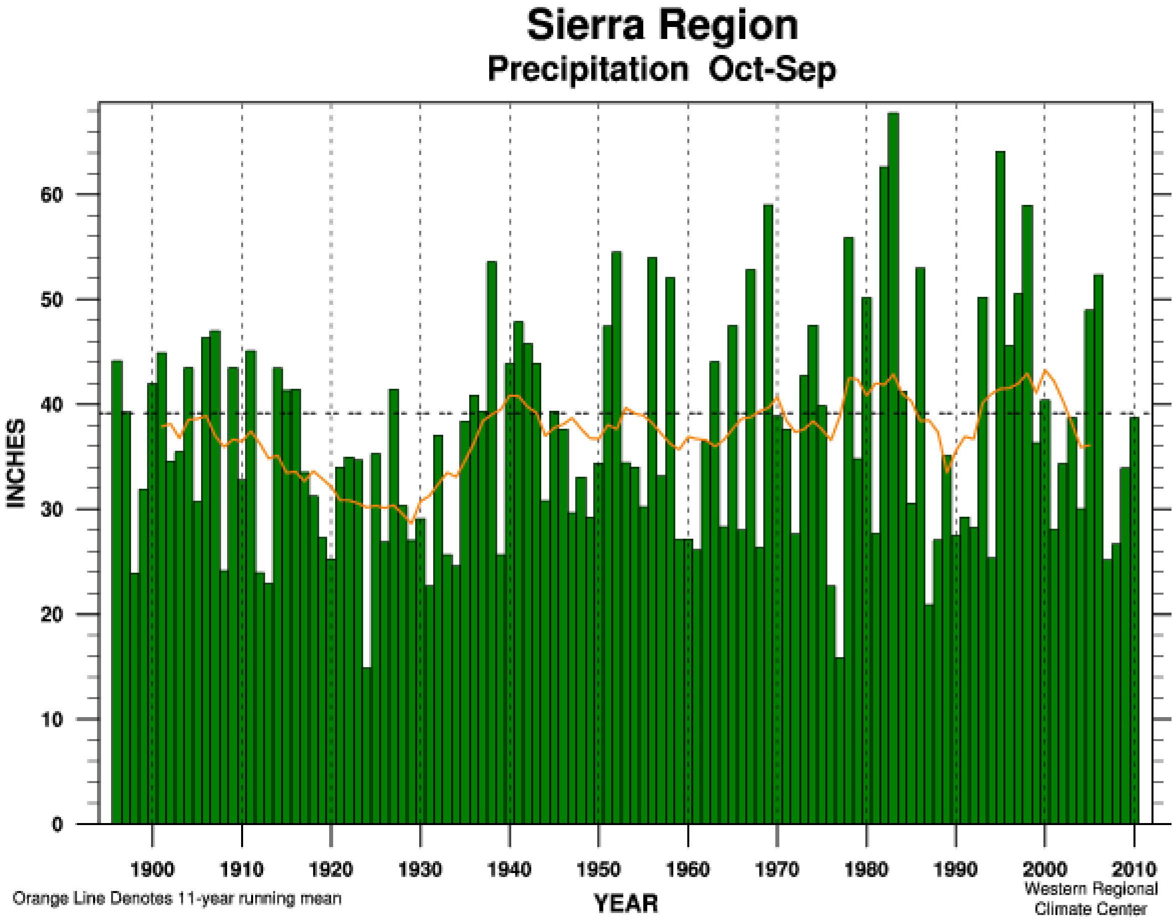
Drought is not a pathological condition but rather an integral part of the climatic backdrop to which biological organisms and communities have adapted. Drought is an expected and normal occurrence and provides certain members of the ecological web with temporary evolutionary advantages and disadvantages. In fact, every departure from long term climate is advantageous for some organism. Drought affects fire regimes and all the cascading further effects. As a form of extended "disturbance", drought can alter conditions to favor invasive species. Insects (native or non-native) can take advantage of the lowered defenses of trees when water is short. Yellowjackets and other irritating insects are more active in hot, dry weather. Droughts and other climate anomalies can be folded into the interpretive activities as they happen.

Longer records of climate reconstructed from tree rings and other proxy evidence from paleoclimate studies show that drought has been present for centuries, and that the overall likelihood of drought in any given year shifts through time. Furthermore, they show that extended drought is rare but not unknown, and that once or twice a century a significant multi-year drought is seen. Figure 17 shows a history of precipitation for the Sierra Nevada (approximately Mount Lassen to the Kern River) from the WRCC California Climate Tracker (www.wrcc.dri.edu/monitor/cal-mon/index.html). The paleoclimate reconstructions also show that droughts of 10, 20 and 30 years duration, and longer, have occurred. Stine (1994) has discussed the long periods of low surface levels of Tenaya Lake and Mono Lake, and of the flow of the Walker River, which in part drains the northeast corner of YOSE. Similar evidence is also found in sediments (Davis 1999).

Global Climate Change and Climate Modeling

Climate model projections for the next century indicate warming for the Sierra Nevada and for the state of California in general (Dettinger 2005). A 2006 report issued by the California Energy Commission (CEC 2006) gives a range of 3 to 10.5 degrees F (1.7 to 5.8 degrees C) warming by the end of the 21st century, under three different emissions scenarios. Temperature increases are expected in all seasons, but not quite equally in each season (Cayan et al. 2008). Annual precipitation is generally expected to change little, with possible increases in the winter, and decreases in the spring and summer (Knowles and Cayan 2004, Maurer and Duffy 2005).

General Circulation Models (also, Global Climate Models, or GCMs), simulate climate by solving the set of equations that govern the physical behavior of air and its movement. An analogous set of equations govern the movement of the ocean. In recent years the primary models in climate research have evolved to utilize a "coupled" approach, taking into account how the oceans and atmosphere interact and influence each other. To a large degree, most GCMs in use today incorporate atmosphere, land, ocean, and ice processes into a single model. Some higher resolution regional models also take into account land use or land cover change, atmospheric chemistry, and regional hydrological processes.



Linear Trend 1895-present		+ 4.47 ± 5.89 in.	(+ 11 ± 15%) per 100 yr	
Linear Trend 1949-present		- 0.57 ± 17.84 in.	(- 1 ± 45%) per 100 yr	
Linear Trend 1975-present		- 3.17 ± 46.72 in.	(- 8 ± 119%) per 100 yr	
Wettest Year		67.79 in. (173%)	in 1983	MEAN 39.15 in.
Driest Year		14.89 in. (38%)	in 1924	STDEV 12.33 in.
Oct-Sep	2010	38.68 in. (98%)		RANK 67 of 115

Figure 17. Sierra Nevada winter-centered precipitation annual time series**.** Values for October-September total precipitation, plotted in ending year, for period 1895/1896 thru 2009/2010. Statistics and trends shown below. *WRCC California Climate Tracker.*

These simulations represent the ocean and atmosphere either as a 3-dimensional latticework (grid models) or as superpositions of many periodic mathematical waves of different size (spectral models). The recent generation of widely used GCMs has an equivalent grid size of about 2 degrees latitude by 2 degrees longitude, with many now improved to 1x1 degree. One-degree grids are about 111 x 90 km (latitude x longitude) in size at 36° N latitude. In mountainous terrain, important processes take place at spatial scales on the order of 1 km or less. The only way to represent these scales is via “downscaling,” relating small-scale processes to large scale information. This can be achieved by statistical procedures, or by dynamical procedures using embedded finer scale meshes of limited spatial extent. The former is rapid and cheap but constrained within the observed range, whereas the latter is internally consistent and can be extended outside the experience base, at the cost of being computationally complex and expensive.

Many of the main issues in understanding climate change involve the responses of the climate system to changes in the way that energy in the form of radiation moves from one point to another. The flow of radiative energy is dependent on wavelength, sometimes very sensitively so. The computation of radiative transfer of energy can be extremely complicated and difficult, and even then is still an approximation.

Of these radiation issues, the greenhouse effect, and the gases that enhance this effect beyond its natural level, is generally the subject most widely referred to in the public domain. Higher greenhouse gas concentrations reduce the earth’s loss of energy to space, without appreciably affecting the inflow of energy from the sun. When gain exceeds loss, energy accumulates, and the planet begins to warm. This is often described in force/response terminology: the radiative imbalance acts as a driver that constitutes the climate “forcing” and the way climate adjusts is called the “response.” The warmer system causes increases in the energy loss to space, and enough warming restores the gain-loss difference to nearly zero. With continual addition of greenhouse gases, the system can never quite reach equilibrium and thus continues to warm. Many feedback processes act to determine the sensitivity, defined as the increment of climate response (degrees C of warming) per unit of change in energy forcing (measured as changes in energy flux into and out of the climate system, usually expressed in Watts per meter squared, where a Watt is one Joule (of energy) per second).

However, climate change is about more than just the greenhouse gas issue. Other radiative factors are at work in changing the climate as well. Changes in land use and land cover type (both natural and human-caused) affect the absorption of radiation at the surface, and therefore the amount and distribution of energy absorbed by the climate system. Pollution and other small particles in the atmosphere, also natural and human-caused, are collectively called “aerosols” and act to generally cool the planet (some aerosols warm, others cool; in the net, cooling dominates). Volcanoes, as a special case, produce one type of aerosol that can cool climate for 2-3 years if lifted high enough in the atmosphere (into the stratosphere). Human-caused aerosols are generally held as providing a partial “brake” on greenhouse warming, but in the long run it is widely held that the greenhouse warming influences will increasingly dominate over aerosol cooling. We appear to have entered this era in the last decade or two.

In addition, clouds are bright and reflect incoming sunlight (a cooling influence), but also block outgoing terrestrial radiation (a warming influence), because water is such a good absorber at those wavelengths. Different cloud types have differing and competing effects on radiation, but the net effect of clouds averaged over the globe appears to be to cool the planet. With an increase in global temperature, the water cycle may also be enhanced (IPCC 2007). If this is the case, one result may be that atmospheric water vapor would increase and along with it cloud development. However, clouds and how they are represented are a source of large uncertainty in today's GCMs.

Aerosols can also have an impact on the formation and evolution of clouds, and could affect the areal extent of clouds, or their brightness, or both. The addition, via air pollution, of large numbers of very small aerosols, of the type that cloud droplets condense around, can lead to an unusual abundance of very small cloud droplets. Because of their small size, these cloud droplets do not readily coalesce into droplets large enough to fall to earth as precipitation. Thus, tiny aerosols can inhibit precipitation where it would otherwise occur (Borys et al. 2003). This mechanism does not seem to be widely appreciated, and was recently studied in California (Givati and Rosenfeld 2004).

The United Nations-sponsored Intergovernmental Panel on Climate Change (IPCC) has commissioned several assessments of the status of climate change research and knowledge. The latest of these, the IPCC 4th Assessment Report (AR4), was released in 2007. A new round is under way (AR5) but results will not appear soon enough for this report. Parts of AR4 have utilized approximately 20 climate models from around the world, with scenarios reflecting low, medium, and high growth rates of greenhouse gas introduction to the atmosphere over the next century. Over the next 2-4 decades, the emissions scenarios do not differ appreciably from each other.

The IPCC's Special Report on Emissions Scenarios (IPCC 1997) developed a standardized set of greenhouse gas emissions scenarios for use in climate modeling. They represent a number of factors, including population growth, energy sources and their greenhouse gas emissions, economic growth and land use change. Most commonly modelers use a high, low, and moderate emissions scenario to "bracket" the problem with climate model output. This means in essence they will create worst-case, best-case and in-between modeled outcomes. It is worth noting that observations of recent actual emissions show that they are increasing faster than even the standard worst-case scenario.

We can use combinations of models and scenarios, and in some cases multiple runs with different initial conditions (to address chaos issues), to form frequency distributions (probability density functions, or PDFs) of potential outcomes (Kalnay 2002). This method creates an "ensemble", or group of forecasts. These provide one measure of uncertainty around a single consensus value such as the mean or median. Most often, they appear as the familiar bell-shaped curve, but in some cases this curve has asymmetries (especially in the tails) or more than one maximum. Though somewhat more complex, this is a superior method to single, deterministic estimates and is now standard procedure in daily weather forecasting (ensemble forecasting) and increasingly in climate research. Experience has shown that consensus forecasts obtained in this way are more accurate than nearly any of the constituent forecasts taken individually.

This ensemble approach is illustrated with Figure 18 and Figure 19. Three emissions scenarios were utilized to represent a range of future greenhouse gas emissions:

- B1, lower economic growth, green color;
- A1B, medium economic growth, blue color;
- A2, business as usual, red color.

The trends are organized by season where DJF= winter, MAM=spring, JJA=summer, and SON= fall. A “+” represents each individual model’s projected average temperature for that season. Circles represent the mean, and a filled circle is statistically significant at the 95% level. A one degree Celsius rise in temperature is approximately equivalent to moving a given temperature about 150 m / 500 ft higher in elevation, with a typical temperature lapse rate of 6.5 C / km. Note also that the reference period 1971-2000 is itself somewhat elevated above the long term mean.

Of interest, observations over the past decade show that the actual rise of greenhouse gasses is exceeding all of these projections made about a decade ago. At present there appear to be few global human forces poised to reduce this rate of rise.

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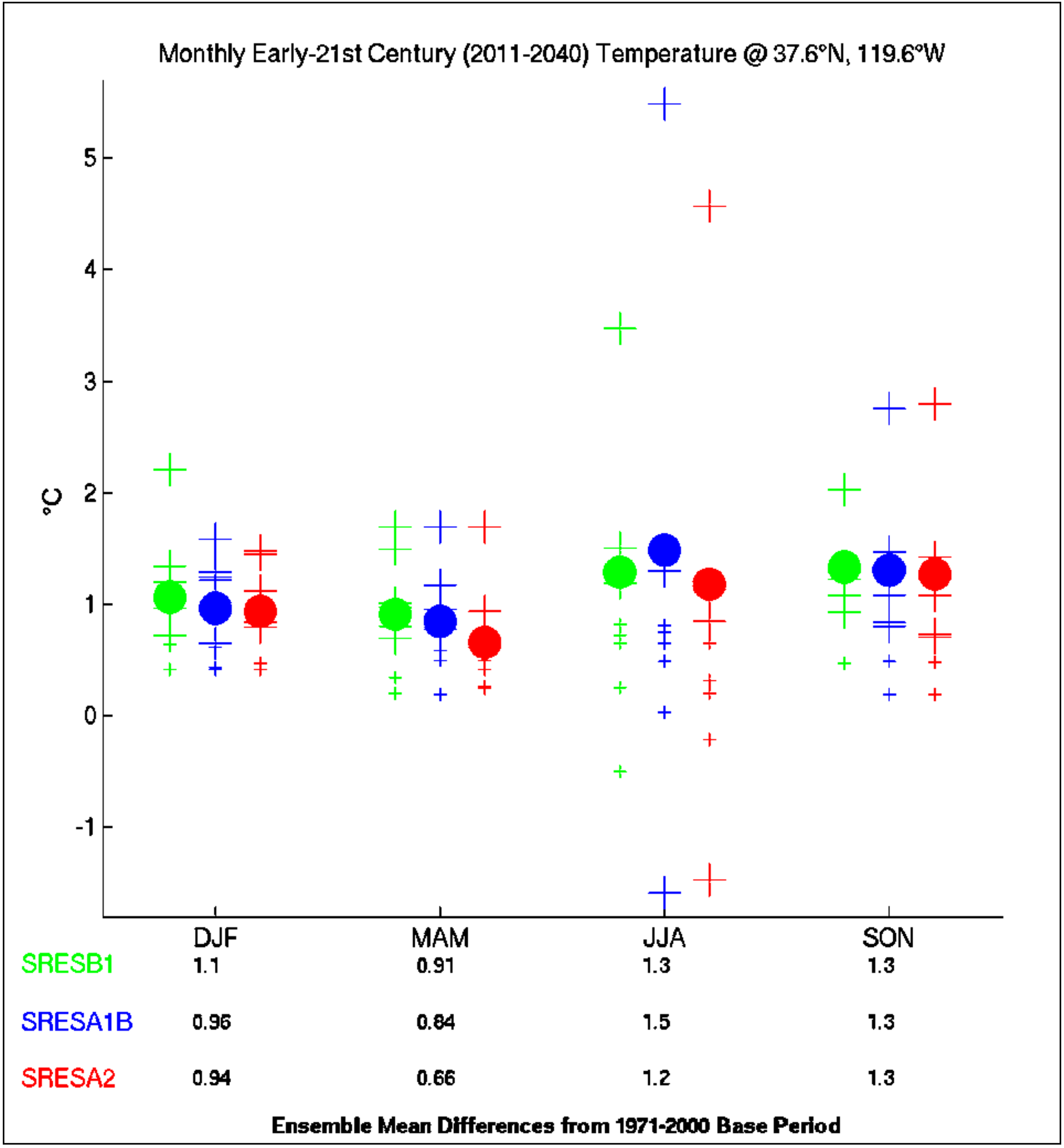


Figure 18. Seasonal temperature changes, all models, near Yosemite, 21st century. Distribution of temperature changes from eight different climate models, relative to 1971-2000 reference period, in degrees C. Location 37.5 N, 119.5 N, near Yosemite. Early 21st century, 2011-2040. Colors represent the three future emission scenarios. *Prepared by John Abatzoglou.*

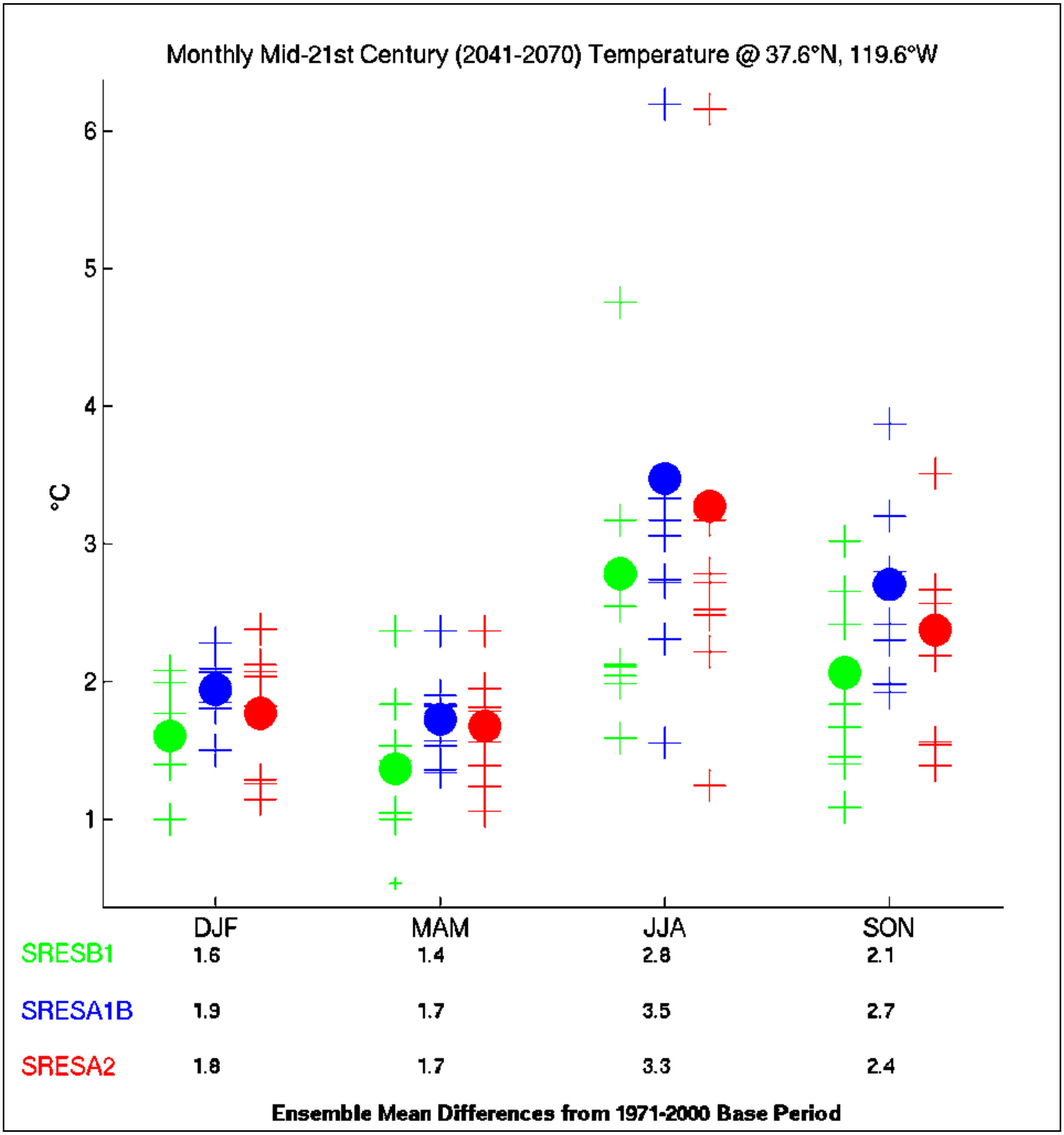


Figure 18. Seasonal temperature changes, all models, near Yosemite, 21st century. Distribution of temperature changes from eight different climate models, relative to 1971-2000 reference period, in degrees C. Location 37.5 N, 119.5 N, near Yosemite. Mid 21st century, 2041-2070. Colors represent the three future emission scenarios. *Prepared by John Abatzoglou* (continued).

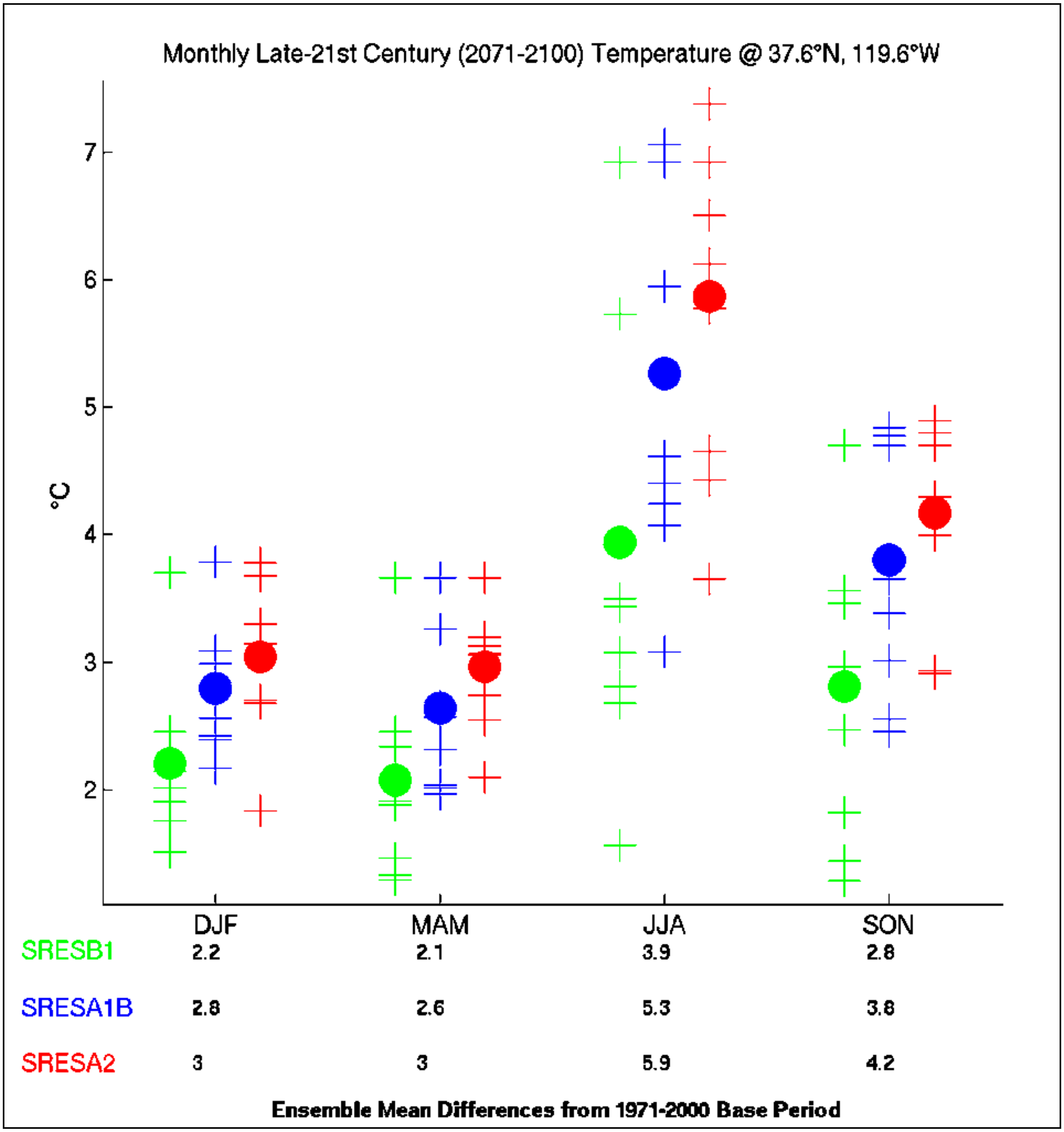


Figure 18. Seasonal temperature changes, all models, near Yosemite, 21st century. Distribution of temperature changes from eight different climate models, relative to 1971-2000 reference period, in degrees C. Location 37.5 N, 119.5 N, near Yosemite. Late 21st century, 2071-2100. Colors represent the three future emission scenarios. *Prepared by John Abatzoglou* (continued).

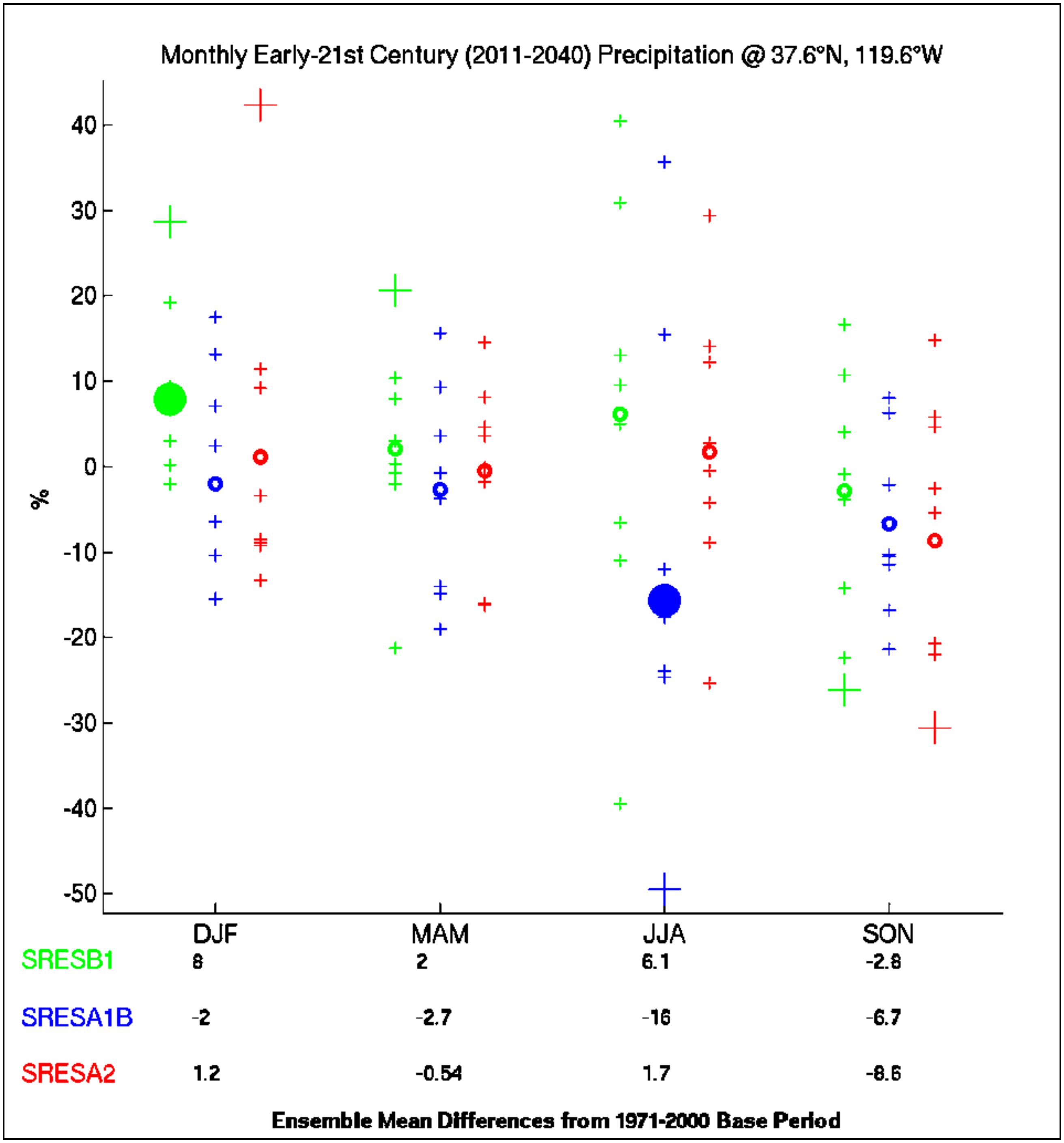
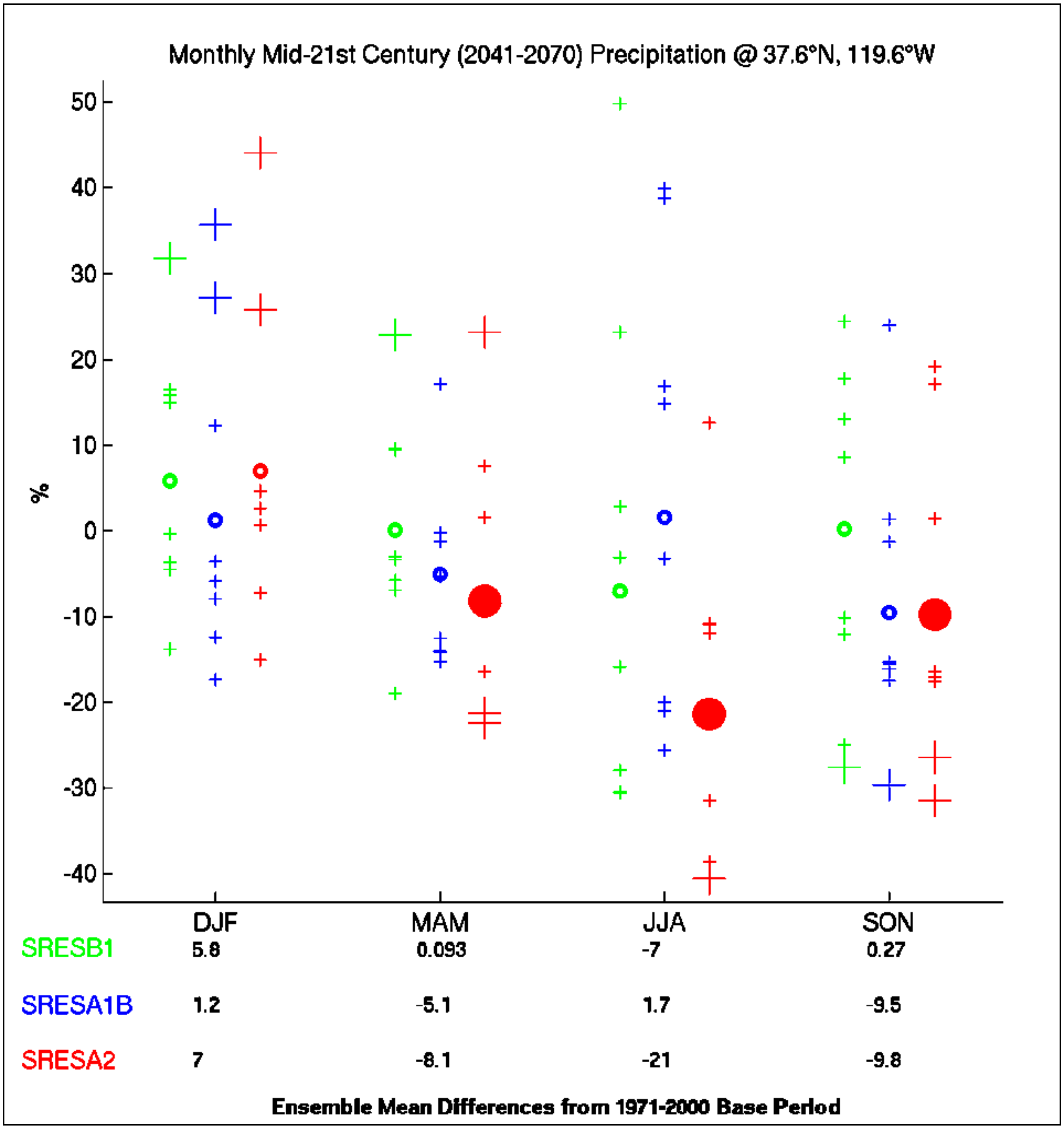


Figure 19. Seasonal precipitation changes, all models, near Yosemite, 21st century. Distribution of precipitation changes (as percent of 1971-2000 base period) from eight different climate models. Location is 37.5 N, 119.5 N, near Yosemite. Early 21st century, 2011-2040. Colors represent three future emissions scenarios. *Prepared by John Abatzoglou.*



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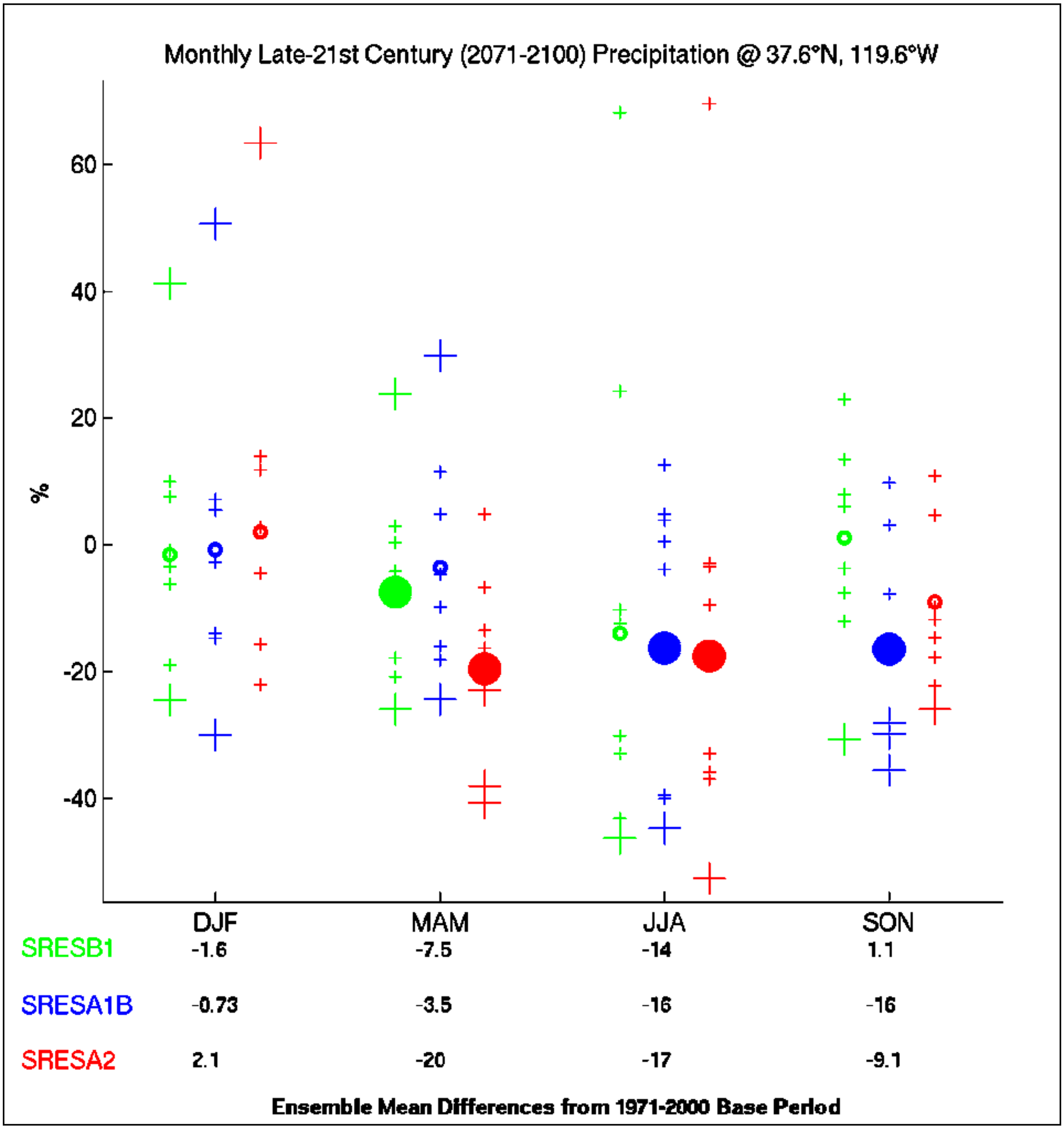

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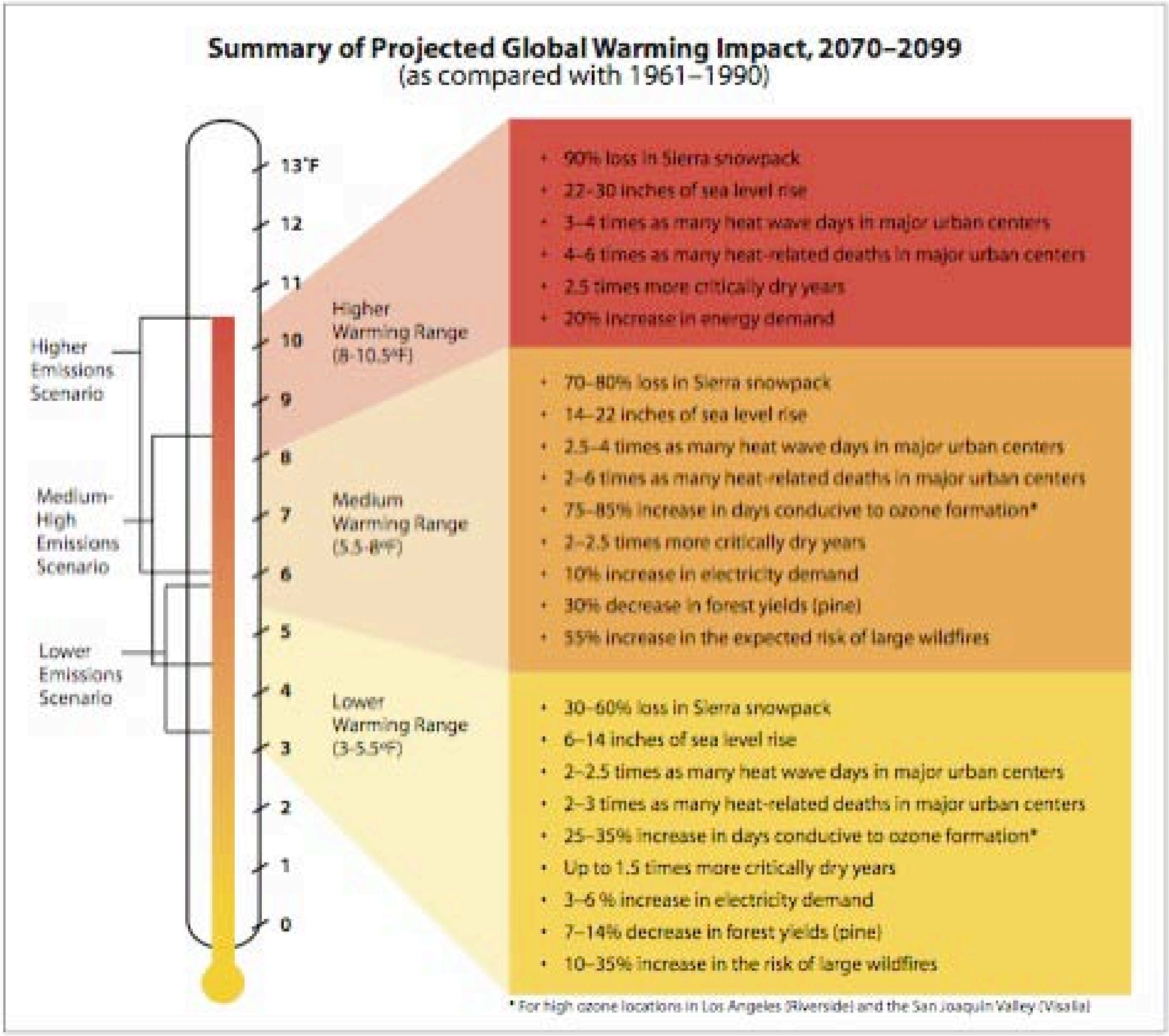
Climate change impacts on the Sierra Nevada Network

A useful summary of climate models and impacts for California has been prepared by the California Energy Commission (CEC 2006) in their report *Our Changing Climate: Assessing the risks to California.* In this document the CEC addresses concerns for agriculture, water supply, energy and other sectors in response to a changing climate. A concluding figure from that summary is presented below (Figure 20).



Summary of Projected Global Warming Impact, 2070–2099
(as compared with 1961–1990)

- 90% loss in Sierra snowpack
- 22-30 inches of sea level rise
- 3–4 times as many heat wave days in major urban centers
- 4–6 times as many heat-related deaths in major urban centers
- 2.5 times more critically dry years
- 20% increase in energy demand

- 70–80% loss in Sierra snowpack
- 14–22 inches of sea level rise
- 2.5–4 times as many heat wave days in major urban centers
- 2–6 times as many heat-related deaths in major urban centers
- 75–85% increase in days conducive to ozone formation*
- 2–2.5 times more critically dry years
- 10% increase in electricity demand
- 30% decrease in forest yields (pine)
- 55% increase in the expected risk of large wildfires

- 30–60% loss in Sierra snowpack
- 6–14 inches of sea level rise
- 2–2.5 times as many heat wave days in major urban centers
- 2–3 times as many heat-related deaths in major urban centers
- 25–35% increase in days conducive to ozone formation*
- Up to 1.5 times more critically dry years
- 3–6 % increase in electricity demand
- 7–14% decrease in forest yields (pine)
- 10–35% increase in the risk of large wildfires

* For high ozone locations in Los Angeles (Riverside) and the San Joaquin Valley (Visalia)

Figure 20. Summary of global warming impacts on California. Based on 3 SRES emissions scenarios, by the end of the 21st century (CEC 2006).

In addition, a number of research papers in recent years have been devoted primarily to mountain climates in the western US, and the SIEN in particular. There appears to be a consensus among climate models that there has been, and will continue to be, a rise in temperature in the Sierra Nevada throughout the 21st century of about +2.4 degrees C (Dettinger 2005, Dettinger et al. 2004). Changes in precipitation amount aren't as clear in California (Dettinger 2005, Dettinger et al. 2004, Seager et al. 2007). Starting with these model results as a basis, others have investigated and modeled the change in snowpack (Mote et al. 2005, Mote 2006, Knowles and Cayan 2004), runoff amount and timing, and fraction of precipitation that falls as rain vs. snow (Knowles et al. 2006).

Mote et al. (2005) describe reductions in snowpack in response to a warming climate throughout many regions of the western US. This has potential impacts on the ecology and hydrology of the SIEN region. Mote et al. (2005) use April 1 snow water equivalent (SWE) as an indicator for maximum snowpack. Figure 21 shows a spatial analysis of their results, both from the observations and from the Variable Infiltration Capacity (VIC) hydrologic model.

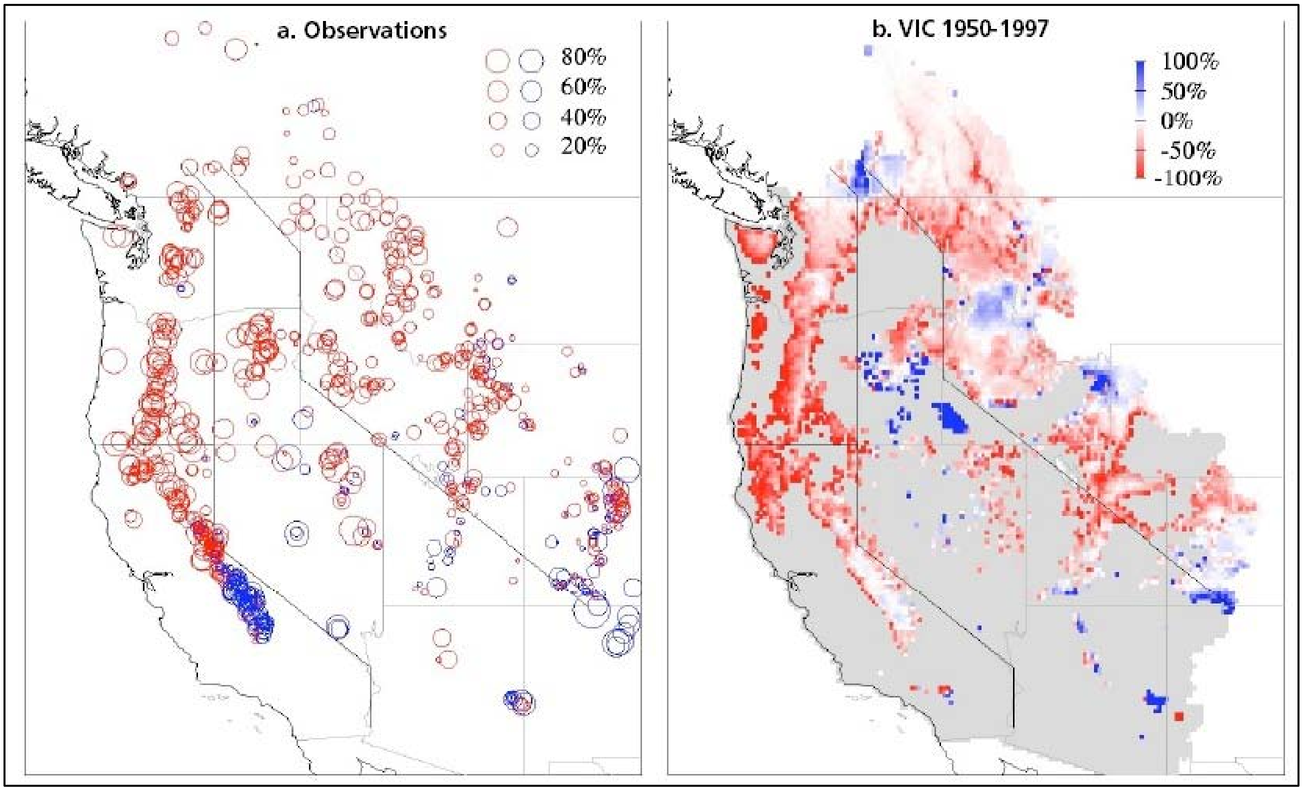


Figure 21. Linear trends in Spring snowpack from models and observations. Linear trends in April 1 SWE for 1950-1997, as determined from a) observations and b) VIC hydrologic model. *From Mote et al. 2005.*

Focusing on the Sierra Nevada, Knowles and Cayan (2004) modeled the future possible reduction in snowpack for the 21st century, as shown in Figure 22. They demonstrate that the historical trends found by Mote et al. (2005) above are projected to continue through the end of the century. Given a scenario that has less warming, they predict a 60% reduction in April 1 SWE in 2070-2099 compared to the 1961-1990 period. With a medium warming scenario, an 80% reduction in April 1 SWE (compared to 1961-1990) is projected by the end of the century.

Dettinger et al. (2004) investigated the response of three Sierra Nevada rivers to climate change, including the Merced River in YOSE. Conducting a thorough study by employing the "business as usual" Special Report on Emissions Scenario (SRES), the Parallel Climate Model, and a watershed model, they found that the models performed well in combination. They were able to reproduce annual streamflow, daily streamflow timing and other parameters of interest. One result was that the simulated fraction of April-July streamflow to total annual flow gradually reduces through the end of the 21st century, from about 60% at present day to 40% by 2099 for the Merced River at Happy Isles. In addition, mean monthly streamflow rates indicate that May will continue to have peak mean monthly streamflow, until the last 30 years of the 21st century where this peak is projected to migrate towards April, according to the models they utilized.

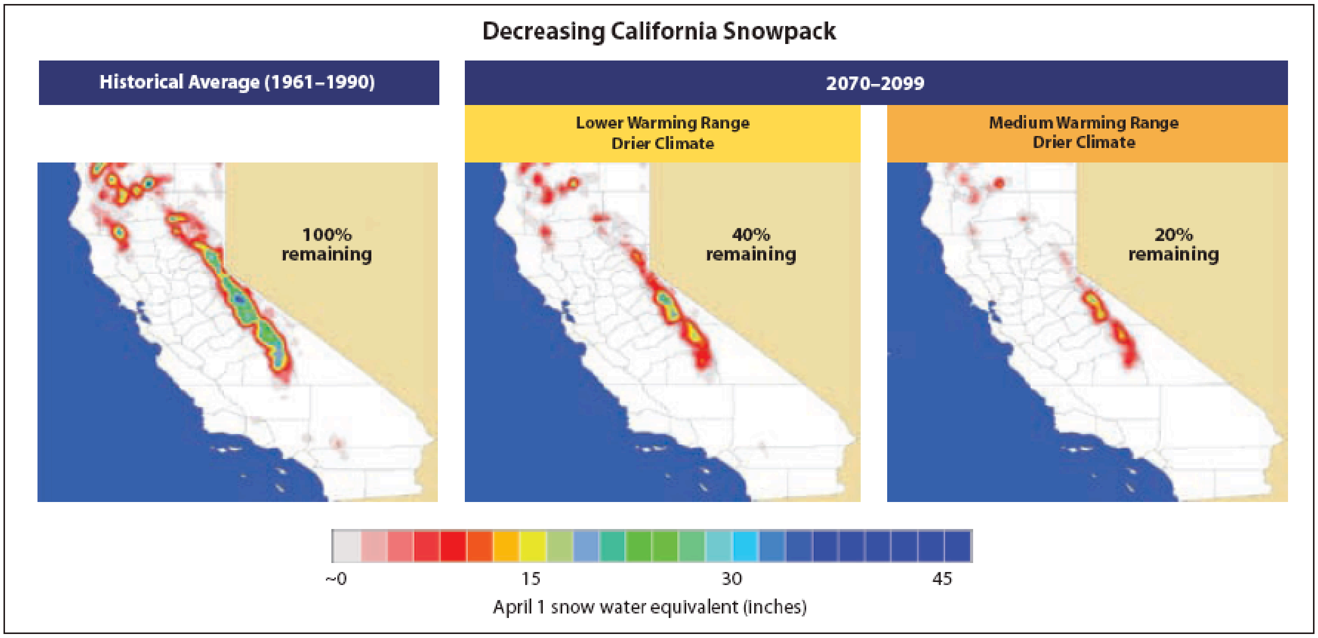


Figure 22. Projected April 1 snowpack reduction in the Sierra Nevada during 21st century. *From CEC 2006; based on and Knowles and Cayan 2004.*

The uneven seasonal warming trends have been well-documented (Diaz and Quayle 1980, Dettinger and Cayan 1995, Cayan et al. 2001, Abatzoglou and Redmond 2007). As an example, we have highlighted one study to illustrate the trend toward earlier spring onset. Stewart et al. (2004) defined the center of mass flow (center timing - CT) as an index of streamflow timing in western US rivers. For the years 1948-2000, a trend towards earlier streamflow was found in most watersheds, and very few with later CT. In the central Sierra Nevada, these historical trends indicated an earlier melt of about 5-10 days earlier for that 52-year period. In addition, they used a climate model to project the future CT for these same watersheds. With just a 1-degree Celsius rise in their temperature index, CT moved significantly earlier, by as much as 12 days or more, than in the historical period. For the San Joaquin River, whose headwaters are in or near SEKI and DEPO, this would mean a change of CT to two weeks earlier than present day, with CT occurring as early as April 1 by the year 2100.

Nonetheless, the climate system exhibits significant variability at the decadal scale. Therefore, even if climate change is under way, lengthy departures from overall trends, with durations of a few years to a decade or more, are expected. As an example, the strong trend toward spring warming was strongly disrupted by a series of very cool late springs and early summers over the last three years (2009-2011).

With warmer temperatures, one might expect more precipitation to fall as rain instead of snow. Knowles et al. (2006) determined that for the period of 1949-2004, winter precipitation reduced slightly in the central Sierra Nevada, but that there is a widespread reduction of snowfall as compared to total precipitation.

Christy and Hnilo (2010) have recently attempted to reconstruct the snowfall record at the NWS Huntington Lake COOP Station from 1916-2009, midway between YOSE and SEKI. For this overall period they found a slight upward trend in mean annual snowfall of +0.5 cm (+0.08%) +/- 13.1 cm/decade about a mean of 624 cm. More recent trends for the 50 years ending 2009 were -3.9 cm/decade (-0.6%), and for the 25 years ending 2009 were +15.9 (+2.6%) cm/decade, against a background of very high variability. None of these were statistically significant. They were likewise similarly unable to discern any statistically significant trends for 1930-2009 for snow courses in the southern Sierra Nevada, including sites within YOSE and SEKI. Essentially, seasonal snowfall in this area has remained relatively constant, within sampling error. Christy (2011 *submitted*) has reached similar conclusions for the state of California as a whole.

Lundquist et al. (2004) have also investigated the response of various elevations to snowmelt, and the differences between synchronous and non-synchronous years. Synchronous years are those where snow melts at all elevations at the same time, and non-synchronous years are those in which melt occurs at different elevations at different times. The apparent indicator is spring storm activity in March. When there is little or no storm activity, spring melt occurs gradually, and is dependent on elevation and aspect. But with a more active storm pattern, especially following warmer than average winters and cooler than average March temperatures, synchronous melt can occur at nearly all elevations.

Fluvial periods (non-drought, or wet) will also continue in the SIEN’s future climate. But climate models predict that the extremes will be worse, with drier and longer droughts and bigger, more devastating floods. NPS managers should be aware and consider consequences of extended drought, which remains elusive to forecast in the long term. Recent years (2004-2006) demonstrate the wild fluctuations in precipitation and temperature that are possible in the SIEN.

II. Data: Existing Climate and Hydroclimate Monitoring Networks

A recent inventory by Davey et al. (2007) identified 49 climate stations then active within park boundaries in the SIEN, and 98 stations that have been active at some time within park boundaries, with the longest recording stations dating to the early 1900s. For this report, we initially consider stations with daily data, and that are currently active with at least 30 years of record (with some exceptions to cover unique locations), to assess the long-term climate trends of the 4 park units within SIEN. We also consider stations with hourly data, which generally have shorter (often, much shorter) records and fewer quality checking procedures. We show one example from each network in this section, and more thorough descriptions of individual sites in the next section.

Networks Operating Weather Stations in SIEN Parks

National Weather Service Cooperative Observer Program (COOP) Stations

This network records once daily precipitation, maximum temperature and minimum temperature. Precipitation by definition includes both liquid and frozen types, and all measurements are made manually by a human observer. Observers who participate in this network are primarily unpaid volunteers; in the SIEN parks the primary observers are park rangers or dispatch staff who typically collect the data at the beginning of their work day, first thing in the morning. An example of some of the equipment used at a COOP site is shown in Figure 23. The data from this network are collected by NWS and archived at the National Climatic Data Center (NCDC) and WRCC.

Figure 23. Yosemite south entrance COOP site. With 8" diameter rain gauge (left item in image with yellow funnel top) and maximum/minimum temperature system sensor (MMTS, on taller post). Looking toward west, 2006 October 4. *Photo by Kelly Redmond.*

NOAA Climate Reference Network (CRN) Stations

In 2007, a new Climate Reference Network (CRN) station was installed at Crane Flat Lookout, near the RAWS location (Figure 24). The CRN is owned and operated by NOAA, with data archived at NCDC. The establishment of this site in the SIEN is significant because of the great lengths the CRN has gone to in order to create a multi-decade (50 or more years) stable network of high quality climate observing stations. The CRN consists of about 120 sites nationwide, with seven in California, putting the site at Crane Flat Lookout among an elite group; CRN locations go through an extensive siting procedure to select the best quality locations. An agreement is created with the site host (here, NPS) to minimize human disturbance to the site, with the exception of maintaining vegetation to avoid changing its influence on the instrumentation (i.e., maintaining open exposure for instrumentation, and not allowing vegetation to grow into or near sensors, but making allowances for fire or other natural disturbances to remove ground cover). In addition, the CRN provides regular annual maintenance at each station, to calibrate instrumentation, ensure data quality and a complete observational record, minimizing any disruptions in communications.

Figure 24. CRN temperature tower at Crane Flat. A portion of the CRN site suite of instruments at Crane Flat Lookout (CRN station name Yosemite Village 12 W), winter 2006-07. This photograph includes temperature sensors, pyranometer (solar radiation), wind speed gauge, communication equipment, and data logger. Other equipment at the site includes an all-weather rain gauge with a wind shield. Heliport area is above in background. *NPS photo*.

Remote Automated Weather Stations (RAWS)

Remote Automated Weather Stations (RAWS) record and transmit data on an hourly basis. Station owners and operators include NPS, Bureau of Land Management (BLM), US Forest Service, California Department of Forestry, and many others. Data are received continuously and archived at WRCC through an arrangement with the National Interagency Fire Center (NIFC) in Boise, ID, where all stations are transmitted for immediate access and viewing. Although the original purpose for this network was for fire weather information, RAWS have existed for as long as 25 years or more in some locations, rendering them useful for climate studies. In general, most operators maintain good equipment and siting, although quality varies among station operators. Though records are shorter, data from these locations provide valuable local detail, and are used in conjunction with the COOP data in this study to assess trends in climate. An example of the station at Mariposa Grove in Yosemite is shown in Figure 25.

Figure 25. Mariposa Grove RAWS station, Yosemite National Park. *Photo by Greg McCurdy.*

California Department of Water Resources (CDWR) Stations

California's Department of Water Resources (CDWR) operates a number of snow survey sites in and around the SIEN. There are both automated sites (Figure 26 and 27) and manual observing sites (Figure 28). At the manual sites, called snow courses, observers visit the site once a month in the winter season (usually at the beginning of the month) to measure snow depth and snow water equivalent (i.e., water content of the melted snow). Automated sites are equipped to perform these measurements without human intervention, typically once per hour, and are often augmented with air temperature sensors. CDWR is also in the process of adding soil moisture sensors at many of their sites. CDWR automated sites have one-way satellite communications to relay data to California Data Exchange Center (CDEC) on a regular basis, where they are publicly available. WRCC continuously pulls these into its archived database via CDEC.

Figure 26. Portion of CDWR Gin Flat automated snow survey site. Shown is portion of the CDWR Gin Flat automated snow survey site, which includes a tower of meteorological instruments. Small tower on right measures temperature every half hour at six inch intervals within snowpack. *Photo by Mike Anderson.*

Figure 27. Farewell Gap, a DWR automated snow survey site in SEKI. *Photo courtesy of Frank Gehrke.*

Figure 28. DWR manual snow course site at YOSE Gin Flat in summer. *Photo by Mike Anderson.*

Other Networks and Stations

Data from unique stations have also been collected. The two most complete records of interest include stations located at Tuolumne Meadows and Valentine Eastern Sierra (UC) Reserve. Tuolumne Meadows records consist of daily max/min temperature, precipitation, snowfall, and snow depth taken by NPS rangers. The unique feature of this record is that it includes manual data during the winter season when Tioga Pass is closed to vehicular access. Park rangers winter over at the ranger station, and take daily weather observations among their duties. The data from Tuolumne Meadows include a hybrid of digitized data from another researcher doing work at YOSE (J. Lundquist, University of Washington) and paper forms that WRCC received separately from a private citizen. Climate records (hourly temperature and precipitation) were also obtained for Emerald Lake and Topaz Lake in SEKI from Michael Colee at University of California, Santa Barbara (UCSB).

A new meteorological station was installed at DEPO in 2005. This was a cooperative effort with Devils Postpile National Monument, Sierra Nevada Network I&M program, Sequoia and Kings Canyon National Parks, California DWR, Scripps Institution of Oceanography's Climate Research Division, U.S. Geological Survey, and California Energy Commission (Figure 29). This station is located near an old Remote Automated Weather Station (RAWS) site, the visitor center, and the San Joaquin River, and is highlighted at DEPO with an interpretive panel. Data are uploaded real-time to CDEC via Geostationary Operational Environmental Satellite (GOES), and Scripps has an archive as well. SIEN reported the installation, sensor array, and data access methods in detail (Balmat and Scott 2010).

A RAWS station operated from 1993-2004 on US Forest Service land in this vicinity (along the ridge in the background of the photo, but more to the left and outside of the photo of the DEPO site).

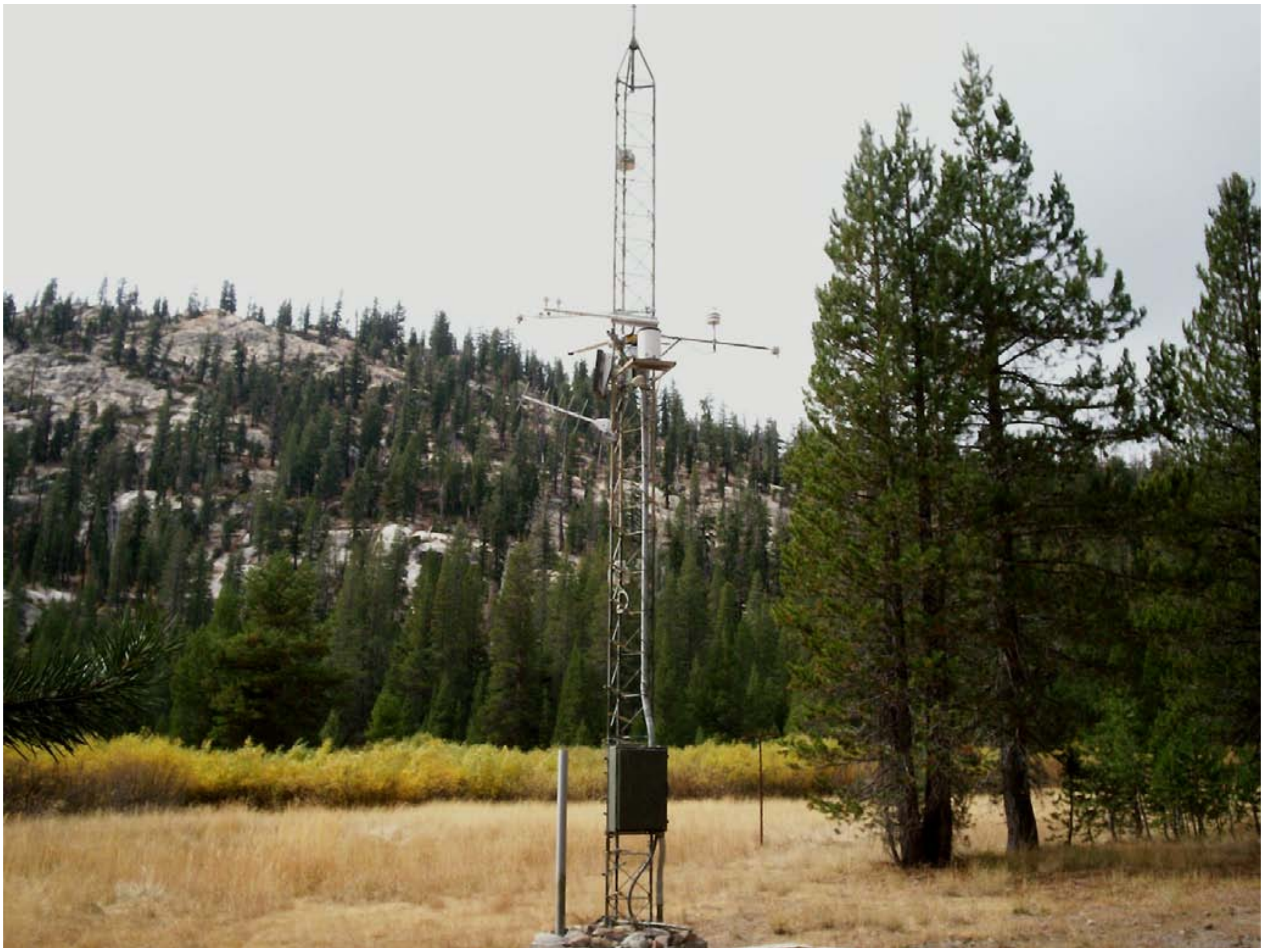


Figure 29. Climate observing station installed in DEPO in 2006.

The Valentine Eastern Sierra Reserve is operated by the Sierra Nevada Aquatic Research Laboratory (SNARL) and the University of California. The SNARL dataset is sub-daily, and has since been posted online at the Western Regional Climate Center (http://www.wrcc.dri.edu/cgi-bin/rawMAIN.pl?cavesr). SNARL data include solar radiation, wind direction and speed, temperature, relative humidity and precipitation, reported hourly since 1987.

Methods

For this report, monthly data are utilized because it is the temporal resolution that provides the longest period of record, and simplifies the analysis. Daily data (i.e., COOP) are summarized into monthly averages (temperature) and totals (precipitation). Data that are reported at sub-daily intervals (i.e., RAWS) are summarized to daily values and then to monthly. Stations with complete records (no missing data) are preferred, but in practice are nearly impossible to obtain. Therefore, an estimation method is used to fill in data gaps, using a regression analysis of nearby stations. This method is described in the Data and Analysis section.

Maps of stations in a number of networks in and near the SIEN are included below in Figure 30 and Figure 31. These figures do not distinguish between stations that are presently in operation and those that have been decommissioned. It is important to document all stations as retired stations can provide data for trend analyses and climate modeling. The SIEN maintains a list of all past and present stations with metadata, including the operator and dates of operation; contact SIEN staff for further information (http://science.nature.nps.gov/im/units/sien/monitoring/Climate/Climate.cfm). A list of stations in the metadata database at WRCC is included in Appendix B. In these figures we have had to make use in some cases of station lists prepared elsewhere, particularly by NOAA at NCDC. The NCDC metadata listings for the NWS Cooperative network sometimes include stations that were tracked in prior decades (but no longer are), and that did not provide data to NOAA. Thus, even though data may have been gathered, and stored (somewhere), these records are not necessarily available from NCDC or from WRCC. We have tried to remove these stations from the "within-park" lists, but have not done this for the much larger number of "outside-park" stations. The checking process is rather laborious, and two or three semi-independent sources must be consulted. In some cases we can check WRCC data archives as well, to verify the lack of any data records. Sometimes, the measurements from stations listed by NCDC as having operated at some time in the past 50-100 years were never actually taken, or were taken and stored by another agency and are now difficult to locate or access. In general, our preference is to mention data for which there is at least some prospect of obtaining, but this itself can often be very difficult to ascertain, even for those with much expertise and access to many sources of climate data.

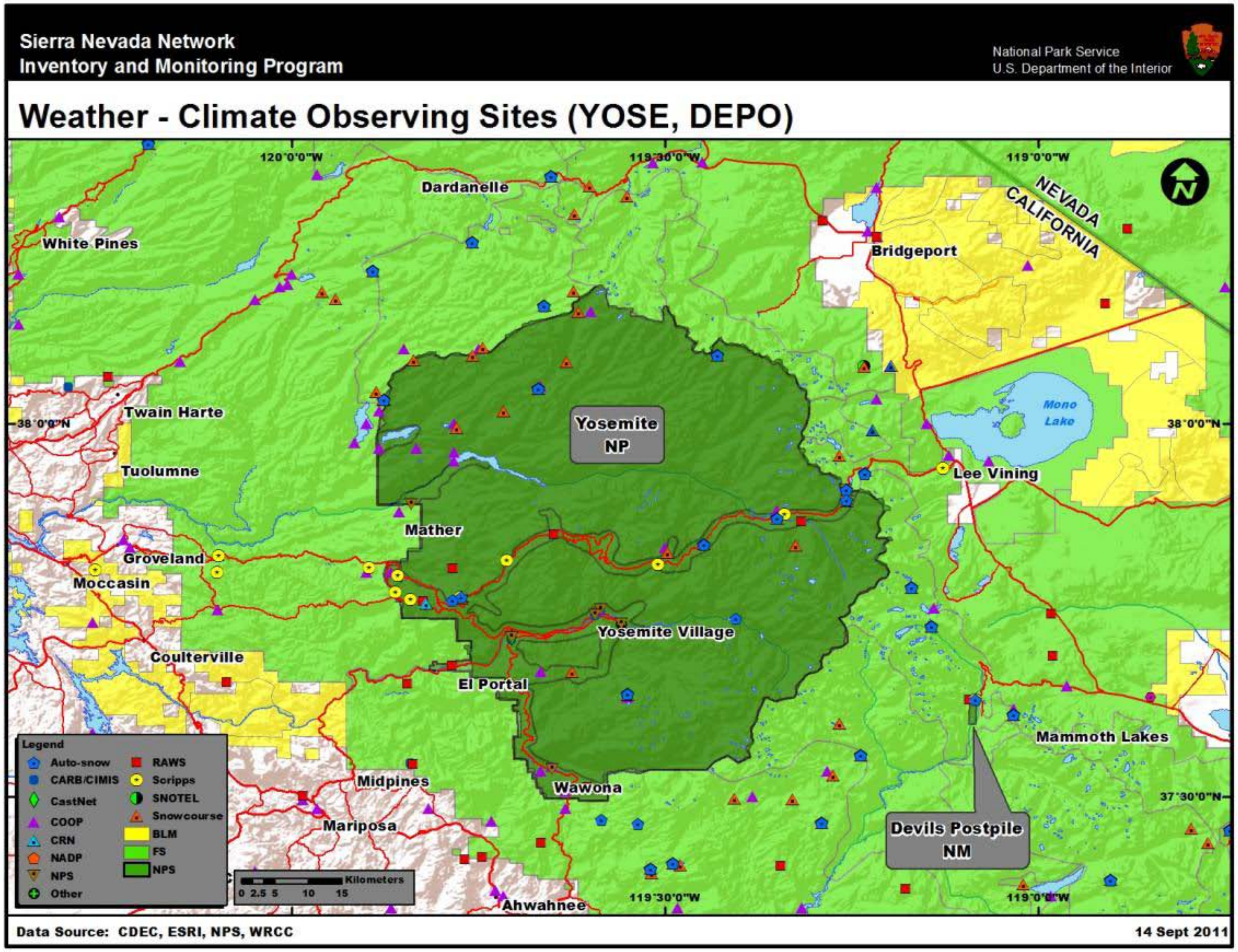


Figure 30. Existing and retired climate observing sites in the YOSE and DEPO park units. Note: This figure does not distinguish between past and presently operating stations; many stations displayed are no longer in operation. *Graphic prepared by David Simeral.*

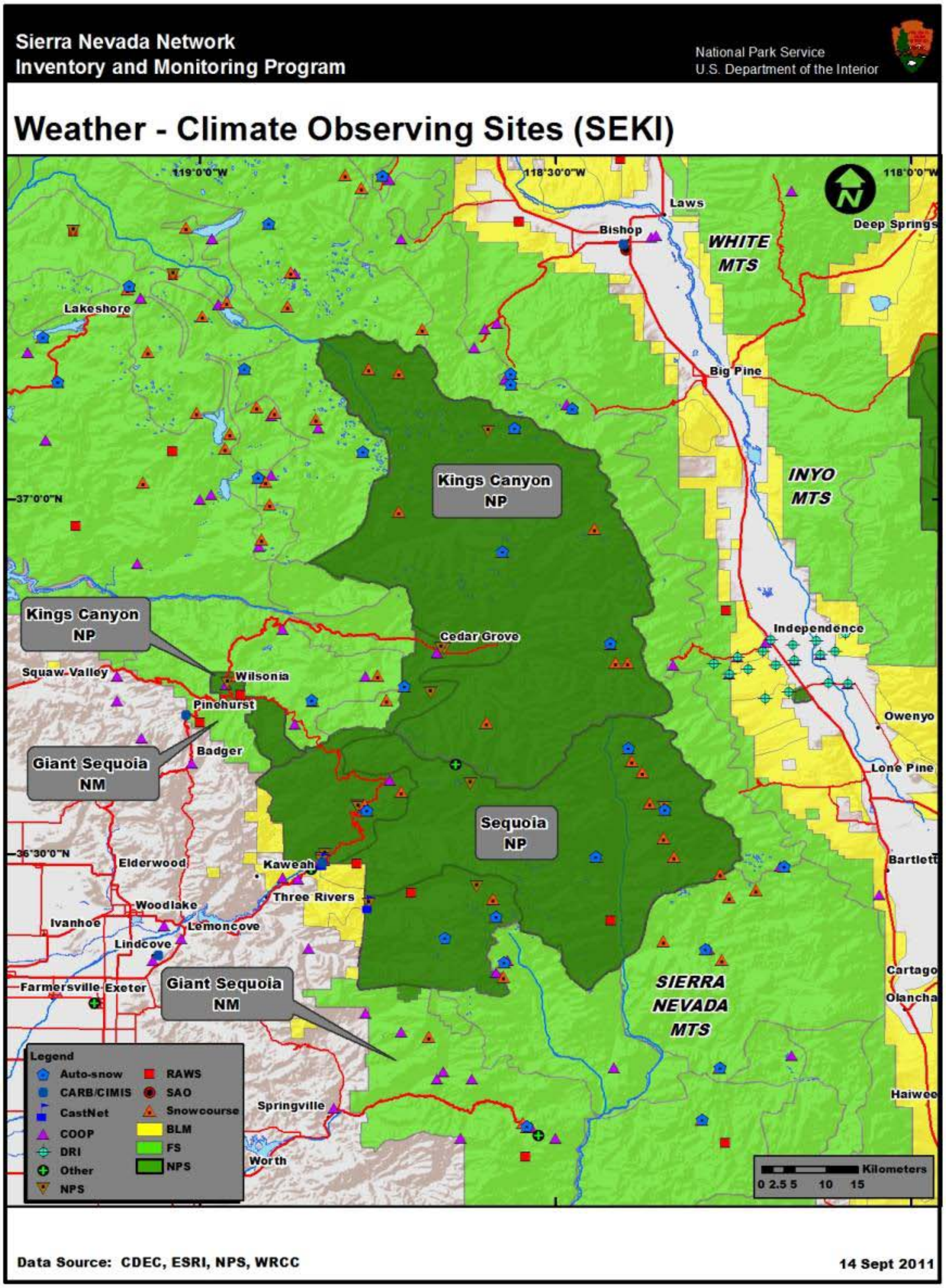


Figure 31. Existing and retired climate observing sites in and near SEKI. Note: This figure does not distinguish between past and presently operating stations; many stations displayed are no longer in operation. *Graphic prepared by David Simeral.*

Observations of climatic trends using Reanalysis data

Temporal trends at higher elevations

Gridded values of atmospheric temperature from 1948 onward have been reanalyzed by the National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR). The Reanalysis product incorporates available observational records (e.g., surface, radiosonde, aircraft observations). It employs a fixed data assimilation and model over the period of record to derive dynamically consistent fields of atmospheric and land surface variables. This NCEP-NCAR Global Reanalysis ("Reanalysis", Kalnay et al. 1996) is available on a global 2.5-degree grid at 6-hour intervals. We have used this data set to develop information on temporal trends at higher elevations for the SIEN region, using a grid value at 37.5 N latitude, 120 W longitude, near the town of Mariposa. This location is used in all of the graphs in this section.

Information from the Reanalysis are more representative of "free atmosphere" conditions, since the primary inputs are from weather balloon, aircraft, and satellite observations, and surface pressure data. Almost no surface information is incorporated. Thus, in many ways this is a separate data set almost independent of the surface data. Also, because near-surface processes affect temperature, humidity, and wind flow, and because there is considerable spatial variability in topographically diverse terrain, the values measured at any particular location on the surface will usually not be the same as those averaged over a 2.5 degree grid (111 x 88 km, or 70 x 56 mi). What *is* expected is that the variations in time will be approximately similar, even if the fluctuations are about a different average. There has not been sufficient validation of Reanalysis data in complex terrain to establish the accuracy of this assumption.

Seasonal trends and variability at the 10,000 ft elevation are depicted in Figure 32. The 10,000 ft level was chosen because it is very close to the 700 hPa (millibar) pressure level in the atmosphere, a commonly available atmospheric data set, and because this is approximately the elevation of passes in the High Sierra (Tioga Pass is at 9943 ft, 3030 m), where much of the snowpack is found. As is seen throughout much of the West (Abatzoglou and Redmond 2007), increasing temperature trends in spring are of the greatest magnitude, mostly beginning in about the mid 1970s (Figure 32). Summer has displayed relatively little trend, until recently, when a spate of warm summers began around 2000. Winter has some trend, and autumn shows almost no long-term rise in temperature.

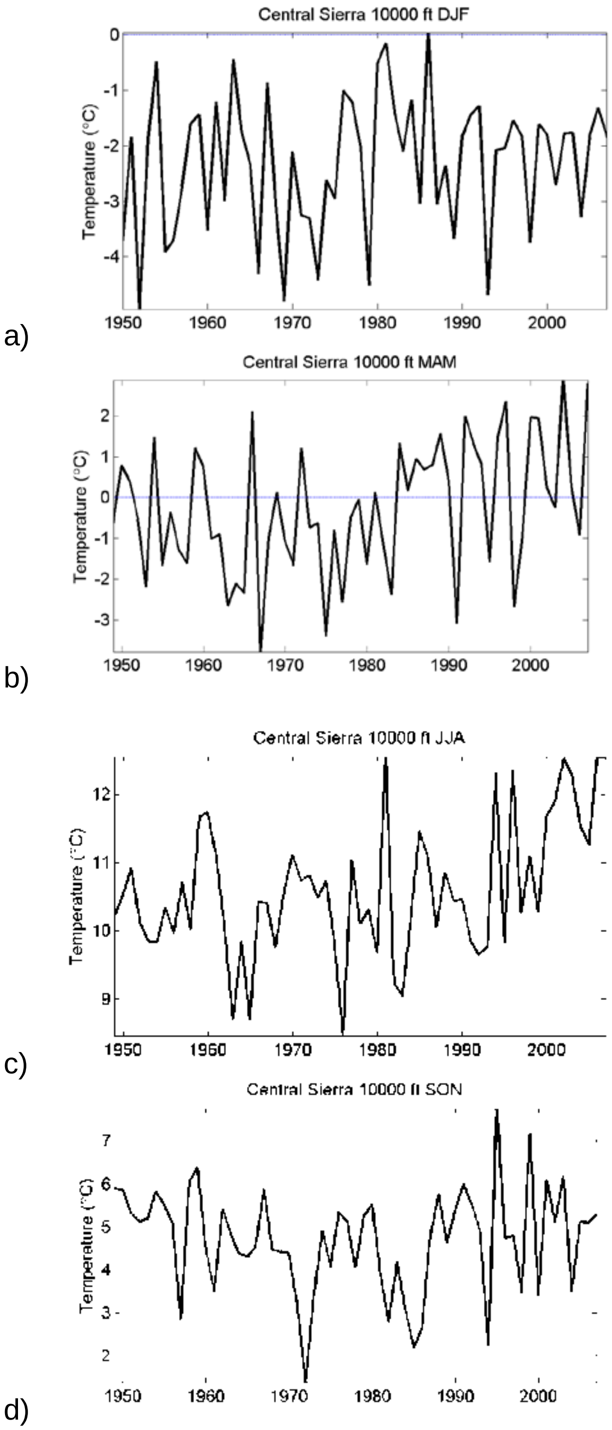


Figure 32. Seasonal Sierra Nevada temperature trends and variability, 10,000 ft (3000 m). Values from NCEP/NCAR Reanalysis, 1948-2007: a) Winter, b) Spring, c) Summer, d) Autumn. *Figures by John Abatzoglou.*

Mean annual temperatures at the 10,000 ft level began an unsteady rise around the middle 1970s (Figure 33). Furthermore, it is quite evident that starting in 2000, the last eight years in this sequence behave very differently from the other years. All of these years are unusually warm, and the average over the last seven years is clearly unlike any other 7-year average period since 1950. The total rise in temperature over the past 30 years has been about 1.2 C (2.2 F).

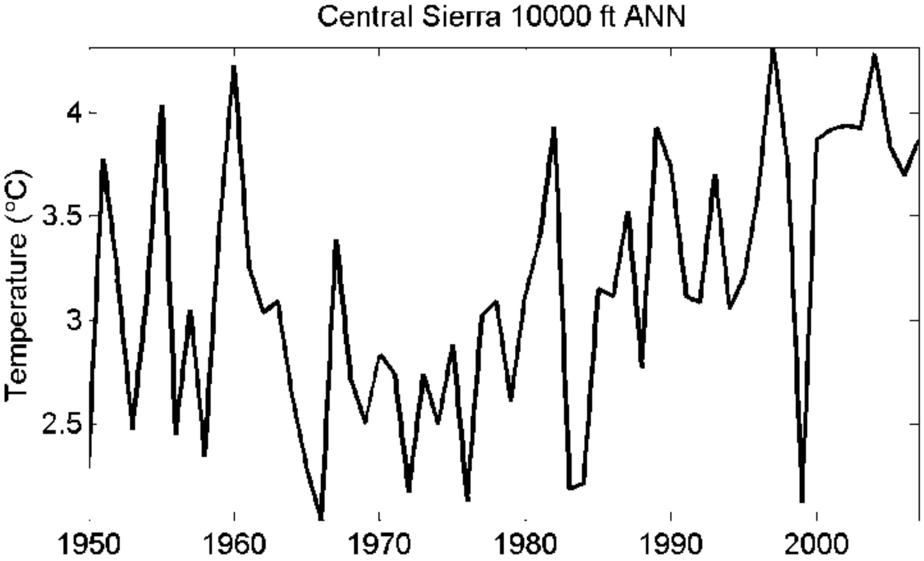


Figure 33. Annual variability and trend of temperature at 10,000 ft (3000 m) over Mariposa. Utilizes the grid point centered near Mariposa CA, taken from NCEP Global Reanalysis. *Figure by John Abatzoglou.*

Figure 34 shows the linear trends from data taken from 1958 through November 2007, by month, as a function of elevation. Reanalysis temperature estimates are somewhat more reliable during this period, as compared to the earlier years of 1949-1957. In 1958, a modernized network was used for data assimilated into the Reanalysis. Colors are proportional to the magnitude of the trend. Cooling is observed in only a few elevation bands and in just three of the months (February, October, and December), and all cooling trends are quite small. Much larger warming trends are noted, and in general, warming trends are somewhat larger at higher altitudes. Warming trends are especially notable in the spring and early summer (March through July) and in November, with lesser warming in August and September. March has been warming the most, followed closely by May. There is an indication that the greatest temperature trends are found at those elevations where the snow contribution to runoff is greatest, from about 6,000-12,000 feet (1800-3700 m).

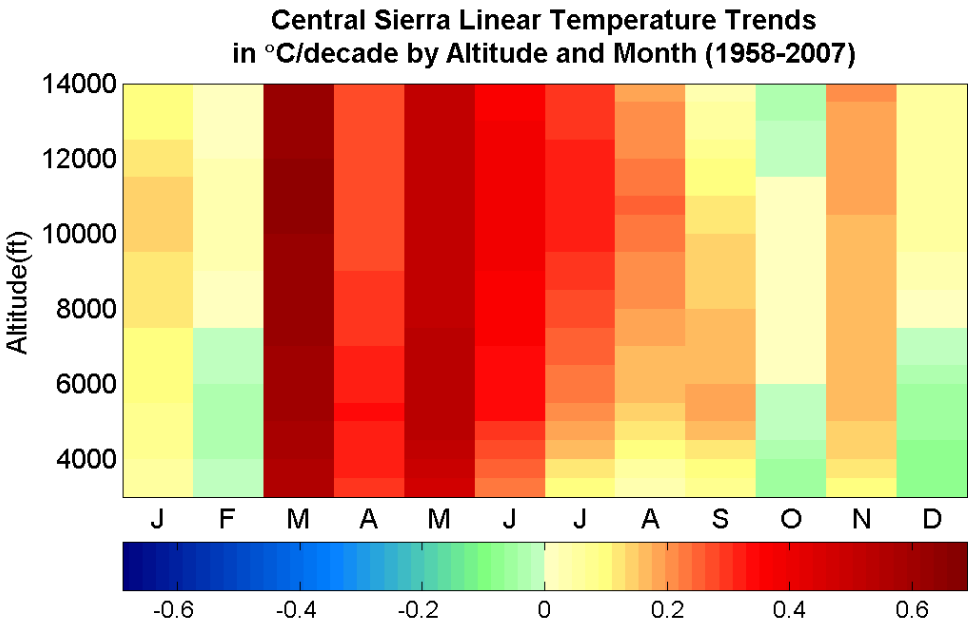


Figure 34. Trends by month for 1958-2007 as a function of elevation over Mariposa. Values (in degrees C per decade) obtained from NCEP Global Reanalysis grid point centered near Mariposa CA. *Figure by John Abatzoglou.*

Temperature trends are summarized for the last 50 years in Figure 35 and 36. In spring and summer, statistically significant trends are seen at most elevations. There is not a great deal of variation in trend magnitude with elevation, but generally the largest trends are found at higher altitudes. Consistent with the global temperature record, we note that this warming has been most pronounced over the last four decades, with trends of about 0.30-0.35 C per decade since 1970.

Temperature histories can be stratified and conditioned on the occurrence or non-occurrence of precipitation. Figure 37 shows that 5000 ft (1600 m) appears to be a particularly sensitive elevation for the type of precipitation (rain versus snow). By this it is meant that, at this elevation, there has been a noticeable drop in the percentage of the total annual precipitation that falls when daily mean free-atmospheric temperatures are below 0 C. In other words, more of the precipitation at this elevation has been rain in the past 1-2 decades rather than snow, compared with earlier decades. For the entire SIEN area at the 4000 ft (1200 m) level, including the floor of Yosemite Valley, over the past decade there has been a period of sustained low ratios, and very little of the total annual precipitation has fallen as snow.

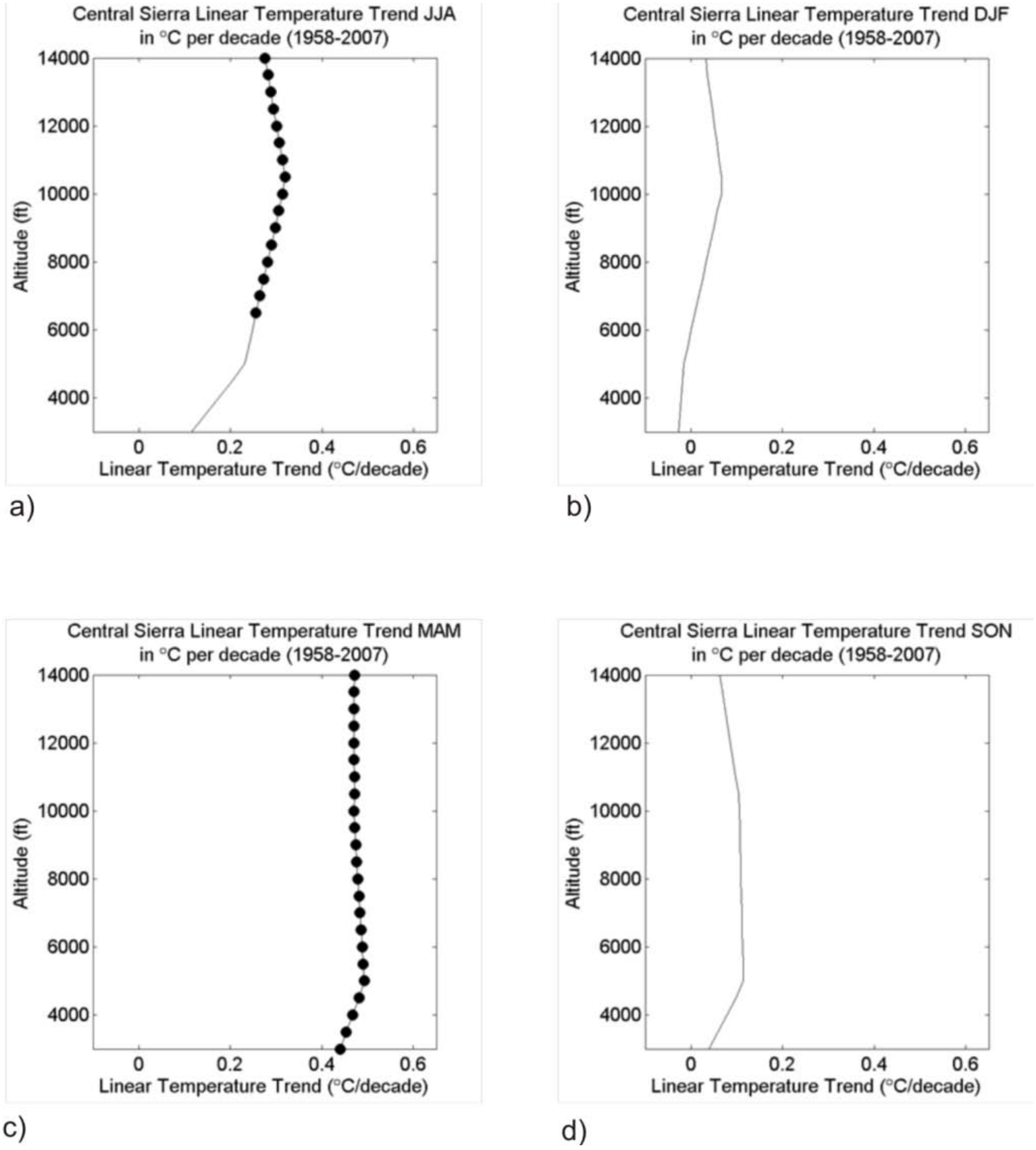


Figure 35. Temperature trends by elevation and season near Yosemite, 1958-2007. Temperature trends for south central Sierra Nevada, altitude range 3000 to 14000 ft, from Global Reanalysis, for (a) Winter, (b) Spring, (c) Summer, and (d) Autumn conditions. A dotted line indicates significance at the 95% confidence level. Figure by John Abatzoglou.

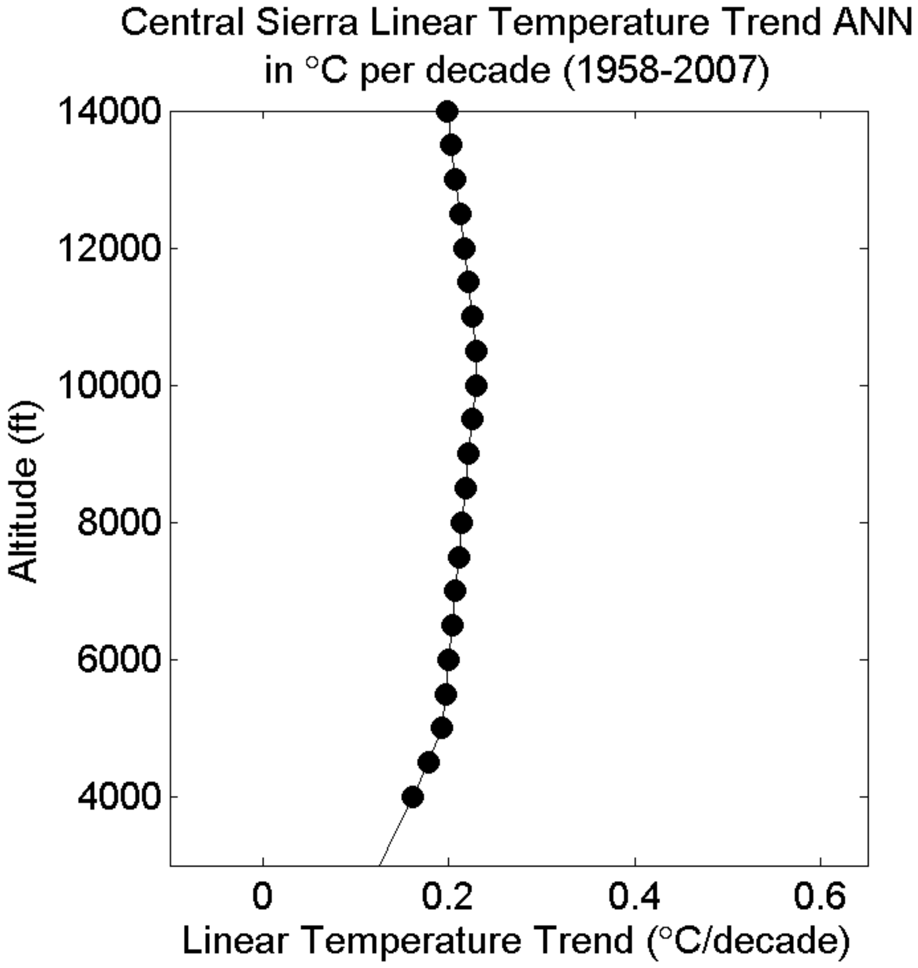


Figure 36. Temperature trends for south central Sierra Nevada, altitude range 3000 to 14000 ft, from Global Reanalysis, for annual conditions. A dotted line indicates significance at the 95% confidence level. Same as previous figure, for annual trend. *Figure by John Abatzoglou.*

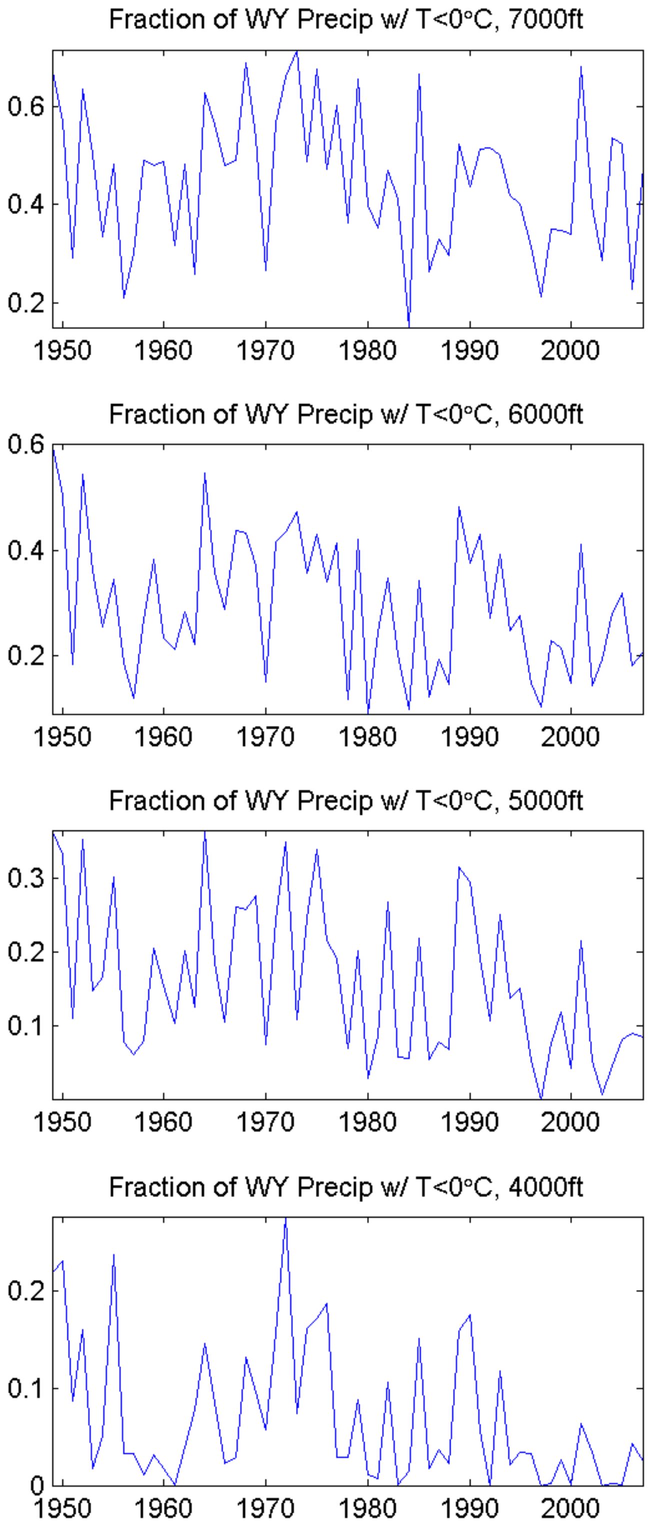


Figure 37. Time history of rain versus snow at different elevations over Yosemite. Figure shows the fraction of the annual water year (Oct-Sept) precipitation that has fallen while the temperature is below 0^{o}C at the indicated elevation, for each water year from 1950 to 2007. Smaller values are indicative of warmer conditions. *Figure by John Abatzoglou.*

Atmospheric freezing levels

The elevation in the atmosphere at which freezing temperatures are found is an important metric of hydroclimate. The snow level usually extends somewhat below the freezing level. The freezing level can be defined as a fixed elevation under normal atmospheric conditions whereby temperature decreases with height (as is generally the case during precipitation events). However, under isothermal (temperature nearly constant with height) or inversion conditions there can be an upper and a lower freezing level.

Variability in the mean elevation of the freezing level has a number of hydrological ramifications over mountainous areas. Among these are: 1) the level of the rain/snow line when precipitation is falling, 2) the temperature of the soil surface onto which the first snow in autumn falls (frozen or not, at that elevation), 3) the evolution of snowpack density, depth, and internal temperature structure during winter, 4) sublimation conditions during winter, 5) the readiness for melting when spring temperatures arrive, and 6) the evolution of the melt season.

The seasonal freezing level histories shown in Figure 38 are related to the mean seasonal temperature trends shown in Figure 35-36. The largest trends are in spring, and once again summer shows a distinct rise in freezing level in recent years. On an annual basis, the mean freezing level in the 1950s, about 10,900 ft (3320 m), is about 500-600 feet (150-180 m) lower than the more recent average of about 11,450 ft (3490 m) since the year 2000 (Figure 39). This is likely part of the reason why Sierra Nevada ice glaciers and rock glaciers are observed to be in a state of decline (Basagic 2005, Guyton 1998).

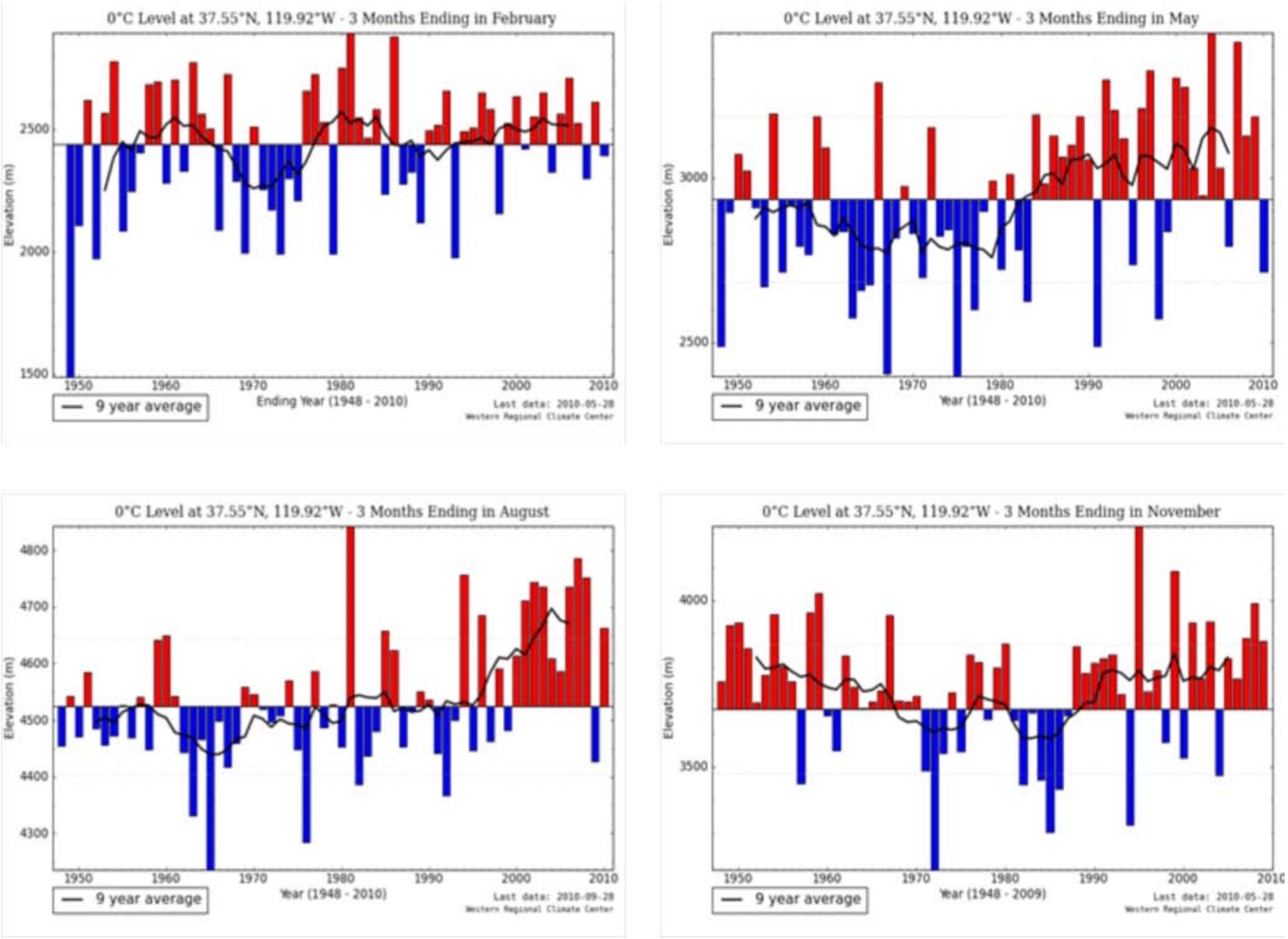


Figure 38. Freezing level time series over Mariposa, by season, 1948-2010. The height of the 0^{o}C isotherm (“freezing level”) in (top) winter, spring, (bottom) summer, autumn. Values in meters above (red, warm) or below (blue, cold) period of record mean (1948-2009). Source: Interactive WRCC North American Freezing Level Tracker at www.wrcc.dri.edu/cwd/products.

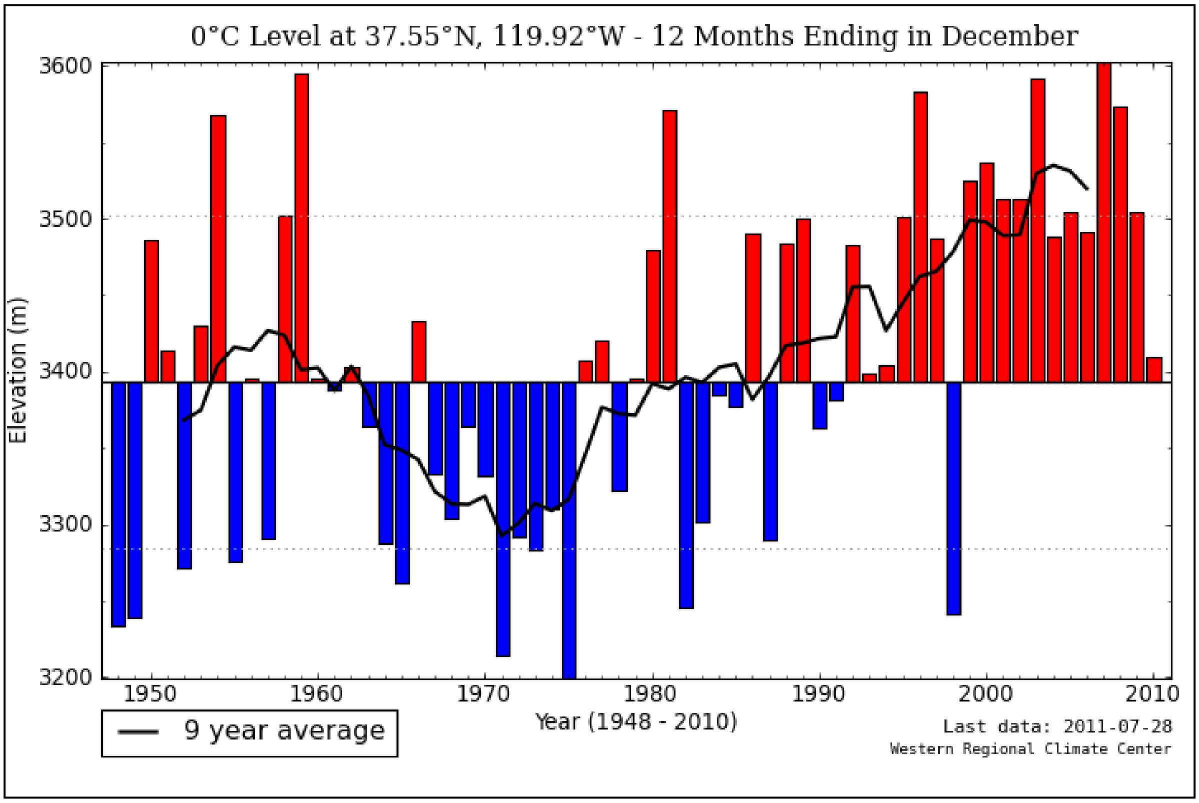


Figure 39. Mean annual freezing level over Mariposa, time series 1948-2010.The height of the 0 C isotherm ("freezing level") averaged from January through December, by year. Values in meters above (red, warm) or below (blue, cold) period mean (1948-2010). Source: Interactive WRCC North American Freezing Level Tracker at www.wrcc.dri.edu/cwd/products.

Because of the phase change of water that occurs at 0 C, there are also important biological implications. Chemical and biological activity can be very sensitive to temperature, and below freezing most biological systems are shut down. Freezing temperatures also act to regulate the activity of insects and pathogens that can damage or kill trees. Although native insects, fungi, rusts, and other organisms are considered important factors in plant community dynamics in national parks, increases in tree mortality from insects or disease have been documented in recent years (Berg et al. 2006, Raffa et al. 2008). Modeling suggests that at the highest elevations, predicted warmer conditions will result in increases in areas suitable for outbreaks of insects such as the mountain pine beetle (Hicke et al. 2006).

Figure 40 shows the number of days per year where freezing levels are below 6000 ft (1828 m). This number has been dwindling in recent decades, including a readily apparent drop around 1980, more reminiscent of a step change than a gradual change. Similarly, at 14,245 ft (4340 m), where WRCC maintains at least one climate station (atop White Mountain Summit), the number of days with freezing levels not reaching down below 14,000 feet (4267 m) has been diminishing (Figure 41). A pronounced decrease in summer freezing is noted starting about the year 2000.

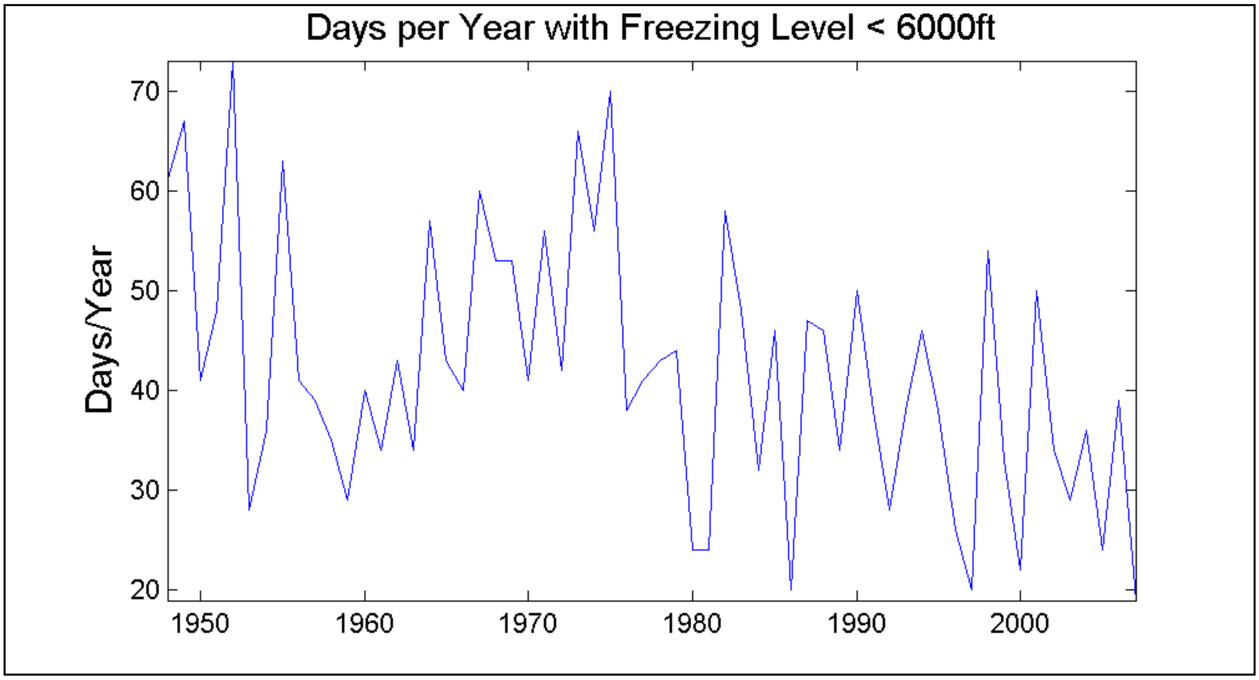


Figure 40. Frequency of freezing levels found below 6000 ft (1829 m) near Mariposa. Number of days per year with mean daily freezing levels below 6000 ft (1829 m)for a grid point near Mariposa, CA, from Global Reanalysis, 1948-2007. *Figure provided by John Abatzoglou.*

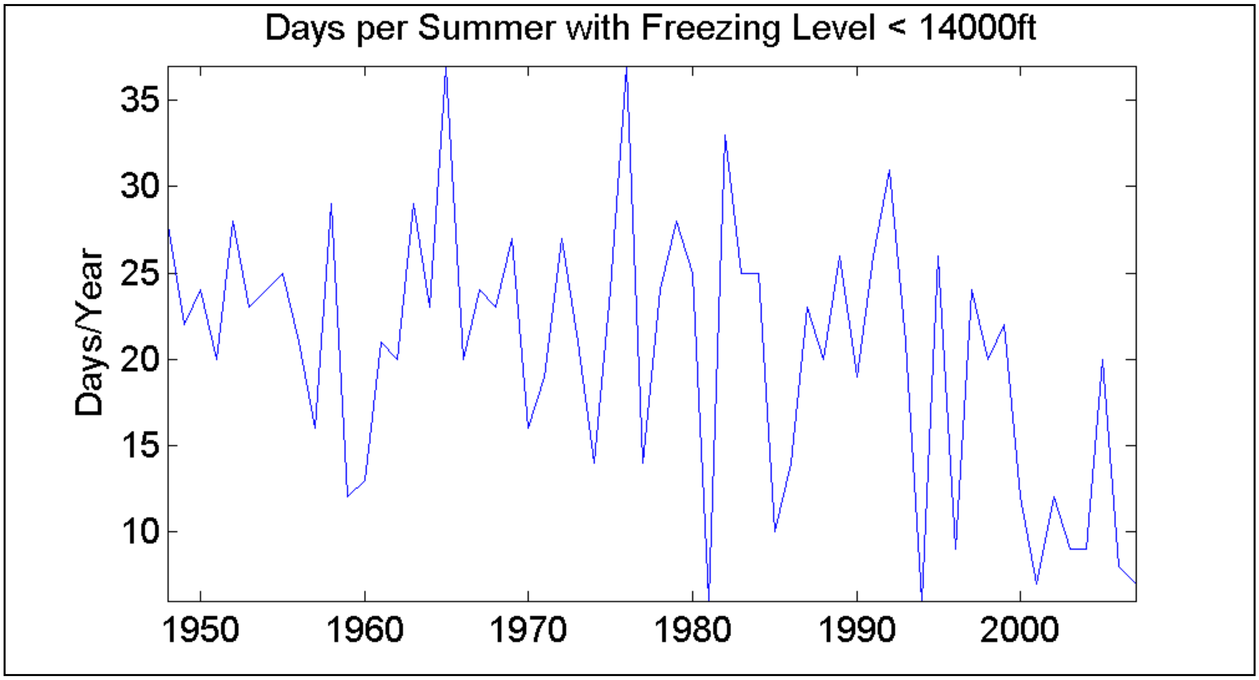


Figure 41. Frequency of summer freezing levels below 14,000 ft (4267 m) near Mariposa. Number of days per year in the summer months (June-August) when the mean daily freezing level has been below 14,000 ft, (4267 m) for 1948-2007. Lower is cooler. *Figure provided by John Abatzoglou.*

These changes in temperature at high elevation affect the living conditions for plants and animals. Recent updates by the Museum of Vertebrate Zoology (2006) on the Grinnell Studies of the last century have reported such changes in Yosemite (Nijhuis 2005, Moritz et al. 2008, Moritz et al. 2011) and in the Great Basin (Beever et al. 2003). In forest plots monitored in SEKI and YOSE, an increase in tree deaths attributed to stress and biotic causes coincided with a temperature-driven index of drought (van Mantgem and Stephenson 2007). Figure 42 shows small tufts of grass starting to grow near a newly placed climate station atop Mount Warren (12327 ft, 3757 m) a few miles east of the Tioga Pass entrance station in Yosemite National Park. This station was damaged during the heavy snows of 2010-2011; the site will likely either be restored or moved to a similar nearby ridge.

Figure 42. Climate station and sparse vegetation atop Mount Warren. Tufts of grass starting to grow near the summit climate station atop Mount Warren,12,327 ft (3757 m), west of Lee Vining, CA, just east of Yosemite National Park. *Photo by Dave Simeral, summer 2006.*

III. Analysis and Discussion

This section begins with an analysis of station data to determine how well the climate histories of stations in the SIEN region inter-relate by east-west and north-south location, by elevation, by time of year, and by climate element (temperature or precipitation). There are many ways to do this; we chose to use correlations. The intent is to develop information about how independent station records are of each other, depending on where in the region they are situated. The discussion provides descriptions of important or representative individual observing sites in SIEN, and concludes with a description of the factors that constitute good network design.

Spatial Correlation Analysis

One method of assessing the quality and representativeness of station data is to correlate records from pairs of stations. High correlations between the time series of climate elements indicate similar climatic regimes, and similar responses to the larger scale drivers of climate. Strong correlations do not necessarily imply similar climates. A station in a high elevation tundra regime may be colder and wetter than a station several thousand feet lower in a mid-elevation setting that is warmer and drier, and thus in a different basic climate regime. However, if the climate time series co-vary in a similar manner, the records from one site can be used to estimate missing data from the other site. High correlations are indicative of a true relationship. Low correlations (absolute value), by contrast, can indicate either a poor relationship, or poor data that are corrupting the computation. Thus, a low absolute correlation is not necessarily a foolproof indicator of a poor climate relationship.

There are a variety of pattern correlation methods that could be employed. For this analysis we used the Pearson correlation coefficient (“r”) (Wilks 2006). For our analyses we selected stations with long records in and near the SIEN area, preferably those with at least 30 years of continuous observations; stations with shorter records in unusual or remote locations were also utilized (the number of years is shown in the tables). It was not necessary that all stations were currently operating, as we assume that the most basic spatial relationships do not change greatly through time. The analyses concentrated on temperature and precipitation. Stations selected were in either the National Weather Service Cooperative Network (COOP) or the Remote Automated Weather Station (RAWS) Network. RAWS records are generally shorter, though some are approximately 20 years long at the time of this report. Due to unheated gauges, RAWS precipitation records are unreliable when precipitation is frozen, so only temperature was examined at RAWS stations. These are the only two elements common to both RAWS and COOP stations. Other elements available from RAWS stations (e.g., wind, humidity) could also be compared between RAWS stations, but such analyses were not undertaken for this report. Data were only used for a particular month if no more than 10 days were missing, or for hourly stations, if there were no more than about 240 hours of missing data, a standard comparable to that used for the COOP data by the National Climate Data Center (NCDC).

We would have liked to use other records, such as those from air quality or NPS networks. However, the difficulty of obtaining these historical records, and then transforming them into monthly time series suitable for analysis, was far too time-consuming. Records from the California Department of Water Resources (CDWR) stations were, at the time of this analysis, equally difficult to transform into the necessary format, though they have since become much more accessible as a result of interactions between WRCC and CDWR.

Climate relationships vary seasonally, so it is to be expected that correlation values between stations would/could vary from winter to summer or from one month to another. Correlations were thus determined for 21 different combinations of months, with an automated routine, for each pair of stations. These included each of the 12 months individually, the four 3-month seasons (DJF, MAM, JJA, SON), two definitions of the cool season (Oct-Mar and Nov-Apr), and three definitions of the year (calendar, Water Year (Oct-Sep), and July-June). At times the way in which a season or the year is defined can affect the correlation. A month with poor correlations that does not contribute much precipitation to a whole season may have relatively little effect on a seasonal correlation that includes that month.

The stations selected are shown in Table 3. The correlation values for temperature are shown in Table 4 and for precipitation in Table 5. Shown in Figure 43 are visual examples of relations between variables with correlation coefficients ranging from r=0.0 to r= 1.00. For the purposes at hand, whether or not these correlations pass significance tests is of lesser interest. What is of more utility is whether the correlations are poor, good, very good, or excellent.

Table 3. Stations used for correlation analyses, with annotation. An abbreviated site name is assigned to each location for use in the correlation tables, and specialized notes are given below.

ID	NAME	LAT	LON	ELEV(M)	START	END	NOTE	ABBR
COOP Stations								
040343	Ash Mtn	36.491	118.825	521	1927	2007		ASH
040449	Balch Power House	36.909	119.088	524	1950	2007		
040755	Big Creek PH 1	37.206	119.242	1487	1915	2007	9	
040822	Bishop Airport	37.371	118.358	1250	1930	2007		BIH
040819	Bishop Creek Intake 2	37.248	118.581	2485	1959	2006		BINT
040823	Bishop Fire Stn	37.368	118.365	1252	1996	2007		
040824	Bishop Union Carbide	37.367	118.717	2864	1957	1970		
040943	Bodie	38.212	119.014	2551	1964	2007		BODI
041470	Camp Wishon	36.183	118.667	1159	1948	1971		
041072	Bridgeport	38.258	119.229	1972	1948	2007		
041075	Bridegeport Dam	38.317	119.229	1972	1925	1957		
041588	Catheys Valley Bull Run Rnch	37.400	120.05	436	1948	1977		CATH
041609	Cedar Grove	36.783	118.667	1418	1940	1963	8	
041630	Central Camp	37.350	119.483	1635	1923	1948		
041697	Cherry Valley Dam	37.975	119.916	1452	1955	2007		
041878	Coarsegold 1 SW	37.250	119.705	680	1957	2007		COAR
042173	Crocker Stn	37.800	119.9	1434	1904	1953		
042539	Dudleys	37.750	120.1	915	1908	1976		
042756	Ellery Lake	37.396	119.231	2135	1924	2006		ELLL
043261	Friant Government Camp	36.997	119.707	125	1939	2007		FRIA
043369	Gem Lake	37.752	119.140	2734	1924	2006	2	GEML
043397	Giant Forest	36.567	118.767	1955	1921	1968		GIFO
043551	Grant Grove	36.739	118.963	2012	1940	2007		GRGR
043666	Groveland	37.833	120.217	854	1905	1954	3	
043669	Groveland 2	37.844	120.226	853	1948	2007	4	GROV

Table 3. Stations used for correlation analyses, with annotation. An abbreviated site name is assigned to each location for use in the correlation tables, and specialized notes are given below (continued).

ID	NAME	LAT	LON	ELEV(M)	START	END	NOTE	ABBR
043672	Groveland Ranger Stn	37.823	120.098	959	1955	2007	5	
043939	Hetch Hetchy	37.961	119.783	1180	1910	2007		HECH
044389	Johnsondale	35.967	118.533	1427	1954	1979	10	
044176	Huntington Lake	37.228	119.221	2140	1915	2007	6	
044232	Independence	36.798	118.204	1204	1893	2007	11	IND
044518	Kern River Intake 3	35.950	118.483	1113	1952	1966	12	
044520	Kern River PH 1	35.467	118.783	296	1931	1991		
044523	Kern River PH 3	35.783	118.439	824	1948	2007		
044705	Lake Sabrina	37.213	118.614	2763	1925	2006	13	
044881	Lee Vining	37.957	119.119	2072	1988	2007		LEEV
044884	Le Grand	37.233	120.250	79	1899	1980		LEGR
044890	Lemon Cove	36.382	119.026	156	1899	2007	14	
044957	Lindsay	36.203	119.058	128	1913	2007		
045026	Lodgepole	36.604	118.733	2053	1968	2007		LODG
045028	Lodgepole Ranger Stn	36.604	118.733	2044	1951	1955		
045280	Mammoth Lakes Ranger Stn	37.648	118.962	2379	1993	2007		MAMM
045346	Mariposa	37.483	119.967	613	1893	2007	7	
045352	Mariposa Ranger Stn	37.495	119.986	640	1953	2007		
045532	Merced Airport	37.286	120.512	47	1899	2007		MERC
045400	Mather	37.881	119.856	1375	1947	2007		MTHR
045779	Mono Lake	38.000	119.150	1966	1943	1988		MONO
046252	North Fork Ranger Stn	37.231	119.507	802	1904	2007		NFRS
046325	Oakhurst	37.331	119.653	680	1999	2007		
046857	Piedra	36.800	119.383	177	1912	1964		
046896	Pine Flat Dam	36.824	119.336	186	1964	2007	16	
047077	Porterville	36.068	119.020	120	1902	2004		
048380	South Entrance Yosemite	37.508	119.634	1566	1941	2007		SENT
048406	South Lake	37.168	118.571	2920	1924	2006	17	SOUL
048455	Springville 3 ENE	36.150	118.767	753	1953	1974		
048914	Three Rivers Edison PH 2	36.467	118.883	290	1909	1971		
048917	Three Rivers PH 1 Hammond	36.465	118.862	347	1948	2007	19	
049481	Wawona							
049855	Yosemite Park HQ	37.750	119.590	1209	1905	2007		YPHQ
969063	Tuolumne Meadow Rgr Stn	37.883	119.350	2638	1980	2007	1	TMRS
RAWS								
ccdg	Cedar Grove	36.788	118.656	1439	1999	2007		CCDG
ccmo	Case Mountain	36.411	118.809	1966	2002	2007		CCMO
ccra	Crane Flat	37.762	119.825	2025	1991	2007		CCRA

Table 3. Stations used for correlation analyses, with annotation. An abbreviated site name is assigned to each location for use in the correlation tables, and specialized notes are given below (continued).

ID	NAME	LAT	LON	ELEV(M)	START	END	NOTE	ABBR
	Lookout							
cdpp	Devils Postpile	37.630	119.093	2304	1993	2004		CDPP
cjer	Jerseydale	37.544	119.839	1189	2002	2007		CJER
cmar	Mariposa Grove	37.513	119.605	1951	1988	2007		CMAR
cmet	Metcalf Gap	37.409	119.768	938	1990	2007		CMET
cmsa	Mariposa	37.504	119.987	680	1990	2007		CMSA
cowv	Owens Valley	37.390	118.551	1414	1992	2007		COWV
cpkr	Park Ridge	36.433	118.943	2298	1997	2007		CPKR
crtl	Rattlesnake	36.407	118.422	2621	1992	2007		CRTL
cshq	Shadequarter	36.567	118.956	1240	1990	2007		CSHQ
csug	Sugarloaf	36.727	118.675	2475	1992	2007		CSUG
ctuo	Gaylor (Tuolumne) Meadow	37.868	119.318	2825	1988	2007		CTUO
cwol	Wolverton	36.445	118.703	1597	1996	2007		CWOL
cwwo	White Wolf	37.851	119.650	2446	1992	2007		CWWO
OTHER								
emer	Emerald Lake	36.598	118.674	2808	1990	2007	20	EMER
topz	Topaz Lake	36.625	118.639	3221	1995	2007	20	TOPZ

NOTES

001 Dummy number assigned to Tuolumne Meadows by WRCC for this report (since formally established by NWS as 049063)
002 Precip only
003 Gap from 1917-1948
004 Gap from 1952-2000
005 Starting date for paper data is given as 1906, precip. only
006 Gap from 1962-1974
007 Gap from 1896-1909, no temp
008 Summer months only
009 Gap from 1963-1998
010 Precip. only
011 Complete after 1925. Also a station that collects hourly daily precip. data (HPD).
012 Precip. only
013 Gap from 1954-1975
014 Very complete record
015 Precip. only
016 Precip. only
017 T & P 192412-194807. Precip. only 197501-200406. Unofficial since.
018 Precip. only
019 Gap 195110 thru 197106
020 Temp., with unheated Tipping Bucket

The list in Table 3 represents stations that record temperature and / or precipitation. For stations in other than COOP or RAWS networks, the records are sent to a wide variety of locations in a number of different formats. Each station requires extensive manipulation to put them into a form compatible with the WRCC storage system.

A more complete inventory of stations was generated for the NPS Climate Inventory Project (see Davey et al. 2007). A revised excerpt from that list is included here as Appendix B.

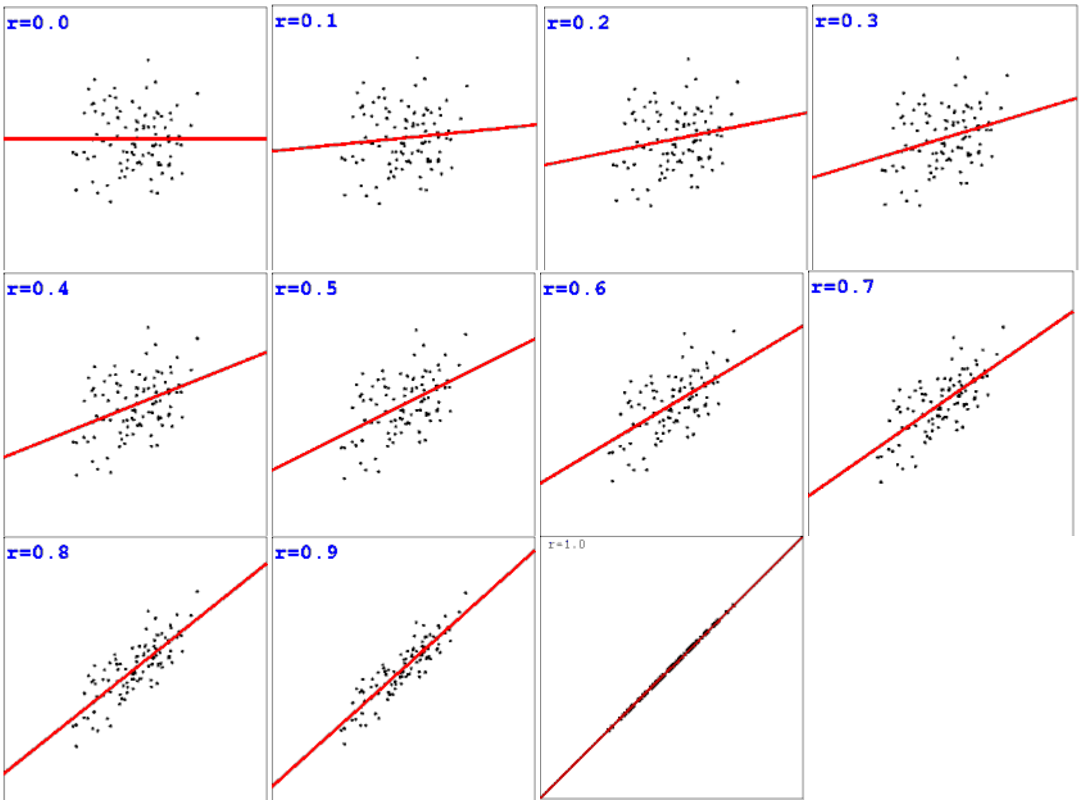


Figure 43. Visual interpretation of scatter plots and correlation coefficients. Examples of scatter plots for variables constructed to have correlation coefficients ranging from r = 0.00 through r = 1.00, based on random placement of 250 points, subject to correlation constraint.

Temperature correlations

Temperature correlation results are shown in Table 4 for each station pair with the top line for each pair showing the correlation coefficient and the bottom line showing the number of years used in the correlation. For example, the first line shows the temperature correlation between COOP data from Ash Mountain (ASH, elevation 1709 ft / 521 m) and Giant Forest (GIFO, elevation 6414 ft / 1955 m). Abbreviations are arbitrary, and purely for the purposes of this discussion. In January, r=0.78, low enough to indicate that there are enough days within some Januarys that are not similarly warm or cold at both locations. On many days, temperature either decreases with height or is constant with height. On other days, such as clear and mainly calm winter days, temperature inversions are present, and temperature increases with height, up to some level at the top of the inversion. If one station is located in the warm air above the inversion, and the other is located in the cold air below the inversion, the departures from long-term average temperatures will be different between the two stations on days with an inversion versus those days without an inversion. The resulting scatter plot will have a “fatter” ellipse, and the correlations may only be in the 0.60 to 0.80 range. During mid-winter in the Central Valley of California, such inversions are common, and the air cools enough for broad expanses of “Tule Fog” to form. The top of this inversion is often between 2000 and 3000 feet (600-900 m). The fog can often persist all day, so that maximum temperatures at lower elevations are suppressed, whereas temperatures at higher elevations in the sun are not suppressed.

These fog episodes occur much less frequently when the sun is higher, and in mid to late spring, the surface layers of the atmosphere begin to warm, while the higher layers of the atmosphere have still not warmed significantly from their winter values. This is an unstable situation (warm air below cold air) that promotes vertical overturning of the atmosphere, and thus vertical mixing is promoted between lower and upper atmosphere. On such days, relative warm or cool conditions are experienced simultaneously at lower and higher stations, and thus they will correlate quite well. There is diurnal variation as well. Inversions form frequently at night, but only in winter are they typically able to persist all day. The mean daily and monthly temperatures we are examining are the average of daytime and nighttime conditions. The ASH / GIFO correlation rises to 0.94 in April, the highest value of the year. It is quite typical for spring correlations to be this high. The correlation drops back to 0.78 in July, which may reflect day/night differences between these two stations. The annual correlations of 0.61 (calendar) and 0.67 (Oct-Sep and Jul-Jun) are smaller than the correlation of any of the individual months, and illustrate that intra-annual variations are not the same from year to year.

A similar pair, ASH and Grant Grove (GRGR, elevation 6601 ft / 2012 m), with about 65 years or more of overlap, shows a similar pattern of monthly correlations but with a somewhat higher annual correlation. Then, as might be anticipated, GRGR and GIFO, at similar elevations, are much better correlated with each other (0.87) in January, and very well in spring (0.98 in May over 28 years).

We are also interested in west-side/east-side correlations across the Sierra crest, and along the east side. Bishop airport (BIH, 4101 ft, 1250 m) temperature correlates well with the COOP measurements at Independence (IND, 3950 ft, 1204 m). BIH also correlates well with the readings at the Bishop water intake on Bishop Creek (BINT, 8153 ft / 2485 m), with a minimum in late summer and autumn, perhaps due to Great Basin inversions as summer days decrease in length.

Also, in comparing RAWS data (Owens Valley RAWS, COWV) with COOP (who usually do not observe at midnight) and airport data (midnight observations), we typically see better correlations with automated stations that have a fixed observing time. COOP stations make their readings once a day, at a time convenient to the observer, usually morning, afternoon, or midnight. The values reported on their forms represent a summary of the past 24 hours, ending on the date entered (this data set is often referred to as SOD - Summary of the Day, for this reason). There is a strict protocol for this. These observation times do matter; a morning observer will record a colder climate than an afternoon observer, given the very same sequence of temperatures. COOP stations may vary their observation times somewhat due to their schedules, and some morning observers shift their maximum temperatures back to what they perceive as the “correct” day (but procedurally incorrect, according to the observing protocols), and sometimes they do not make this mistake in a consistent manner through time. This may sound arcane, but is well understood.

East-side low and high elevation site temperatures correlate well in parts of the year but not others. Lee Vining (LEEV, 6798 ft / 2072 m) has a correlation of 0.26 in January with Tuolumne Meadows Ranger Station (TMRS, 8655 ft / 2638 m). Correlations are much higher in spring, but on an annual basis is a mere -0.17 over 8 years, a sign that the two stations act independently on an annual basis, since there was a robust range of temperatures. The TMRS site was unofficial during this period (now is a formal COOP station), but appears to have an excellent snowfall, precipitation, and air temperature record.

Hetch Hetchy (HECH, 3872 ft / 1180 m) has modest correlation with LEEV in mid winter (0.60 in January), and quite good correlations in spring. Over a 90-year period HECH correlates quite well with Yosemite Headquarters on the valley floor (YPHQ, 3967 ft / 1209 m). The lowest monthly correlations, curiously, are in July and August. There is less variability at this time of year, so local observational factors can influence readings proportionately more, but it is not clear what could account for such low correlations during high sun. We speculate that the difference might arise with night conditions, perhaps in the way drainage winds differ. A similar annual pattern is seen between HECH and Yosemite South Entrance (SENT, 5138 ft / 1566 m). Annual correlations between HECH and SENT, and between YPHQ and SENT, are modest at 0.30 and 0.41 respectively, perhaps a sign that these sites are near a sensitive elevation.

Sites in the Central Valley such as Friant (FRIA, 410 ft / 125 m), Cathey's Valley (CATH, 1431 ft / 436 m) and Le Grande (LEGR, 259 ft / 79 m) correlate poorly (around 0.50) in January and improve to typically 0.90 or higher during spring months. Again, July and August near the valley floor correlate poorly with mid elevation YPHQ (0.35 – 0.55), and only somewhat better on an annual basis (0.45 to 0.60).

FRIA and ASH, both at relatively low elevations, correlate well with each other even in winter, implying that if there is an inversion they are both likely to be on the same side of it (underneath). Low elevation FRIA does not correlate nearly as well in mid-winter with higher GRGR and GIFO, again implying that they experience inversion conditions in a different way when they do happen. Also, the annual correlations between low stations are higher than the same period across an elevation range that spans the typical winter inversion height.

Winter correlations with the high elevation TMRS site are rather low with the Central Valley floor, but improve considerably once the elevations of Hetch Hetchy and Yosemite Valley are reached. Continuing higher, the short 12-15 year overlap record of the Gaylor (Tuolumne) RAWS Station near Gaylor Lake trail (CTUO, 9269 ft / 2825 m) has very high temperature correlations with TMRS in every month of the year, and exceeding 0.95 in March, October and November. This is indeed very heartening, speaking to the quality of both stations, and clearly an indicator that both need to keep functioning, to act as suitable backups and for quality control.

The Crane Flat Lookout RAWS (CCRA, 6640 ft / 2025 m) correlates well with the Mariposa (town) RAWS site (CMSA, 2231 ft / 680 m) in the foothills during spring, falling to 0.39 over 12 Decembers and 0.57 over 12 Januaries when inversions are more likely. Annual correlations are near -0.2 over 8 years, so these locations do not form good annual surrogates for each other. CCRA is much more similar to the Mariposa Grove site (CMAR, 6401 ft / 1951 m). The 239 ft elevation difference results in December correlations of 0.86 over 11 years and January correlations of 0.90 over 8 years. These stations follow the same protocols, indicating that strict adherence to observing protocols enhances the comparability of similarly situated stations. Except in June (0.62) and July (0.64) CCRA correlates well with CMSA. It may be that CMAR is just low enough that summer influences there are different from those slightly higher up. It is also interesting to note that CCRA correlates very well with Wolverton RAWS (CWOL) , located in SEKI about 100 mi / 160 km south and at the same elevation (5240 ft / 1597 m), ranging from 0.95 to 0.99 for January thru May over 8 years. Higher elevation readings at well-exposed sites are representative of larger spatial areas.

There is a modest gap in the Sierra Nevada where the San Joaquin River originates, in the vicinity of DEPO and Mammoth Mountain, compared with the crest height to the north and to the south. In the presence of this gap, one might expect west-side temperature patterns to more readily extend across the Sierra Nevada axis where there is less resistance to airflow across the crest from west-side to east-side. The rather low site at Metcalf Gap RAWS (CMET, 3078 ft / 938 m) on the west side correlates well with the now-defunct Devils Postpile RAWS (CDPP, 7559 ft / 2304 m), with values of 0.85 or higher in every month except July and August. CMET continues to correlate modestly well with the Owens Valley RAWS site (COWV, 4639 ft / 1414 m) east of the crest in nearly every month, ranging from 0.68 (July) and 0.66 (August) and 0.74 (January) to 0.93 in May and 0.95 in March. During their 13-16 year overlap the CMET always correlates at 0.86 or higher in all months with similar-elevation Shadequarter RAWS (CSHQ, 4068 ft / 1240 m).

CDPP correlates with relatively close Mammoth Ranger Station COOP (MAMM, 7805 ft / 2379 m) at 0.88 or higher in all months but August (0.61) and September (0.73).

In and near SEKI, during summer when the higher elevation RAWS stations (8000 ft +, 2400 m +) are operating, cross correlations are very high between adjoining high elevation sites. This is largely an expression of the freer movement of air at these elevations. Many of these stations are not tended during winter, or are covered with snow.

For temperature we find in general that climate variability segregates somewhat by elevation zone, and that as a rule similar elevation zones experience similar climate variability. The winter inversion, which often tops out at 2000-3500 ft (600-1000 m), causes temperature records above and below the inversion to be different, especially in December and January. At somewhat higher elevations, the presence or absence of snow on the ground around a climate station, determines whether the station acts like a “cold” or a “warm” station, and in which months. Lingering snowpack causes local radiative effects on the temperature climate near the sensor, and these readings may not correlate well with readings from other elevations where the snow has already melted or was not present at all. At higher elevations, single stations are more representative of a larger area. However, there are few such records, and a sufficient number (certainly more than one) are needed for redundancy and quality control, in order to produce the high-elevation continuous records so necessary for climate studies. The RAWS stations have surprisingly good spatial coherence, a reflection of generally good maintenance procedures (and a testimony to the value of regular maintenance), consistent and similar observation times, and the general quality of the temperature data. The stations examined tend not to be completely buried by snow.

Data from UC Santa Barbara research stations at Emerald and Topaz Lakes became available later in the analysis phase. Precipitation measurement is unreliable in winter, so only temperature was examined. As with RAWS stations, only those months with no more than the equivalent of about nine missing days (216 missing hours) were used, so that in effect about two-thirds of the observations needed to be present. Emerald and Topaz Lakes correlate well (r>0.90) with each other in all months except January (0.75), August (0.64) and October (0.54), and from February through July at 0.94-0.99. This is not surprising given their high and similar elevations. There is no obvious reason why correlations should be lower in August or October. One potential source of different time histories would be differences in snow cover between the two nearby sites, but those differences would most likely be present near the end of the snow melt season or the beginning of the snow accumulation season.

By accident, during a first analysis some months at Emerald and Topaz were included that mistakenly had more missing data than the criteria above. The presence of those months noticeably weakened all the correlations. This was heartening to see. It is likely that more stringent criteria for tolerance of missing data would have improved the lower correlations noted above, but sample sizes then decrease and data gaps increase.

Emerald Lake temperatures were compared with other temperature records at nearby sites in SEKI, with sites at similar elevations near YOSE, and with lower elevations toward the Central Valley. As expected, correlations were generally very high with nearby sites, as long as they were high enough elevation. Nearby Wolverton correlated especially well in all months, except in October (0.55) and November (0.70), for reasons we do not know. However, and slightly surprisingly, Emerald Lake correlated well in all months with the nearby lower elevation site at Cedar Grove in SEKI. Correlations with the temperature record at distant but similar elevation Tuolumne Meadows Ranger Station in YOSE were greater than 0.80 for every month, over 0.85 for nine months, and over 0.90 for four months. This speaks to the quality of both records.

These high elevation sites do not correlate well with lower elevation sites such as Ash Mountain (ASH) in the middle of winter (especially December and January) and in August. A comparison with Merced Airport on the valley floor showed very low correlations in December, January, and February, likely a result of being on opposite sides of the inversion associated with Tule fog in the Central Valley. Low correlations with Merced Airport also occur in August and September. Clearly, these sites are in different climate regimes and experience different climate histories. Correlations are highest in March, April, and May, when the atmosphere is most unstable and thus communicates well vertically because it is well-mixed, so that low and high elevations can experience similar climate anomalies.

Precipitation correlations

Monthly and seasonal precipitation fields, and their pattern correlations, are expected to have different structure from those for temperature, and we see this in our analysis. The entire region has its wet season in winter, as expected in a Mediterranean climate, and this is especially true on the west side of the crest, which faces the direction that storms typically encounter the Sierra Nevada range. In winter precipitation oftentimes “spills over” to the east side to varying extent and to varying distance east of the Sierra crest. In the drier areas on the east side of the SIEN park units, spring or summer have a greater chance to contribute a non-negligible fraction of the annual precipitation for a given year, or climatologically. On the west side, during the extended very dry summer season, one might also expect that the meager amounts that do fall will be the result of a day or two of convective storm systems (thundershowers), and that spatial correlations might not be large, unless the cause of a thunderstorm day is an atmospheric wave that has larger spatial extent.

As an example, over a 42-year period of overlap, low elevation Ash Mountain (ASH) correlates with much higher and wetter Giant Forest (GIFO) at between 0.93 and 0.99 for all months from November through April. The lowest correlation is during the nearly rainless months of July (0.34) and August (0.59), with all three definitions of a year showing correlations of 0.95 or 0.96. Between Grant Grove (GRGR) and Lodgepole (LODG, 6736 ft / 2053 m), during the 39-year overlap, monthly correlations range from 0.94 to 0.98 for each month from October thru April. Only two months have modest correlations, July (0.76) and August (0.60), and since these months do not contribute substantially to the annual total, the annual correlations is 0.95. These values are large enough to indicate there is not as much need to use as many stations on the west side (for precipitation, but not for temperature), because the story is fairly clear.

Over the Sierra Nevada range to the east, however, the spatial correspondence is not as strong. Along US 395, Bishop Airport (BIH) and Independence (IND), with about 60 years of overlap, are generally correlated at 0.80 to 0.90 in the winter months. Correlations between them fall to 0.54 in May and 0.56 in July. The summer monsoon is not usually experienced as much in July as in August, this far to the west of its primary area of influence. Correlations from May through September are between 0.54 and 0.69. The annual correlation between these two sites is a modest 0.77 with 50 full years of record. BIH correlations with also-dry Lee Vining (LEEV) to the north range from 0.63 to 0.88 over a 20-year span, for all months except July, August and September, all with 0.30. The valley station at BIH correlates fairly well with the higher elevation mountain station at Bishop Intake # 2 (BINT), at values of 0.82 to 0.89 over a 45 year period for the individual months of December through April, and a respectable minimum correlation in July of 0.58.

The Ellery Lake COOP site (ELLL), just east of the crest at 7005 ft (2135 m) along the Yosemite corridor atop the Tioga Grade, has a very long record that correlates moderately but not spectacularly well with a similar station at Gem Lake (GEML, 8970 ft / 2734 m), west of the June Lake loop, on Rush Creek, which drains into Mono Lake. Over their 75 year overlap, monthly correlations between October and April range from 0.75 to 0.89, not quite as high as one might expect. Lowest correlations are in the late spring convective season of May, June and July (0.68, 0.62, 0.69). Another lake in the upper portion of the east side, South Lake (SOUL), west of Bishop at 9580 ft / 2920 m, correlates from 0.78 to 0.96 over the months of November through April with the west side station at GIFO, with a 24-year overlap. The SOUL correlations with GRGR are comparable, and average 0.88 for the November-April total. The GRGR correlations across the mountain range to BINT are a little less than with SOUL, and between GRGR and BIH are somewhat less yet, but still ranging from 0.78 to 0.84 for individual months from December through March, and for the water year at 0.86 for 63 years of overlap. The GRGR correlation with BIH drops to 0.12 in July, and is only somewhat higher in summer, as might be expected when the monsoon season preferentially affects locations farther to the east from the western Sierra foothills.

In comparing the records from Tuolumne Meadows Ranger Station (TMRS) and ELLL, we uncover correlations of from 0.78 to 0.96 for the months from October through May, indicating very good correspondence. As the crow flies, these stations are within about 10 mi (16 km) of each other. Annual correlations between these two sites range from 0.91 (Water Year) to 0.97 (Calendar Year). By contrast, the correlations between TMRS and GEML are not so high during their 13-25 years of overlap. This corresponds well with the comparison of ELLL and GEML, and indicates that perhaps the GEML record is not as good as ELLL for adjusting and comparing precipitation values. The correspondence gives added confidence in the TMRS unofficial values.

We compared the west-side records from Hetch Hetchy (HECH, a station likely never to be shut down due to its importance for the reservoir) with precipitation records at nearby Mather (MTHR, 4511 ft / 1375 m), at TMRS just west of Tioga Pass, and at ELLL just east of Tioga Pass. HECH and MTHR correlate at 0.96 to 0.98 in September and from November through April, and for the water year at 0.98, with about 50-55 years of overlap. HECH correlates at 0.93 to 0.96 from November through April with TMRS over a 17-20 year period, an impressive value for an unofficial volunteer station. During the dry season August correlates lowest at 0.16, with several adjacent months from May to September at 0.50 to 0.62. Water year totals correlate at 0.95 between HECH and TMRS. HECH correlations with ELLL fall off somewhat from the TMRS values, but are in the range 0.79 to 0.90 from October through March, with a water year value of 0.75, different enough to claim some degree of independence. Mather correlates nearly equally well with both Yosemite Park Headquarters in Yosemite Valley (YPHQ), and with the Yosemite South Entrance station (SENT), at 0.89 to 0.95 from September through April over 52-55 years, and a water year correlation of 0.94 over 41 years.

From north to south along the west side, the correlations between SENT and both North Fork Ranger Station south of Yosemite (NFRS, 2631 ft / 802 m) and GRGR inside SEKI, are between 0.90 and 0.92 for individual months from September through April for NFRS, and 0.89 to 0.94 from October through May for GRGR, and both at 0.94 for the water year, with 48-66 years of comparisons. These correlations show that there does not appear to be a great deal of difference between the percentage of average (i.e., precipitation relative to average) recorded at Yosemite compared with Sequoia and Kings Canyon. This does seem just slightly surprising, since certain large scale relationships to climate (such as El Niño / La Niña) suggest a different relation for the southern Sierra compared with the Central Sierra in the vicinity of Lake Tahoe. Perhaps both Yosemite and Sequoia are both far enough south to be in the same climatic regime with respect to this one source (ENSO) of variability.

To summarize, there is surprisingly good correspondence in percentage if not absolute terms, between precipitation on the lower and upper west side, between the mid-level west side and the Sierra Crest, and on over into the upper higher-elevation portions of the east side canyons. These relationships even extend fairly reliably out to the center of the first valley east of the Sierra crest, or approximately the route of US 395. There is very good winter correspondence in these east-west records, and modest warm season correspondence, with typically the least spatial coherence of patterns in July, the driest month in most locations. Also of particular note, the record from Ellery Lake appears to be especially good. Of even more importance, the record from the backcountry rangers at Tuolumne Meadows Ranger Station is clearly of excellent quality, and should continue and be supported at all costs. This high elevation, remote site is a unique location from which we have manual observations, and this record is very useful and necessary for future studies. For consistency's sake, even if an automated observation were emplaced at Tuolumne Meadows, the manual record should be maintained.

Table 4. Correlations for temperature in and around the SIEN. For each station pair, the top line shows the correlation coefficient and the bottom line shows the number of years used in the correlation.

Site Mean Temp.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	DJF	MAM	JJA	SON	Oct-Mar	Nov-Apr	Oct-Sep	Jul-Jun	Jan-Dec
ASH/GIFO	0.78	0.86	0.90	0.91	0.94	0.92	0.78	0.85	0.82	0.90	0.83	0.76	0.72	0.90	0.78	0.75	0.70	0.70	0.67	0.67	0.61
	38	38	38	38	37	38	38	38	37	37	37	37	37	37	38	35	36	37	34	34	34
ASH/GRGR	0.75	0.85	0.96	0.95	0.95	0.93	0.79	0.81	0.86	0.92	0.9	0.83	0.83	0.93	0.8	0.84	0.88	0.89	0.85	0.84	0.74
	66	65	65	66	67	65	68	66	66	66	68	65	62	64	64	64	58	59	54	52	55
GIFO/GRGR	0.87	0.88	0.86	0.96	0.98	0.96	0.82	0.78	0.90	0.96	0.90	0.82	0.76	0.92	0.81	0.90	0.73	0.63	0.80	0.86	0.72
	28	28	27	28	27	28	29	28	29	28	28	27	27	26	28	27	25	26	24	23	23
BIH/BINT	0.88	0.92	0.95	0.97	0.88	0.95	0.88	0.80	0.85	0.87	0.81	0.85	0.96	0.92	0.87	0.74	0.87	0.92	0.99	0.92	0.98
	8	9	10	12	13	12	13	12	13	12	13	12	7	10	11	12	6	7	5	6	5
BIH/IND	0.83	0.89	0.94	0.94	0.88	0.88	0.80	0.78	0.70	0.88	0.85	0.87	0.76	0.91	0.79	0.70	0.64	0.70	0.65	0.64	0.64
	42	52	51	51	44	55	44	53	46	50	40	43	36	36	37	37	34	33	30	31	30
BIH/COWV	0.95	0.91	0.96	0.98	0.99	0.99	0.93	0.96	0.93	0.96	0.97	0.84	0.89	0.98	0.97	0.98	0.87	0.90	0.94	0.91	0.93
	14	14	15	15	15	15	15	15	15	16	15	15	14	15	15	14	13	13	13	12	12
IND/COWV	0.95	0.87	0.97	0.97	0.96	0.95	0.88	0.91	0.86	0.95	0.98	0.87	0.91	0.96	0.91	0.94	0.90	0.92	0.91	0.84	0.59
	13	14	13	14	15	14	14	15	14	15	14	13	11	13	13	13	10	10	9	8	10
LEEV/BODI	0.61	0.90	0.88	0.96	0.92	0.90	0.88	0.68	0.86	0.93	0.90	0.87	0.80	0.94	0.79	0.92	0.78	0.82	0.73	0.73	0.18
	19	19	17	19	19	19	19	20	19	18	18	17	17	17	18	17	15	16	14	14	12
LEEV/TMRS	0.26	0.81	0.76	0.90	0.96	0.81	0.95	0.72	0.50	0.90	0.89	0.69	0.46	0.92	0.90	0.94	0.59	0.52	0.75	0.71	-0.17
	18	17	16	18	15	15	17	18	17	14	16	18	15	14	13	12	8	11	7	7	8
HECH/LEEV	0.60	0.76	0.82	0.94	0.95	0.87	0.83	0.64	0.76	0.97	0.84	0.83	0.64	0.94	0.80	0.90	0.68	0.72	0.75	0.75	0.72
	19	19	17	19	19	19	18	20	19	18	18	17	17	17	17	17	14	15	12	13	11
HECH/YPHQ	0.90	0.94	0.94	0.90	0.83	0.79	0.54	0.51	0.78	0.92	0.89	0.90	0.92	0.84	0.53	0.82	0.91	0.88	0.78	0.80	0.77
	94	93	94	94	94	92	90	92	93	89	92	90	88	93	83	86	82	83	75	74	75
HECH/SENT	0.84	0.88	0.88	0.93	0.87	0.79	0.64	0.59	0.82	0.86	0.88	0.87	0.79	0.81	0.52	0.73	0.64	0.65	0.42	0.35	0.30
	60	61	61	64	65	64	63	66	65	62	64	61	58	61	61	60	55	57	50	51	48
YPHQ/SENT	0.85	0.94	0.95	0.95	0.92	0.82	0.60	0.59	0.83	0.87	0.86	0.78	0.78	0.90	0.46	0.73	0.69	0.72	0.50	0.48	0.41
	60	59	59	62	63	62	60	63	62	61	62	59	55	58	55	57	50	52	43	45	44
LEGR/YPHQ	0.49	0.57	0.80	0.72	0.50	0.62	0.35	0.42	0.56	0.81	0.78	0.52	0.55	0.62	0.28	0.67	0.73	0.73	0.56	0.60	0.45
	71	72	71	73	72	70	67	67	70	70	72	72	67	70	62	66	60	63	50	49	51
CATH/YPHQ	0.53	0.63	0.92	0.97	0.93	0.92	0.79	0.89	0.89	0.90	0.83	0.71	0.61	0.94	0.84	0.83	0.70	0.72	0.70	0.73	0.72
	23	23	23	23	23	22	21	20	21	22	22	22	22	23	19	21	21	21	17	17	18

Table 4. Correlations for temperature in and around the SIEN. For each station pair, the top line shows the correlation coefficient and the bottom line shows the number of years used in the correlation (continued).

Site Mean Temp.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	DJF	MAM	JJA	SON	Oct-Mar	Nov-Apr	Oct-Sep	Jul-Jun	Jan-Dec
MERC/YPHQ	0.44	0.66	0.85	0.78	0.81	0.65	0.53	0.48	0.73	0.85	0.76	0.38	0.45	0.75	0.41	0.75	0.66	0.61	0.63	0.55	0.57
	98	99	97	97	94	93	93	96	95	96	96	95	92	92	83	89	84	85	68	65	65
FRIA/YPHQ	0.56	0.62	0.85	0.91	0.89	0.90	0.73	0.75	0.83	0.89	0.85	0.63	0.63	0.85	0.71	0.80	0.75	0.74	0.69	0.71	0.62
	65	64	65	65	65	64	63	66	66	66	65	64	60	63	59	63	56	57	53	53	54
FRIA/ASH	0.82	0.85	0.91	0.92	0.91	0.92	0.87	0.88	0.90	0.93	0.92	0.78	0.84	0.89	0.81	0.89	0.85	0.83	0.77	0.79	0.73
	65	66	66	67	67	65	67	69	67	68	68	68	64	65	64	66	61	62	58	58	60
FRIA/GIFO	0.58	0.78	0.93	0.94	0.87	0.90	0.75	0.91	0.80	0.91	0.82	0.59	0.67	0.90	0.78	0.82	0.82	0.78	0.70	0.81	0.61
	28	28	28	28	28	29	30	30	30	30	29	29	28	27	29	29	28	28	27	27	26
FRIA/GRGR	0.40	0.63	0.88	0.92	0.89	0.88	0.80	0.79	0.84	0.88	0.83	0.47	0.59	0.90	0.76	0.84	0.74	0.71	0.73	0.72	0.62
	63	63	65	65	65	65	66	66	68	67	67	65	58	63	62	66	56	56	53	50	54
FRIA/TMRS	0.21	0.77	0.90	0.84	0.88	0.82	0.81	0.62	0.73	0.81	0.74	0.35	0.46	0.85	0.77	0.83	0.71	0.58	0.70	0.63	0.46
	20	19	23	22	17	18	27	28	24	18	20	24	18	16	17	13	9	14	7	7	10
HECH/TMRS	0.70	0.88	0.92	0.88	0.91	0.78	0.71	0.66	0.79	0.89	0.75	0.71	0.66	0.91	0.76	0.87	0.75	0.72	0.85	0.88	0.69
	21	20	23	22	17	19	27	28	24	18	21	23	18	16	17	14	10	15	8	9	11
YPHQ/TMRS	0.73	0.94	0.91	0.88	0.95	0.84	0.78	0.75	0.84	0.88	0.78	0.65	0.80	0.93	0.85	0.90	0.79	0.87	0.92	0.92	0.87
	20	20	22	21	16	17	25	27	23	16	20	22	18	14	14	12	8	13	6	7	9
YPHQ/CTUO	0.86	0.85	0.98	0.91	0.87	0.87	0.79	0.42	0.96	0.89	0.96	0.86	0.80	0.91	0.78	0.93	0.85	0.88	0.69	0.68	0.45
	14	14	11	11	11	11	10	12	14	14	15	13	13	10	8	12	9	9	7	6	7
SENT/TMRS	0.79	0.91	0.90	0.91	0.93	0.84	0.87	0.60	0.81	0.93	0.78	0.66	0.89	0.93	0.79	0.96	0.77	0.86	0.92	0.91	0.85
	20	20	23	22	17	19	28	28	23	18	21	24	18	16	18	13	10	15	8	9	10
TMRS/CTUO	0.93	0.86	0.97	0.95	0.82	0.87	0.95	0.80	0.91	0.97	0.98	0.90	0.78	0.88	0.92	0.96	0.82	0.91	0.69	0.67	0.46
	15	13	12	12	11	11	12	12	14	14	16	15	13	11	10	13	8	11	7	7	9
HECH/CCRA	0.63	0.85	0.97	0.96	0.98	0.74	0.73	0.65	0.83	0.95	0.93	0.57	0.40	0.98	0.54	0.93	0.76	0.63	0.57	0.77	0.38
	12	12	12	11	12	12	12	15	15	14	15	14	11	10	10	14	9	9	6	7	7
CCRA/YPHQ	0.73	0.93	0.98	0.98	0.98	0.73	0.70	0.83	0.77	0.90	0.97	0.66	0.73	0.99	0.49	0.91	0.94	0.89	0.27	0.25	-0.17
	12	12	11	10	11	12	11	14	14	13	15	10	8	9	13	7	7	6	5	5	6
CCRA/CMSA	0.57	0.89	0.97	0.94	0.99	0.72	0.72	0.80	0.90	0.64	0.86	0.39	0.63	0.98	0.58	0.78	0.71	0.86	0.48	0.58	-0.16
	12	12	12	11	11	11	12	14	14	13	13	12	10	10	10	13	9	8	7	7	8
CCRA/CMAR	0.90	0.95	0.97	0.86	0.97	0.62	0.64	0.88	0.92	0.90	0.81	0.86	0.80	0.94	0.56	0.89	0.97	0.87	0.99	0.99	0.82
	8	9	8	7	9	9	11	13	12	12	14	11	7	6	9	11	4	6	3	3	3
CCRA/CWWO	0.83	0.83	0.99	0.94	0.96	0.91	0.86	0.81	0.84	0.97	0.93	0.80	0.69	0.96	0.85	0.94	0.88	0.86	0.92	1.00	0.75
	10	8	8	7	8	8	9	12	14	14	15	14	8	6	7	13	7	7	4	2	5
CCRA/CTUO	0.86	0.79	0.97	0.86	0.85	0.70	0.71	0.62	0.83	0.90	0.98	0.91	0.91	0.83	0.70	0.91	0.99	0.98	0.82	0.88	0.38

Table 4. Correlations for temperature in and around the SIEN. For each station pair, the top line shows the correlation coefficient and the bottom line shows the number of years used in the correlation (continued).

Site Mean Temp.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	DJF	MAM	JJA	SON	Oct-Mar	Nov-Apr	Oct-Sep	Jul-Jun	Jan-Dec
	12	11	9	9	9	9	11	12	13	13	15	13	11	8	9	13	7	9	6	5	8
CCRA/CWOL	0.98	0.96	0.97	0.95	0.99	0.71	0.67	0.94	0.87	0.52	0.75	0.85	0.81	1.00	0.54	0.54	0.28	0.70	0.33	0.26	-0.03
	9	8	9	8	8	8	8	10	11	11	11	10	8	7	7	11	8	7	6	6	6
CWWO/CTUO	0.90	0.87	0.99	0.98	0.90	0.97	0.89	0.74	0.93	0.94	0.95	0.88	0.72	0.93	0.86	0.89	0.87	0.91	0.95	1.00	0.71
	12	11	9	8	9	10	10	12	15	14	16	15	11	8	9	11	6	8	4	2	5
YPHQ/CMAR	0.85	0.97	0.96	0.80	0.96	0.94	0.56	0.82	0.68	0.82	0.84	0.72	0.87	0.94	0.83	0.76	0.90	0.90	0.92	0.87	0.71
	13	12	12	12	12	12	12	13	16	14	16	13	11	11	9	14	9	10	7	7	8
CMAR/CTUO	0.84	0.82	0.97	0.74	0.82	0.92	0.88	0.23	0.82	0.91	0.82	0.91	0.85	0.92	0.69	0.84	0.83	0.89	0.73	0.78	0.16
	11	11	9	10	11	11	11	13	12	14	15	12	10	9	11	11	7	9	7	5	5
CMSA/CMAR	-0.06	0.73	0.95	0.82	0.92	0.96	0.85	0.78	0.91	0.50	0.78	0.65	0.30	0.91	0.85	0.74	0.84	0.75	0.65	0.79	0.69
	12	12	11	12	13	12	13	14	13	13	12	11	9	11	12	10	6	7	6	6	7
CMSA/CTUO	0.55	0.66	0.96	0.82	0.80	0.92	0.79	0.33	0.87	0.52	0.87	0.76	0.11	0.88	0.77	0.60	0.44	0.66	0.22	0.37	0.44
	14	14	12	12	12	11	12	13	14	14	13	13	13	12	11	12	9	10	9	8	9
CMET/CCMO	0.96	0.90	0.99	0.95	0.69	0.96	0.02	0.44	0.96	0.95	0.98	0.96	0.95	0.99	-0.22	0.86	0.81	0.60	0.71	0.52	0.81
	5	5	5	5	5	6	5	6	6	6	6	5	5	5	5	6	5	5	4	4	3
CMET/CMSA	0.80	0.91	0.98	0.98	0.85	0.97	0.98	0.96	0.97	0.69	0.92	0.92	0.88	0.94	0.98	0.86	0.82	0.92	0.95	0.98	0.97
	15	15	15	15	15	15	14	16	15	15	14	14	14	14	12	14	12	12	10	11	10
CMET/CMAR	0.59	0.94	0.98	0.87	0.66	0.94	0.78	0.80	0.89	0.93	0.86	0.79	0.54	0.85	0.70	0.94	0.88	0.72	0.52	1.00	0.60
	12	12	11	12	12	12	12	14	12	14	14	12	10	10	10	11	6	7	5	4	4
CMET/CDPP	0.90	0.98	0.94	0.94	0.98	0.97	0.76	0.44	0.85	0.98	0.96	0.88	0.88	0.97	0.77	0.97	0.86	0.81	0.99	0.95	0.97
	10	10	9	9	9	9	11	11	10	10	10	11	10	9	9	10	9	9	8	9	8
CMET/COWV	0.74	0.83	0.95	0.82	0.93	0.90	0.68	0.66	0.86	0.95	0.95	0.80	0.59	0.94	0.74	0.96	0.65	0.65	0.76	0.84	0.78
	14	14	14	14	14	14	14	14	14	16	15	15	14	14	12	13	12	12	10	9	9
CMET/CPKR	0.86	0.94	1.00	0.93	0.28	0.92	0.84	0.49	0.94	0.97	0.87	0.88	0.85	0.99	0.46	0.84	0.69	0.70	-0.60	-0.10	-0.72
	7	7	5	5	6	9	9	11	11	11	8	7	7	5	8	8	5	5	4	4	3
CMET/CSHQ	0.89	0.97	0.98	0.98	0.86	0.93	0.95	0.90	0.95	0.98	0.96	0.91	0.95	0.94	0.90	0.96	0.96	0.98	0.98	0.97	0.41
	14	15	14	14	14	15	13	16	14	15	14	14	13	13	11	13	12	12	8	8	8
CMET/CWOL	0.87	0.92	0.99	0.98	0.99	0.99	0.96	0.93	0.95	0.63	0.62	0.88	0.74	0.99	0.97	0.64	0.82	0.94	0.93	0.95	0.91
	11	11	11	11	11	11	10	11	12	12	12	11	11	11	9	12	11	11	9	10	9
CRTL/CSUG	0.00	0.00	0.00	0.00	0.00	0.99	0.99	0.52	0.96	0.61	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
	0	0	0	0	0	3	8	13	14	6	0	0	0	0	3	0	0	0	0	0	0
CSHQ/CWOL	0.98	0.98	1.00	0.99	1.00	0.98	0.98	0.95	0.97	0.65	0.66	0.93	0.89	1.00	1.00	0.56	0.77	0.95	0.85	0.93	0.55

Table 4. Correlations for temperature in and around the SIEN. For each station pair, the top line shows the correlation coefficient and the bottom line shows the number of years used in the correlation (continued).

Site Mean Temp.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	DJF	MAM	JJA	SON	Oct-Mar	Nov-Apr	Oct-Sep	Jul-Jun	Jan-Dec
	11	11	11	11	10	11	10	11	11	12	12	11	11	10	9	11	11	11	8	8	8
CWOL/CMAR	0.66	0.97	0.98	0.80	0.91	0.99	0.91	0.78	0.93	0.29	0.26	0.94	0.70	0.91	0.84	0.23	0.45	0.75	0.73	0.80	0.62
	7	7	7	7	8	8	8	9	9	9	10	8	6	7	7	8	5	6	4	5	4
CWOL/COWV	0.82	0.84	0.94	0.91	0.96	0.98	0.84	0.81	0.90	0.61	0.72	0.95	0.68	0.96	0.87	0.60	0.24	0.65	0.54	0.58	0.77
	10	10	11	11	11	11	11	11	12	12	11	11	10	11	10	11	9	9	8	9	8
CDPP/MAMM	0.88	0.98	0.93	0.98	0.97	0.98	0.94	0.61	0.73	0.98	0.98	0.88	0.96	0.99	0.87	0.97	0.97	0.98	0.97	0.94	0.79
	10	10	9	10	10	10	10	11	8	9	10	11	10	9	9	8	8	9	4	7	5
CCDG/CDPP	0.90	0.93	0.81	0.96	0.72	0.67	0.78	0.12	0.89	0.96	0.92	0.76	0.87	0.72	-0.10	0.94	0.71	0.75	0.78	0.46	-0.23
	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	4	4	4
CCDG/CMAR	0.48	0.80	0.95	0.85	0.73	0.93	0.88	0.41	0.91	0.94	0.88	0.81	0.74	0.84	0.67	0.94	0.79	0.80	0.65	0.93	-0.91
	6	6	6	6	7	7	7	7	7	7	8	7	6	6	7	6	5	6	5	4	3
CCDG/COWV	0.79	0.87	0.94	0.92	0.89	0.93	0.88	0.76	0.91	0.97	0.95	0.79	0.65	0.91	0.63	0.93	0.71	0.85	0.78	0.70	0.85
	7	7	8	8	8	8	8	8	9	9	9	8	7	8	8	9	7	7	7	6	6
CCDG/CSUG	0.00	0.00	0.00	0.00	0.00	0.54	0.92	0.74	0.96	1.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00	0.00	0.00
	0	0	0	0	0	3	8	8	9	5	0	0	0	0	3	0	0	0	0	0	0
CCDG/CWOL	0.75	0.80	0.94	0.86	0.71	0.96	0.94	0.81	0.99	0.62	0.75	0.86	0.73	0.84	0.46	0.59	0.68	0.94	0.89	0.88	-0.13
	8	8	8	8	8	8	7	7	9	9	9	8	8	8	7	9	8	8	7	7	7
EMER/TOPZ	0.76	0.97	0.99	0.97	0.97	0.94	0.98	0.64	0.96	0.54	0.89	0.87	0.88	0.96	0.83	0.75	0.70	0.80	1.00	0.90	-0.29
	9	9	9	7	8	7	6	6	6	7	8	8	7	7	4	6	6	4	2	4	4
EMER/ASH	0.61	0.80	0.95	0.73	0.88	0.91	0.86	0.63	0.84	0.91	0.94	0.18	0.51	0.83	0.93	0.93	0.68	0.61	0.84	0.92	0.80
	12	14	12	15	14	10	11	13	13	14	13	11	10	11	8	11	9	9	6	4	5
EMER/GRGR	0.80	0.95	0.96	0.86	0.94	0.93	0.91	0.90	0.88	0.95	0.98	0.87	0.68	0.92	0.90	0.97	0.59	0.58	0.63	0.06	-0.37
	12	13	13	14	14	12	11	12	14	14	13	10	8	11	9	12	8	7	6	5	5
EMER/LODG	0.93	0.95	0.94	0.93	0.97	0.91	0.91	0.90	0.89	0.97	0.99	0.60	0.89	0.95	0.95	0.99	0.89	0.99	0.99	0.99	0.99
	9	11	10	11	10	8	8	10	10	10	10	8	7	8	7	9	7	6	5	4	4
EMER/GROV	0.73	0.92	0.99	0.81	0.94	0.96	0.56	0.33	0.99	0.76	0.81	0.26	0.42	0.93	0.02	0.80	0.09	-0.60	0.00	0.03	-1.00
	7	7	6	7	6	5	5	6	7	7	6	5	5	5	4	5	5	5	3	3	2
EMER/TMRS	0.87	0.89	0.96	0.89	0.89	0.89	0.94	0.82	0.81	0.93	0.98	0.88	0.76	0.92	0.93	0.94	0.83	0.91	0.94	0.95	0.93
	12	12	12	14	13	11	10	11	13	12	13	11	8	11	8	11	8	8	6	6	6
EMER/MERC	0.34	0.29	0.87	0.80	0.93	0.77	0.79	0.54	0.46	0.76	0.87	-0.03	0.03	0.87	0.75	0.74	0.31	0.28	0.40	0.51	0.43
	12	14	13	15	14	12	11	13	14	14	13	11	10	12	10	12	10	10	8	7	6
EMER/CCRA	0.88	0.94	0.96	0.76	0.95	0.93	0.91	0.74	0.82	0.90	0.96	0.80	0.77	0.92	0.90	0.91	0.64	0.61	0.71	-	-0.55

Table 4. Correlations for temperature in and around the SIEN. For each station pair, the top line shows the correlation coefficient and the bottom line shows the number of years used in the correlation (continued).

Site Mean Temp.	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**DJF**	**MAM**	**JJA**	**SON**	**Oct-Mar**	**Nov-Apr**	**Oct-Sep**	**Jul-Jun**	**Jan-Dec**
																				0.53	
	10	10	10	10	10	8	8	12	13	13	12	10	7	7	6	11	7	6	3	3	3
EMER/CWOL	0.89	0.95	0.96	0.89	0.96	0.95	0.96	0.88	0.96	0.55	0.70	0.93	0.91	0.94	0.94	0.63	0.64	0.88	0.94	0.93	0.90
	10	11	10	11	10	8	8	9	11	11	10	9	8	9	6	9	8	8	5	6	5
EMER/CCDG	0.83	0.86	0.94	0.89	0.68	0.96	0.98	0.86	0.94	0.90	0.96	0.58	0.67	0.86	0.87	0.90	0.21	0.86	0.97	0.57	-1.00
	7	8	7	8	7	5	5	6	8	8	7	6	5	6	4	6	5	5	3	3	2

Table 5. Correlations for precipitation for the SIEN. For each station pair, the top line shows the correlation coefficient and the bottom line shows the number of years used in the correlation.

Site Precip.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	DJF	MAM	JJA	SON	Oct-Mar	Nov-Apr	Oct-Sep	Jul-Jun	Jan-Dec
ASH/GIFO	0.94	0.99	0.96	0.93	0.87	0.90	0.34	0.59	0.89	0.87	0.93	0.98	0.98	0.94	0.81	0.93	0.97	0.97	0.96	0.96	0.95
	42	42	42	42	42	42	42	42	42	42	42	41	41	42	42	42	41	41	41	41	41
BLCH/LODG	0.95	0.95	0.93	0.91	0.89	0.90	0.62	0.76	0.94	0.90	0.96	0.95	0.96	0.91	0.76	0.94	0.94	0.94	0.94	0.93	0.95
	39	39	38	36	38	38	38	37	37	38	38	38	38	36	36	37	36	34	32	32	33
BIH/BINT	0.87	0.82	0.84	0.89	0.61	0.73	0.58	0.68	0.84	0.69	0.72	0.87	0.87	0.77	0.76	0.81	0.82	0.80	0.77	0.75	0.67
	44	45	44	44	45	45	45	45	45	45	45	45	44	44	45	44	43	43	43	42	43
BIH/IND	0.90	0.80	0.81	0.74	0.54	0.69	0.56	0.67	0.68	0.85	0.75	0.89	0.90	0.74	0.58	0.73	0.86	0.87	0.82	0.84	0.77
	60	62	60	61	61	60	57	60	60	61	60	59	57	59	56	58	56	55	49	51	50
BIH/LEEV	0.83	0.81	0.83	0.65	0.68	0.88	0.30	0.30	0.30	0.84	0.63	0.73	0.74	0.83	0.50	0.81	0.77	0.75	0.71	0.81	0.68
	19	19	18	19	19	19	20	20	19	20	18	19	19	18	19	17	17	17	16	16	14
BIH/MONO	0.71	0.67	0.77	0.67	0.52	0.67	0.47	0.37	0.67	0.40	0.78	0.69	0.70	0.64	0.50	0.70	0.64	0.70	0.67	0.65	0.54
	39	39	38	38	38	38	38	38	38	39	39	38	38	38	38	38	37	37	37	36	37
COAR/SENT	0.89	0.86	0.97	0.87	0.89	0.85	0.88	0.48	0.91	0.87	0.82	0.90	0.91	0.95	0.80	0.87	0.91	0.93	0.95	0.93	0.91
	29	30	31	30	28	28	25	27	28	30	30	29	28	28	22	28	28	28	22	20	22
ELLL/GEML	0.75	0.85	0.87	0.76	0.68	0.62	0.69	0.73	0.86	0.78	0.80	0.89	0.81	0.81	0.71	0.83	0.80	0.81	0.81	0.82	0.81
	75	75	75	74	75	73	73	73	71	72	72	75	73	74	71	68	68	70	63	64	66
GIFO/SOUL	0.88	0.93	0.80	0.78	0.33	0.26	0.61	0.52	0.31	0.57	0.94	0.96	0.91	0.78	0.54	0.85	0.87	0.89	0.81	0.81	0.79
	24	24	24	24	24	23	23	23	23	23	24	24	24	24	23	23	23	23	22	22	23
GRGR/BINT	0.88	0.88	0.84	0.71	0.60	0.36	0.15	0.51	0.76	0.64	0.71	0.85	0.91	0.81	0.24	0.74	0.89	0.89	0.86	0.86	0.82
	44	45	44	44	45	45	45	45	45	45	45	45	44	44	45	44	43	43	43	42	43
GRGR/BIH	0.84	0.82	0.82	0.48	0.46	0.47	0.12	0.45	0.56	0.56	0.66	0.78	0.85	0.67	0.31	0.70	0.87	0.86	0.86	0.84	0.75
	64	64	64	64	64	64	64	64	65	64	63	63	63	64	64	63	63	63	63	63	63
BIH/BUNC	0.89	0.94	0.76	0.64	0.96	-0.19	0.13	0.09	0.60	0.75	0.56	0.71	0.71	0.95	-0.14	-0.09	0.60	0.74	0.67	0.66	0.78
	7	6	7	8	11	11	12	12	11	11	9	8	6	7	11	9	6	6	6	6	5
GRGR/LODG	0.96	0.94	0.97	0.94	0.89	0.94	0.76	0.60	0.91	0.95	0.98	0.94	0.95	0.95	0.86	0.96	0.93	0.93	0.93	0.93	0.95
	39	39	39	39	39	39	39	39	38	39	39	39	39	39	39	38	38	38	37	37	37
GRGR/SOUL	0.94	0.90	0.88	0.68	0.52	0.32	0.26	0.40	0.88	0.82	0.82	0.91	0.92	0.80	0.34	0.87	0.90	0.88	0.87	0.86	0.81
	38	38	37	37	38	35	36	37	36	37	36	37	37	36	34	35	35	34	30	29	31
HECH/ELLL	0.87	0.90	0.84	0.67	0.54	0.62	0.40	0.38	0.75	0.84	0.79	0.86	0.85	0.66	0.42	0.88	0.83	0.80	0.75	0.73	0.72
	76	76	76	75	76	74	74	73	73	74	74	76	74	75	72	72	71	71	66	68	70

Table 5. Correlations for precipitation for the SIEN. For each station pair, the top line shows the correlation coefficient and the bottom line shows the number of years used in the correlation (continued).

Site Precip.	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	DJF	MAM	JJA	SON	Oct-Mar	Nov-Apr	Oct-Sep	Jul-Jun	Jan-Dec
HECH/MTHR	0.98	0.96	0.97	0.97	0.94	0.87	0.91	0.92	0.98	0.92	0.98	0.98	0.98	0.96	0.89	0.97	0.98	0.98	0.98	0.98	0.97
	55	53	51	53	51	52	52	50	52	52	52	51	48	49	49	51	46	46	41	41	42
HECH/TMRS	0.96	0.96	0.96	0.93	0.62	0.58	0.55	0.16	0.50	0.89	0.94	0.96	0.96	0.96	0.65	0.91	0.95	0.94	0.95	0.94	0.95
	19	17	18	17	16	20	28	28	28	20	19	20	16	15	19	17	14	16	12	12	13
LEEV/ELLL	0.82	0.89	0.76	0.81	0.76	0.73	0.58	0.72	0.67	0.81	0.70	0.86	0.83	0.85	0.76	0.72	0.82	0.83	0.88	0.83	0.90
	17	16	15	15	16	15	17	16	15	17	15	17	16	14	14	13	13	12	9	10	9
MTHR/SENT	0.92	0.90	0.92	0.90	0.88	0.70	0.88	0.37	0.94	0.89	0.93	0.95	0.93	0.89	0.50	0.90	0.90	0.91	0.91	0.89	0.88
	55	53	51	53	51	52	52	50	52	52	52	51	48	49	49	51	46	46	41	41	42
MTHR/YPHQ	0.95	0.93	0.90	0.94	0.84	0.74	0.77	0.71	0.90	0.89	0.96	0.95	0.96	0.89	0.69	0.94	0.94	0.94	0.94	0.93	0.93
	55	53	51	53	51	52	52	50	52	52	52	51	48	49	49	51	46	46	41	41	42
MONO/ELLL	0.89	0.93	0.84	0.74	0.87	0.55	0.70	0.51	0.82	0.89	0.90	0.82	0.86	0.88	0.55	0.89	0.86	0.86	0.85	0.80	0.81
	35	35	34	34	34	34	34	34	34	34	34	33	33	34	34	34	32	32	32	32	33
SENT/GRGR	0.94	0.92	0.94	0.94	0.89	0.77	0.75	0.73	0.75	0.89	0.91	0.91	0.95	0.95	0.74	0.88	0.94	0.94	0.94	0.93	0.92
	66	66	66	66	66	66	67	67	67	67	67	66	66	66	66	67	66	66	66	66	65
SENT/NFRS	0.96	0.94	0.95	0.92	0.88	0.79	0.84	0.54	0.96	0.90	0.92	0.95	0.95	0.93	0.74	0.91	0.94	0.94	0.94	0.94	0.92
	62	62	61	64	64	64	66	66	65	63	66	61	56	60	63	62	50	52	46	48	46
TMRS/ELLL	0.96	0.93	0.91	0.92	0.81	0.68	0.62	0.51	0.41	0.90	0.78	0.84	0.89	0.92	0.60	0.88	0.90	0.96	0.91	0.94	0.97
	17	15	16	14	14	17	26	25	25	18	16	18	14	12	15	13	11	12	6	7	8
TMRS/GEML	0.76	0.90	0.86	0.36	0.71	0.46	0.75	0.56	0.53	0.83	0.89	0.78	0.79	0.66	0.46	0.92	0.68	0.65	0.33	0.72	0.81
	16	14	15	14	13	16	25	26	24	16	15	17	13	12	15	11	10	12	5	6	6
GRGR/BINT	0.88	0.88	0.84	0.71	0.60	0.36	0.15	0.51	0.76	0.64	0.72	0.85	0.91	0.81	0.24	0.74	0.89	0.89	0.86	0.86	0.82
	44	45	44	44	45	45	45	45	45	45	45	45	44	44	45	44	43	43	43	42	43
GRGR/BIH	0.84	0.82	0.82	0.48	0.46	0.47	0.12	0.45	0.56	0.56	0.66	0.78	0.85	0.67	0.31	0.70	0.87	0.86	0.86	0.84	0.75
	64	64	64	64	64	64	64	64	65	64	63	63	63	64	64	63	63	63	63	63	63
GRGR/SOUL	0.94	0.90	0.88	0.68	0.52	0.32	0.26	0.40	0.88	0.82	0.82	0.91	0.92	0.80	0.34	0.87	0.90	0.88	0.87	0.86	0.81
	38	38	37	37	38	35	36	37	36	37	36	37	37	36	34	35	35	34	30	29	31

Description of Individual Observing Sites

This section highlights several stations, selected because of length of record, degree of attention and use they receive, need for addressing problems, and potential for additional usefulness. The situation at nearly every station continues to evolve, including during the preparation of this report. Comments here reflect our knowledge of the station circumstances updated through August 2011. This section has benefitted tremendously from discussions with the National Weather Service Weather Forecast Office in Hanford CA.

Yosemite Headquarters COOP station

Yosemite Park Headquarters COOP station (COOP ID 04-9855) is a long-term climate station uniquely situated in the US, with its proximity to two extensive parallel vertical rock faces. The record is used very heavily for a wide variety of applications. The COOP network is managed by the NWS, who does not typically compensate volunteers to make the daily observations. At this site, the measurements are made by park personnel as part of their other duties. The station, by virtue of several metadata characteristics, is considered to be a member of the US Historical Climatology Network (USHCN). The USHCN is not a network per se, but rather simply a designation applied to a subset of the entire COOP network, emphasizing the longest lived stations with the most complete records. The USHCN stations are frequently used preferentially for local, regional, national, and global climate studies. It is worth noting that this status is based entirely on metadata, and not on any measure of data quality. As a member of the USHCN, Yosemite Park HQ is and will continue to be frequently used for climate change and variability studies. Of the 40 USHCN sites in California, Yosemite Park HQ is the only COOP station within the boundaries of the SIEN park units that has met requirements for inclusion in the USHCN data set.

Few COOP stations have perfect records, and in those that extend close to a century, we frequently encounter changes in observers, instruments, surrounding environments, observing techniques, the exact location of the station, and other characteristics. All of these can manifest themselves in properties of the data, and many times these effects are very subtle, and not at all apparent from cursory inspection of station records. Nonetheless, it was disconcerting to see several unexplained discontinuities in the Park Headquarters record when we compared this record with a variety of sites in or near Yosemite, sites that we expect should have good correlations with this one. A sample of discontinuities in daily minimum temperature in a recent 57-year period (1948-2005) is shown in Figure 44. A double mass analysis was performed to determine “change points”, or times when a significant change occurred at Yosemite Park HQ, with respect to simultaneous records from three nearby COOP stations. For these analyses, any change in slope indicates a change in station-to-station relationship. If more than one comparison station has a change in relationship with the candidate station, this furnishes strong evidence that the change, whatever it might be and whatever its source, is at the candidate station and not at the comparison station. The analysis includes a statistical test to objectively identify changes in relationship, indicated by vertical black lines. Several change-points are seen in these 57-years. The most apparent change occurred around 1966. (Since we are using daily data, we can sometimes pinpoint station changes to the nearest day, solely from data behavior. That is not the case here, however.) As a side observation, one might note how well the comparison stations relate to each other (particularly Hetch Hetchy and Auburn).

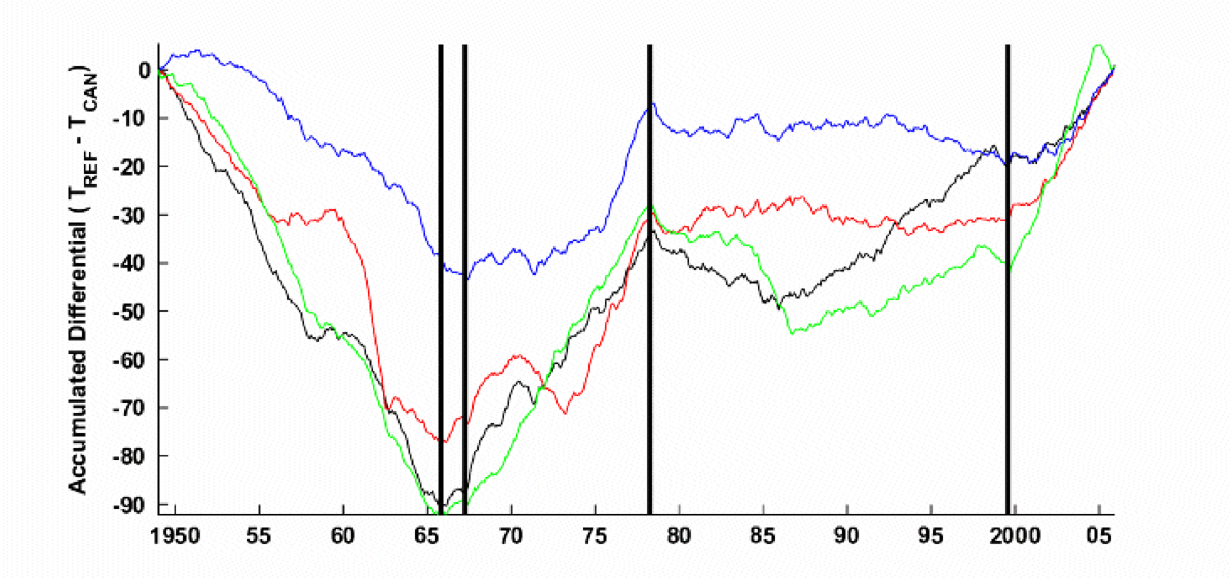


Figure 44. Double mass detection of climate inhomogeneities at Yosemite National Park Headquarters. Residual figure from double mass analysis for monthly mean minimum temperature using candidate station Yosemite Park Headquarters and four reference stations, Hetch Hetchy (green), Calaveras Big Trees (blue), Cherry Valley Dam (red), and Auburn (black). Vertical black dashed lines indicate intervals where three or more stations furnish evidence of an inhomogeneity. *Figure courtesy of John Abatzoglou.*

The metadata maintained by NOAA show that there was a change in observation time from 5 PM to 7 AM in 1967. This typically causes a station to appear to be cooler, but we also note a change in the sign of the slope, so perhaps there was also some other kind of change, such as a change in position. It should be emphasized that moves of only a few tens of feet, or changes in the methodology of the observations, can lead to changes in climate relationships between stations. The effects seen at Park Headquarters are rather striking, and do not lend great confidence to this record. One goal of this kind of analysis is to show just how important it is to maintain consistent observing circumstances, physically and methodologically, and thereby prevent any future artificial changes.

This example demonstrates the usefulness of tools like double mass analysis to identify changes in relationships between stations, and thus in the homogeneity of the records themselves. This method does not rely on metadata, and indeed, very many stations exhibit changes in their records that have no documentation support whatsoever. The quality and completeness of the station documentation has varied over time, and in general this quality has declined over the past two decades. The entire issue is now getting increased attention nationally, as more examples of these shortcomings have come to light.

We have also identified more recent observational problems, of a different nature, at the Park Headquarters COOP station. After several consecutive decades of relatively complete data, starting in 2004 there was a dramatic increase in the number of missing observations, with some months missing 10 to 20 days, and in the number of missing forms, indicating that the records were sometimes not even going into the national archives. Some months had insufficient data to compute monthly averages, and thus for some applications the record appeared to have effectively ended. As the main climate record for Yosemite National Park, this was very much a surprise. We could not discern any of the typical patterns often seen in missing data, such as missing weekends, etc. We also noted problems and inconsistencies in snowfall, snow depth, and precipitation measurements. This is very troubling due to the world-wide significance of this station for documenting day-to-day weather and tracking of variations in climate, its importance for park visitors and employees and the research community who need a long term station with reliable data.

We have seen this incomplete reporting in both temperature and precipitation variables, as illustrated in Figure 45. White pixels in these diagrams indicate days with no observations. The mottled appearance of the decade of the 2000s shows the great deterioration of this station compared with anything in the previous record. On a more positive note, we also found, from the correlation analysis, that the past record does have considerable value, giving motivation to restore this station's observing record to acceptable standards. By virtue of its prominence, the Yosemite Park Headquarters observational record should endeavor to be a model for others to emulate.

During the assembly of the report, a new observer was identified, and the temperature sensor was relocated (to avoid digging a long trench to the existing location). This move occurred on August 20, 2008, from the prior location (shown below in Figure 47) to a new site 140 feet (43 m) and 110 degrees of azimuth (i.e., toward the ESE) from the unchanged location of the 8" Standard Rain Gauge in the fenced area (also seen in Figure 47). This new MMTS thermometer has remained at this position since that day. Note that the NWS official latitude/longitude position of a station refers to the precipitation gauge. The observations improved markedly in quantity and quality. However, not long thereafter, the records began once again to become more sporadic, and eventually appeared to cease altogether, and Yosemite Valley was producing no useful climate records as of Spring 2010. Subsequently, another attempt was made later in 2010 to improve the observational logistics, and so far this seems to be succeeding. This can be seen by the nearly solid line in Figure 45 for 2010.

During 2010, the NWS began a new approach to entering COOP data. Data can be entered each day via the web, through a national application run at WRCC called WeatherCoder. This is a step to go "paperless" for the entire COOP network. At this writing, over 3500 stations have converted to this format. WeatherCoder catches many problems early and has helped to greatly improve the data availability from the COOP Network. This appears to be part of the reason why the record has so greatly improved in 2010 and into the first half of 2011.

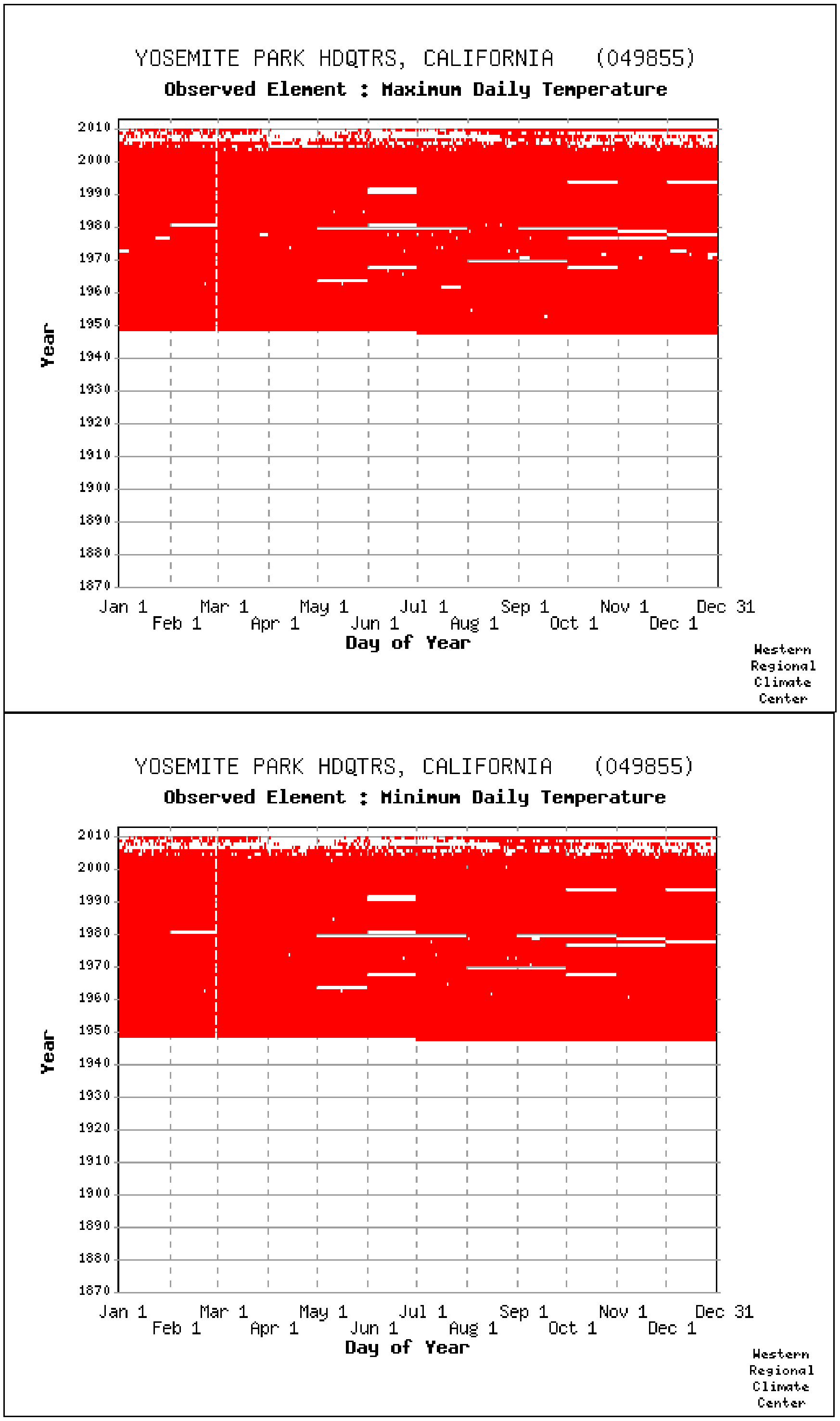


Figure 45. Yosemite Park Headquarters daily data availability graphic 1948-2010 (station 049855 metadata graphics). Data availability for every day in the last 60 years (1948-2010) is represented by a colored (present) or white (missing) pixel. Solid colors indicate periods of no missing data. White horizontal strips of one month duration indicate that the form was not received for keypunching at NCDC. The mottled appearance of recent years indicates a great increase in the number of missing values. *Source: WRCC web site.*

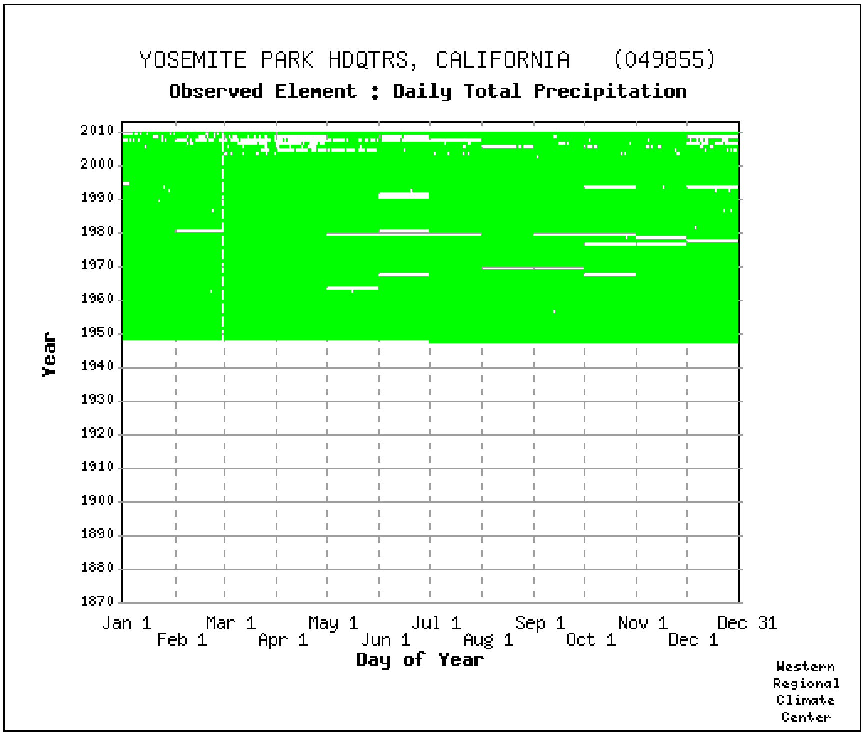
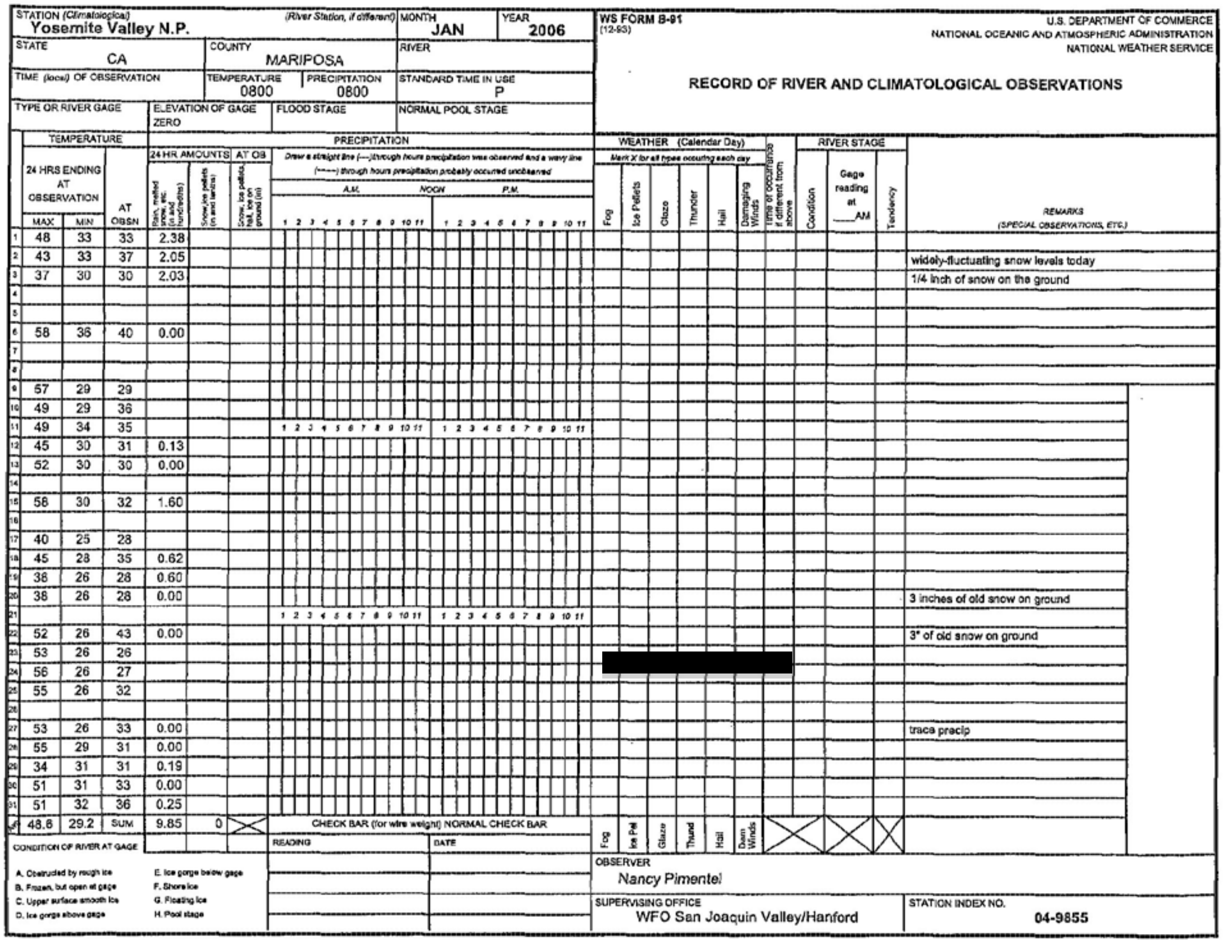


Figure 45. Yosemite Park Headquarters daily data availability graphic 1948-2010 (station 049855 metadata graphics). Data availability for every day in the last 60 years (1948-2010) is represented by a colored (present) or white (missing) pixel. Solid colors indicate periods of no missing data. White horizontal strips of one month duration indicate that the form was not received for keypunching at NCDC. The mottled appearance of recent years indicates a great increase in the number of missing values. *Source: WRCC web site* (continued).

Snowfall is another measurement that holds the keen interest of many, particularly with climate warming. Snowfall is often recorded incorrectly on the form at this site in recent years, and therefore the data have not keypunched correctly in the national database that the research community obtains from the national climate archive. The observer(s) often notes new snowfall, snow water equivalent, and/or snow depth in the "Remarks" section on the observational form, which is not the correct placement of these measurements. There are specific columns for entering these data, and when they are entered in the Remarks section, those values are not entered into the digital archive. Data have been manually keyed at a large facility in Kentucky, where the personnel are instructed to strictly follow the correct protocols, and snow information entered as remarks is ignored for this purpose. As a result, no snowfall was officially reported at Yosemite Park Headquarters since February 2004, despite some measurements noted on the observation forms. This is indeed lamentable at a station of such importance. If the forms have been saved locally, the snowfall amounts could be retrospectively entered into the data base.

An example of the poor observational reporting is shown on the observer form for January 2006, with zero snowfall reported for the month (Figure 46). In looking for corroboration, we noted that for that month Hetch Hetchy (100 feet lower in elevation) recorded 10 inches of snow, and Mather (500 feet higher) reported 38 inches. More surprisingly, we found that Yosemite South Entrance did not report *any* snow for four consecutive winters, from 2003-04 through 2006-07, in a location that averages 106 inches per winter. The observations are not "missing," but rather are positive (explicit) zeros. Non-zero snow observations resumed there in December 2007. These values corrupt the climatological record, and are in the national archive. We have received many inquiries from those performing research who are puzzled by the sudden lack of snow. The snowfall study of Christy and Hnilo (2010) made repeated reference to this puzzling behavior. These are the records that are used in most climate studies, often and unfortunately without an examination of the data for such problems, because these records are presumed to be correctly quality controlled. The quality control techniques at the National Climatic Data Center will not detect such snow problems, because they focus solely on within-month comparisons.

The recent move to WeatherCoder, discussed above, prompts the observer to directly enter snowfall in the proper place on the web interface. The observer must follow the correct protocols or else they will not be allowed to proceed. This electronic entry, which immediately prompts the observer about all irregularities, has produced an immediate and substantial improvement in the quality of manual climate records. We are hopeful that this will resume what once was a very good snowfall record at Yosemite Park Headquarters.



STATION (Climatological) Yosemite Valley N.P.
(River Station, if different)
MONTH JAN
YEAR 2006
STATE CA
COUNTY MARIPOSA
RIVER
TIME (local) OF OBSERVATION
TEMPERATURE 0800
PRECIPITATION 0800
STANDARD TIME IN USE P
TYPE OR RIVER GAGE
ELEVATION OF GAGE ZERO
FLOOD STAGE
NORMAL POOL STAGE

WS FORM B-91
(12-93)

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL WEATHER SERVICE

RECORD OF RIVER AND CLIMATOLOGICAL OBSERVATIONS

PRECIPITATION: Draw a straight line (——) through hours precipitation was observed and a wavy line (~~~~) through hours precipitation probably occurred unobserved. A.M. NOON P.M. 1 2 3 4 5 6 7 8 9 10 11 1 2 3 4 5 6 7 8 9 10 11

WEATHER (Calendar Day): Mark X for all types occurring each day

	TEMPERATURE 24 HRS ENDING AT OBSERVATION MAX	MIN	AT OBSN	PRECIPITATION 24 HR AMOUNTS Rain, melted snow, etc. (in and hundredths)	Snow, ice pellets (in and tenths)	AT OB Snow, ice pellets, hail, ice on ground (in)	Fog	Ice Pellets	Glaze	Thunder	Hail	Damaging Winds	Time of occurrence if different from above	RIVER STAGE Condition	Gage reading at ____AM	Tendency	REMARKS (SPECIAL OBSERVATIONS, ETC.)
1	48	33	33	2.38													
2	43	33	37	2.05													widely-fluctuating snow levels today
3	37	30	30	2.03													1/4 inch of snow on the ground
4																	
5																	
6	58	36	40	0.00													
7																	
8																	
9	57	29	29														
10	49	29	36														
11	49	34	35														
12	45	30	31	0.13													
13	52	30	30	0.00													
14																	
15	58	30	32	1.60													
16																	
17	40	25	28														
18	45	28	35	0.62													
19	38	26	28	0.60													
20	38	26	28	0.00													3 inches of old snow on ground
21																	
22	52	26	43	0.00													3" of old snow on ground
23	53	26	26														
24	56	26	27				[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]				
25	55	26	32														
26																	
27	53	26	33	0.00													trace precip
28	55	29	31	0.00													
29	34	31	31	0.19													
30	51	31	33	0.00													
31	51	32	36	0.25													
	48.6	29.2	SUM	9.85	0		Fog	Ice Pel	Glaze	Thund	Hail	Dam Winds					

CHECK BAR (for wire weight) NORMAL CHECK BAR
READING
DATE

CONDITION OF RIVER AT GAGE
A. Obstructed by rough ice
B. Frozen, but open at gage
C. Upper surface smooth ice
D. Ice gorge above gage
E. Ice gorge below gage
F. Shore ice
G. Floating ice
H. Pool stage

OBSERVER Nancy Pimentel
SUPERVISING OFFICE WFO San Joaquin Valley/Hanford
STATION INDEX NO. 04-9855

Figure 46. Example of a poor quality COOP observation form at Yosemite Park Headquarters. Note the large number of missing temperature values in the left three columns, and snowfall and snow depth are omitted entirely, or in the Remarks (right hand) column, information that is not transcribed into the official digital record.

A moderately complete photodocumentation (about 35 pictures) of the Park Headquarters climate site was performed on 2003 October 9 by Kelly Redmond. Selected photos are shown (Figure 47-53) to illustrate the layout, the overall setting, exposure, proximity to nearby objects, and the condition of the equipment. Most of the equipment belongs to NWS. A separate third-party station consisting of at least an ETI storage precipitation gauge, and an automated temperature sensor, are also located at the site. CDEC information indicates this site belongs to Merced Irrigation District. Note that these photographs pre-date the move of the MMTS thermometer to a location 140 feet to the east-southeast in August 2009.

Images captured from Google Earth (Figures 54 and 55) show aerial views of the environmental circumstances affecting the Yosemite Park Headquarters temperature and precipitation record, at two different spatial scales, both important to interpretation of the climate record.

Figure 47. Yosemite Park Headquarters NWS COOP Station, looking toward south. Of interest, from right: Standard 8-inch NWS precipitation gauge (dark cylinder at right), Fisher-Porter hourly precipitation recording gauge (white tapered top), Cotton Region Shelter that formerly housed liquid-in-glass max/min thermometers (atop aluminum cross-braced stand, now unused), MMTS (Max/Min Temperature System behind Cotton Region Shelter, later moved 140 feet to the left), non-NWS equipment for precipitation event reporting (ETI (the manufacturer) precipitation gauge, a CDEC station, owned by Merced Irrigation District (MID, tall white tubes left rear portion of fenced area). October 9, 2003. *Photo by Kelly Redmond.*

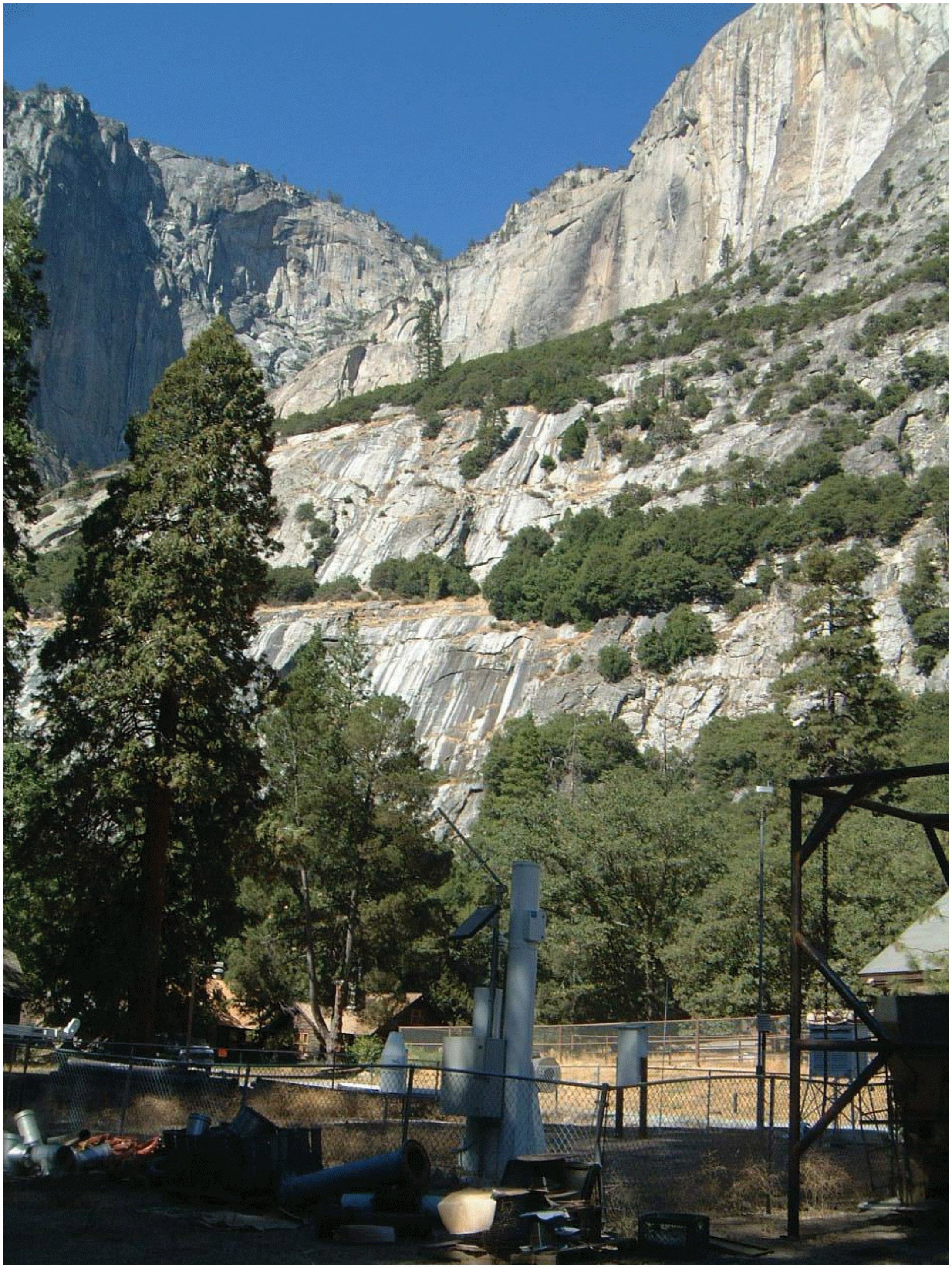


Figure 48. Yosemite Park Headquarters NWS COOP looking toward northwest. Station in foreground, showing proximity to north valley wall. October 9, 2003. *Photo by Kelly Redmond.*

Figure 49. Setting of Yosemite Park Headquarters NWS COOP station, toward due east. The relocated thermometer is 140 feet beyond the dark-colored rain gauge seen about one-fourth frame from the left hand side of the picture, just beyond the tall trees over the yellow truck. October 9, 2003*. Photo by Kelly Redmond.*

Figure 50. Yosemite Park Headquarters NWS COOP station, old and new thermometers. Previous (right, wooden louvred box) and recent (center, MMTS with radiation shields) temperature sensor locations, and ground surface detail. MMTS system was subsequently moved 140 feet to the left of the viewing angle (in August 2009). Manual US Forest Service precipitation gauge on left (not sure if this is in use). Looking toward southwest, October 9, 2003. *Photo by Kelly Redmond.*

Figure 51. Yosemite Park Headquarters NWS COOP station and MID equipment. Prior temperature sensor locations (Cotton Region Shelter, left; and MMTS “beehive” in center), both NWS equipment, now moved about 140 feet to the left. Third party gauge in rear, precipitation storage gauge (left, with fin), and automated temperature sensor, with satellite transmitter. That station belongs to Merced Irrigation District (MID), and reports via telemetry to CDWR/CDEC in Sacramento. Looking toward south southeast, October 9, 2003. *Photo by Kelly Redmond.*

Figure 52. Yosemite Park Headquarters NWS COOP station, toward due west. Foreground: Older Cotton Region Shelter to right, newer style but since-relocated MMTS temperature system to left. Rear: Standard precipitation gauge to right, automated Fisher-Porter precipitation gauge to left. White panel structure to left housed fire weather equipment in the past. October 9, 2003. *Photo by Kelly Redmond.*

Figure 53. Yosemite Park HQ NWS COOP station and relation to parking and facilities. Observers at this date worked in the dispatch and fire building over the white trailer. Looking toward east northeast, October 9, 2003. *Photo by Kelly Redmond.*

Figure 54. Aerial view of Yosemite Park Headquarters climate station and immediate surroundings. The fenced area is just below the numeral “119” near the center. Distance scale at lower left. North is up. *Google Earth image from August 2005.*

Figure 55. Aerial view of Yosemite Park Headquarters climate station in relation to rock faces. The fenced area is just left of and below the numeral "119" near the center. Distance scale at lower left. Rock wall and base of Yosemite Falls is at center left. North is up. *Google Earth Image from August 2005.*

After examination of the photos, it is not clear why there would have been any gaps at all in the daily temperature record. The Max/Min Temperature System (MMTS) shown in the photos has a memory of anywhere from 7-30 days, and an interface that enable previous days to be recalled from memory. Thus, one would expect almost no missing data, since values can be entered on the form retrospectively.

Although there are indications that recent changes have led to considerable improvements, we would strongly advise that climate monitoring activities in YOSE and SEKI continue to be given added attention, and in coordination with the local Hanford NWS Observation Program Leader. It is possible to retrospectively estimate the missing and questionable values at this station by regression on other subsequently available data, but that takes resources to set up and maintain, and it is much better to make complete and accurate measurements from the start.

In addition, an automated station should be deployed in the vicinity of the present long-term site, or elsewhere in the valley. Such a site would:

- Offer backup for data outages at the manual Park Headquarters site
- Be under the sole control of NPS
- Provide hourly or sub-hourly time resolution of climatic elements
- Provide data not now gathered or readily accessible in Yosemite Valley: wind speed and direction, humidity, precipitation, soil moisture, solar radiation, and snow depth
- Report in real time to improve the flow of data and information from the Valley to the outside world.

This station could be a RAWS station with additional equipment, utilizing existing communication options and the facilities of the National Interagency Fire Center and WRCC, or utilize its own short-haul linkages with an internet connection in the valley. Air flow is clearly constrained in Yosemite Valley, but wind affects soil moisture and atmospheric drying of vegetation.

During autumn of 2010, such a station appears to have been identified. A tripod-mounted air quality station already operating near the school and ball park was offered as a potential back-up for use in reconstructing missing days from the main climate station. In addition, this site has wind and humidity measurements, which are not currently measured, with good quality (RM Young) sensors, which address some of the concerns expressed above.

In addition, it appears that the newly refurbished stream gauge at Happy Isles also makes weather measurements of at least a few elements. Although these are not a replacement for the NWS COOP measurements, it is quite likely that the temperature measurements from this site will correlate well with those from the Park HQ COOP station.

At present, another station installed and maintained by Merced Irrigation District (MID) is providing hourly temperature and precipitation measurements just a few feet from the NWS rain gauge. This has hourly values dating from December 1998, available through CDEC. Such data sets can often be used to infill or reconstruct, or provide quality control, for nearby stations. However, a careful look at July 2007 and January 2008 shows that the hourly temperatures from this station seem to have significant problems of their own. A comparison shows that July maximum temperatures from the automated MID sensor runs on average 6.5 degrees F higher than the NWS Yosemite Park HQ COOP site, and that the minimum temperatures are about 4.6 degrees higher than the NWS COOP station. There are methods to filter this bias out, but such big differences within about 150 feet and at nearly the same elevation are quite disconcerting. As of summer 2011, the MID station continues to read systematically higher than the official COOP station.

As of August 2011, the values reported by the NWS COOP site are routinely entering the national archive in the manner intended. To complicate matters, for reasons of expediency and

Yosemite Valley forecast evaluation, as of now the values reported for immediate public consumption in NWS daily summary tables are actually taken from the MID sensor. This is confusing because the official NWS readings and the MID readings do not agree. We hope that if the Park Headquarters COOP record remains complete and up to date, the NWS will revert to using those readings in its daily Regional Temperature and Precipitation (RTP) tables, the source of the values usually reported on their web site and in local newspapers. To be clear, the values now reported in the news are from the MID sensor (NWS Location Identifier YYVC1) and not from the official Park Headquarters thermometer (NWS Location Identifier YPQC1) located 140 feet away.

The situation illustrates very well the central issue of quality control: The assessment, evaluation and improvement of *imperfect data* by making use of *other imperfect data*.

South Entrance Yosemite COOP Station

The South Entrance Yosemite Park COOP station ("South Entrance", ID 048380) is also a site of some concern. Figure 23 shows the setting of the equipment. The vegetation that has been allowed to grow around the precipitation gauge and especially the temperature sensor can have a significant impact on the climate measured at this site. The NWS Cooperative Observer Program website (http://www.nws.noaa.gov/directives/010/pd01013002c.pdf) describes acceptable siting for the temperature sensor and precipitation gauge as follows:

"Air Temperature Sensors. Specific permission to depart from the standards may be granted in writing by the Regional Headquarters and must be documented on the station information forms. Site the temperature sensor according to the following standards:

a. over level terrain (earth or sod) typical of the area around the station, and;

b. at least 100 feet from any extensive concrete or paved surface.

c. All attempts will be made to avoid:

(1) areas where rough terrain or air drainage are proven to result in nonrepresentative temperature data,

(2) areas where water tends to collect, and

(3) areas where drifting snow collects.

d. If the sensor is within a shelter, position the shelter so it opens to the north with the floor 4 to 6 feet above the surface. Shelters should be located no closer to an obstruction than four times the height of the obstruction.

e. In the case of remote sensors not exposed in shelters, the air intake will be 4 to 6 feet above the surface. Remote sensors should be located no closer to an obstruction than four times the height of the obstruction.

f. An object will be considered an obstruction if the object is greater than ten degrees in horizontal width as measured from the sensor and within 200 feet of the sensor.

Precipitation Gauges. The exposure of the precipitation gauge is of primary importance in the accuracy of precipitation measurements, especially snowfall measurements. An ideal exposure would eliminate all turbulence and eddy currents, near the gauge, that tend to carry away the precipitation. The loss of precipitation in this manner tends to increase with wind speed and orifice height.

a. The orifice of the gauge will be horizontal and 3 to 5 feet above the surface. Exceptions must be granted by the Regional Headquarters in writing and described in the station information documentation.

b. The gauge site should have protection in all directions by objects of uniform height. Where the heights of the objects are uniform and the height of these objects and the distance from the gauge is generally uniform, their height above the gauge orifice should not exceed twice their distance from the gauge.

c. In open areas, the heights of obstructions above the orifice should not exceed twice their distance from the gauge."

We recommend that these standards be accommodated at South Entrance where possible, including trimming of vegetation around the gauge if this is within NPS regulations. Site maintenance for NWS cooperative stations is usually a joint effort between the site host and NWS.

This station has been in the current location for about a decade. Prior to that time the station was about a hundred yards to the south, across the highway, near the historic ranger station for this area. The station was moved because of plans to remove the ranger station at that time. The present site was deemed at the time of relocation to be compatible with the prior site, but this assumption has not yet been tested for accuracy.

As is the case at Yosemite Park Headquarters, it should also be noted that Merced Irrigation District has a site very close to the NWS South Entrance COOP station. Their site is behind (north of) the South Entrance Ranger Station, about 100 feet from the building, on the opposite side from the NWS station. This station sits on a steep slope, and the rim of the precipitation gauge for this station is about ten feet above the roof level of the ranger station, and perhaps 30-40 feet higher than the NWS COOP station in the front yard. Thus one would not expect the exact same temperatures at these two nearly coincident sites, but their temperatures and precipitation should track each other in time very closely. Thus, the Merced Irrigation District site may be useful for quality control and infill of the long term South Entrance site, with proper attention to bias removal. Fortunately, this NWS COOP site does not suffer from the large number of missing observations that the Park Headquarters station has in recent years. Further of note, local discussions reveal there have been occasions where temperature values from the back yard MID site have been used interchangeably with values from the front yard NWS COOP site. These stations use a different reporting interval, have different sensors, and have different microclimates, and the temptation to intermingle their measurements, which leads to a corrupted record, should be avoided as much as possible. Numerous training experiences have shown how difficult it can be to convince observers that real and important systematic differences can occur over very small horizontal and vertical distances.

Tuolumne Meadows Ranger Station

The Tuolumne Meadows Ranger Station (TMRS) data were acquired from Dr. Jessica Lundquist and Bob Gregg. This is a unique record because it consists of year-round manual observations at a high-elevation site in the SIEN area, a rare circumstance because these sites are difficult to access year round. We were impressed by the accuracy and completeness of the climate records. As described in the correlation section, TMRS is an extremely useful station with high correlations to other manual and automated sites, and can potentially be used to verify automated measurements, or fill in gaps of missing data should equipment failure occur. This paper record has been digitized into our database for the months and years for which we gained access, and we hope to continue receiving these observation forms in the future. Based on our experience, the quality of observations here are excellent compared to many others, including some NWS COOP inside and outside of the SIEN. It is worthwhile for the SIEN to invest in maintaining this station with their year-round rangers, both for continuity of record and because of the importance of potential climate impacts on this region. WRCC hopes to continue receiving these observations for incorporation into our database for distribution, if the National Park Service parties responsible are agreeable.

The logistics associated with this valuable location, and the great difference between winter and summer, continue to produce challenges. The temperature shelter is moved (personal correspondence, NWS) about 200 yards between winter and summer. Depending on exact local circumstances, including the amount of snow on the ground, such relocations can lead to systematic differences. If these moves never vary from year to year in location or date, the effect on the climate record is reduced. But, such moves can be a source of non-homogeneous climate records, and thus artificial climate change. Also, when the official thermometer cannot be conveniently reached, or when the station must be abandoned (as in April 2011, due to excessive snow and depletion of supplies), temperature readings are sometimes substituted from the Gaylor RAWS station, nearly a mile away and on a side slope. The Gaylor site is only somewhat representative of the Tuolumne Meadows Ranger Station, and such substitutions should be avoided as much as possible. A small high-capacity recording thermometer placed within the same shelter would yield a better estimate, perhaps with simultaneous measurements to develop seasonally varying regression coefficients between the two thermometer systems. Such thermometers, which have reasonably high quality, have become ubiquitous in the last few years.

Stations in Sequoia and Kings Canyon National Parks

WRCC personnel have had much more direct involvement in field projects at YOSE and vicinity than SEKI, and thus have had better access to more station photos and directly acquired metadata for YOSE. Nevertheless, full sets of photos for SEKI (with some limitations) have recently been acquired, and discussions with NWS personnel have been invaluable in better understanding the recent history of SEKI climate stations. Examination of the correlation analysis results, and of the station reporting, shows that the SEKI climate records from NOAA cooperative stations generally appear to be of good or better quality, exhibiting fewer problems with spotty data in recent years than the YOSE stations. We present a selection of photos from north to south in SEKI, with commentary on each site.

Grant Grove

This station has been in the same location for decades, approximately 50-100 feet behind the visitor center. The site was fully photographed by Kelly Redmond in October 2008 (Figures 56-

59). Figure 60 shows the overall setting; NWS personnel (private communication) have indicated that the Google Earth aerial image position is fairly close to the actual position as seen from the ground. The temperature shelter is a fixed distance above the ground, and in response to ranger inquiries NWS has requested that in heavy snow years, when the shelter might become buried, the observer wipe away the snow from all sides of the shelter to permit continued ventilation. This may even result in the shelter sitting in a kind of pit during deep snow pack.

A NOAA capability called permits direct electronic entry of manual measurements into the national distribution system from (currently) about 3800 climate stations around the United States each day. The software was completely re-written by WRCC, which is also the current national entry point for the entire country. Grant Grove data are entered via this system, and for that station the web entry is performed on-site by NPS personnel. Two major advantages of this system are 1) that data are available almost immediately around the country, and 2) quality control at the point of entry is resulting in much better manual data nationwide. WeatherCoder is the means by which the NWS Cooperative Observer Program will eventually become "paperless."

The site appears to be a very good location, well shaded for temperature and protected from wind by low trees for precipitation. The shelter is more open than most, and is in need of paint. However, as of this writing the NWS plans to replace the liquid-in-glass thermometer with an electronic MMTS (Max/Min Temperature System), at the very same location. Overall, we see few issues with this installation, and simply encourage the continued existence of the station at this location for the indefinite future.

Figure 56. Grant Grove NWS COOP station looking toward due west. Thermometer is in Cotton Region Shelter, snow board in foreground (for daily snowfall), 8” US Standard Rain Gauge behind truck bumper. *Photo on October 11, 2008 by Kelly Redmond.*

Figure 57. Grant Grove NWS COOP station looking toward northwest and visitor center. Thermometer is in Cotton Region Shelter, snow board in foreground (for daily snowfall), and relation of site to visitor center in right background. *Photo on October 11, 2008 by Kelly Redmond.*

Figure 58. Grant Grove NWS COOP station looking toward southwest with hydro equipment. Relationship of temperature equipment to precipitation measurements: Thermometer is in Cotton Region Shelter, 8” Standard Rain Gauge to left in background, snow board next left (for daily snowfall), and snow stake (for snow depth) next to truck. *Photo on October 11, 2008 by Kelly Redmond.*

Figure 59. Grant Grove NWS COOP Station Cotton Region Shelter internal detail. Traditional maximum and minimum liquid-in-glass thermometers on Townsend support. Shelter doors always open to due north. Wire mesh has partly replaced louvres. *Photo on October 11, 2008 by Kelly Redmond.*

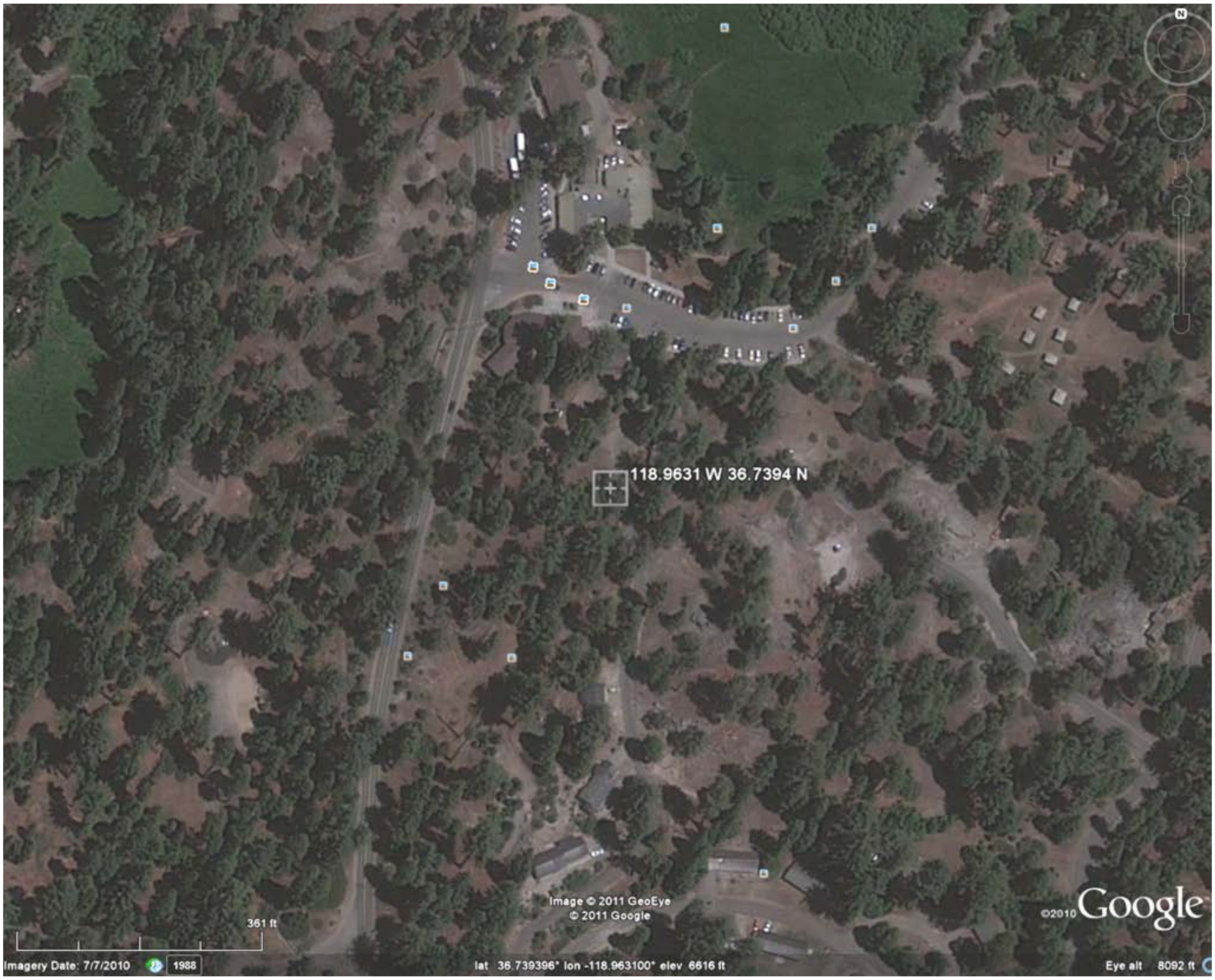


Figure 60. Aerial photo of Grant Grove NWS COOP Station location. Due to position errors, actual location is to the northwest (north is up) about 150 feet (near white dot) from center square. Visitor center roof is southeast of intersection. *Google Earth image from 2010.*

Giant Forest

The NWS COOP station at Giant Forest was a primary SEKI measurement point until relocation in November 1968 to the present Lodgepole site. From past descriptions and evidence, the station appears to have been in the cleared area now occupied by a small log structure (Figure 61). This clearing is visible to the northwest of the center of the aerial photo shown in Figure 62. The climate records from Giant Forest appear to have been of very good quality. At one time the entire Giant Forest area had a number of structures and visitor facilities with drive-up access, but in the intervening decades the meadow and surrounding area have been restored to a much more natural setting.

Figure 61. Approximate estimated location of the former Giant Forest NWS Cooperative Station. This clearing is within the trees bordering the southwest portion of Round Meadow. *Photo October 11, 2008 by Kelly Redmond.*

Figure 62. Aerial view of former Giant Forest NWS COOP Station location. Giant Forest surrounds the green meadow (Round Meadow) above photo center. Plotted position is NWS location to only 2 decimal places. Actual location up to 1968 is likely in cleared area just northwest of central white point. Parking lot and visitor center near left side of photo. *2010 image from Google Earth.*

Lodgepole

The NWS Cooperative station at Lodgepole replaced the previous site at Giant Forest, relocated in November 1968. From climate metadata and discussion with personnel, the station location at Lodgepole does not appear to have moved much since then. The station had a Fisher-Porter recording precipitation gauge until about 2006, when it was removed in part because of an increasingly rickety tower (needed to stay above the snow) and in part because of a temperamental instrument. (Fisher Porter sites can often be identified by the presence of Alter shields, swinging vertical vanes that reduce snow undercatch.) These gauges give hourly resolution. NWS has expressed hopes that a replacement gauge with more modern electronics will be re-installed within the next few years. The station also has an 8” US Standard Rain Gauge, and will continue to do so indefinitely; recording and non-recording gauges are typically run in parallel. The precipitation gauge was out of vertical alignment at the time the photos were obtained, which will reduce the gauge catch until readjusted. The station formerly used a liquid-in-glass thermometer, still mounted inside the Cotton Region Shelter seen in the station photos (Figures 63 to 65). The official reading switched to an MMTS in October 1994. The Cotton Region Shelter was mounted on brackets for lifting above the hanging snow depth. The MMTS cannot be easily raised and lowered above the snowpack (is anchored underground), and so the current location is on an extension from a roof eave of the law enforcement building. This arrangement was not known, and thus not recorded, during the photo-documentation visit by Kelly Redmond in October 2008. This is not a standard mounting, and is usually discouraged as poor siting practice, but at this station deep snow (as in winter 2010-11) necessitates a site that cannot be buried during the most extreme years. Deep snow introduces a number of observing complications. The overall setting for Lodgepole is shown in Figure 66.

In the summer of 2011, the NWS installed a new and separate sensor system at Lodgepole not intended to replace the official MMTS readings, but for the purpose of 1) getting information more quickly and 2) providing access to other elements. A Davis Vantage Pro 2 commercial system was mounted on a roof nearby (probably the law enforcement building). This station is linked to the amateur radio (ham) system for rapid communication (a system called APRS, Automatic Position Reporting System). This station gives a wind reading, an element not measured by the NWS Cooperative Network, and provides rapid hourly updates on temperature to the NWS Forecast Office in Hanford. This is the station used (for the present, at least) for forecast production and evaluation. These two systems are not necessarily compatible, and so the NWS MMTS Cooperative Station data will remain the official reading for the national archive. The APRS readings can serve as a temporary backup if there is ever a problem with the MMTS measurements. As with Grant Grove, the Lodgepole station is entered into the national weather distribution system each day by local Lodgepole staff, using WeatherCoder III, and so is quickly available to the entire country. The NWS has noted a systematic difference in temperature of about 3-5 degrees F between these adjacent sensors, so they should not typically be substituted one for the other. This highlights the strong inadvisability of mixing data from different measurement systems and networks, and the necessity for constant and detailed attention to metadata.

Overall we determined that the measurement situation at Lodgepole has been reasonably consistent for at least the last 10-15 years. The correlation analysis indicates that the station is providing relatively good quality data about precipitation, temperature, and snow fall and depth, and that its long-term record has value for climatological and ecological studies.

Figure 63. Lodgepole NWS COOP Station at Visitor Center. Precipitation gauge, Cotton Region Shelter for former liquid-in-glass measurements (mounted on ratchets), tower for since-removed Fisher-Porter recording gauge, looking toward northeast toward visitor center. *Photo taken October 11, 2008 by Kelly Redmond.*

Figure 64. Lodgepole NWS COOP Station view toward southeast showing exposure. Precipitation gauge, Cotton Region Shelter for former liquid-in-glass measurements, tower for since-removed Fisher-Porter recording gauge, looking toward southeast and Lodgepole access road. *Photo taken October 11, 2008 by Kelly Redmond.*

Figure 65. Lodgepole NWS COOP Station hydrology equipment and temperature sensor. Manual 8" Standard Rain Gauge gauge, snow stake for depth to right, MMTS temperature sensor may be the small object extending outward from the peak roof eave of the distant building. *Photo taken October 11, 2008 by Kelly Redmond.*

Figure 66. Aerial photograph of Lodgepole NWS Cooperative Station environment. Actual site is near exact center of photo just south of the five white ranger vehicles. The MMTS thermometer is attached to the roof of a building near the precipitation and snow measurement site. *Image date 2010 from Google Earth.*

Ash Mountain

The Ash Mountain NWS COOP site had shown a recent trend toward the same deterioration noted at other sites, but during the spring and summer of 2011 the data appeared to be more complete and of better quality than earlier. The data are entered electronically each day over the web via WeatherCoder III by on-site personnel. We have noted that stations that use WeatherCoder generally have much less missing data, and have better quality data requiring less need for attention or flagging. This station has been in its present position atop a very small grassy knoll for many decades, and has generally a very good exposure. The site was thoroughly photographed by Kelly Redmond in October 2008 (Figures 67-69). This site was also a Fire Weather Station, and thus has two Cotton Region Shelters, one for each network. Protocol requires the door to face north, but these are oriented at 90 degrees to each other; the southernmost appears to be the NWS station. The overall setting is shown in Figure 70.

The readings are still made with liquid-in-glass maximum/minimum thermometers. The Cotton Region Shelters in which they are housed need paint and are showing their age. Because of this, and a general nationwide NWS move to electronic thermometers, the present system will be changed to MMTS, likely during autumn of 2011. In addition, the observer will be working from the NPS dispatch office, and may at times work alone and want to be closer to the equipment. For that reason plans by NWS call for the temperature readings to be moved so the south or southeast a horizontal distance of about 150-250 feet (45-75 m). The new temperature and precipitation readings will be about 20-25 feet east of that building, uncomfortably close to an obstruction and an artificial heat source, and about 10-15 feet from each other. The size of the canopy opening appears to be smaller than at present. It would be very useful if simultaneous measurements could be made with the new and old systems, to help interpret any changes in station climate arising from this move. As noted by NWS during discussions of the overall observing programs for SIEN park units, it is increasingly difficult to find sites that are scientifically defensible and yet compatible with administrative and logistical constraints.

The Ash Mountain RAWS site is within a few feet of the Ash Mountain NWS COOP Station (which records at 8 am). Readings are readily accessible via the WRCC web site. A check for the summer of 2011 shows that the RAWS site runs consistently warmer than the COOP site, by typically 3-6 degrees F for maximums and by 5-10 degrees F on the minimums. (Note that RAWS has only hourly values, not true max or min, so daily maximum and minimum should be "less extreme" for the RAWS station.) There is broad correspondence and a positive correlation of anomalies from each station's own climatology (appropriately shifted to allow for observation-time influences). Most of the very rare precipitation amounts agree, but not all (for example one day showed an inch of precipitation at the COOP site and nothing at the RAWS site). Nevertheless, one might expect somewhat better correspondence between these two co-located sites, and the differences over such a short distance remain a puzzle.

Figure 67. Ash Mountain NWS COOP station, looking toward east from visitor center. Two Cotton Region Shelters on right. The rightmost one is likely the NWS site. Standard Rain Gauge and forestry rain gauge to left, and a portion of the RAWS site is visible to left. *Photo October 11, 2008 by Kelly Redmond.*

Figure 68. Ash Mountain NWS COOP station, looking toward south. Site is expected to be moved 150-250 feet toward the background, perhaps to right or left of photo frame. Two Cotton Region Shelters background, Standard Rain Gauge and shorter Forestry gauge, former Fire Weather shelter to right, RAWS framework to far right, wind mast for RAWS in center. *Photo October 11, 2008 by Kelly Redmond.*

Figure 69. Ash Mountain NWS COOP station, looking toward northeast. Two Cotton Region Shelters foreground, Fire Weather shelter in between, taller NWS Standard Rain Gauge and shorter Forestry gauge, RAWS structure to left, RAWS wind mast to right. *Photo October 11, 2008 by Kelly Redmond.*

Figure 70. Aerial photo of the setting at Ash Mountain. The long term locations of the NWS COOP Station and the RAWS station are nearly under the square next to the coordinates. The new COOP location will be toward the south or southeast from its present site. North is up. *2010 image from Google Earth.*

Because SEKI does not have a road bisecting the parks like Tioga Highway in Yosemite, and because the only road that penetrates deeply into the interior of the two parks is at river level and thus low elevation, the middle and higher elevations of SEKI are not sampled as well as those within YOSE, even though a significantly larger fraction of the SEKI region is at high elevations compared with YOSE.

During the compilation of this report, we did not have a very good ability to access and download the data from California Department of Water Resources (CDWR) snow monitoring sites, and then to translate those values into similar files as those used for other analyses. The process at the time was extremely cumbersome. Thus we have said relatively little about those locations. Recent projects with CDWR have greatly improved this ability. There is clearly an immense value to moving data into systems that offer wide access. The barrier to research represented by the inability to acquire and transform data to desired forms often prevents their usage where they might be of great value.

Emerald and Topaz Lakes

We obtained the hourly records for research stations maintained by UC Santa Barbara at Emerald Lake (1990-2007, Figure 71) and Topaz Lake (1995-2007). These sites are near Wolverton in Sequoia National Park. The records are not available in real time, and are not in a form that facilitates easy ingestion and reformatting for comparison with other climate records in the area. After a fairly laborious conversion process, it became apparent that the precipitation data are zero most of the winter, and have non-zero values only during the warm season. Thus we abandoned any analysis of precipitation from those sites as being unreliable for the season of most interest.

The temperature records correlated quite well with records from nearby sites and elevations. These sites did have a number of data gaps, as do many high elevation sites, so redundancy is important to aid in estimating data for missing periods. Emerald even correlated well with Tuolumne Meadows Ranger Station, in all months. The correlations are high enough to give confidence in the data quality, but sufficiently different from 1.00 that it is clear that the sites are different enough to warrant continuation as separate stations. During software testing to convert the station data, and experiments involving different thresholds for allowable missing data, we came to the conclusion that the temperature records from Emerald and Topaz Lakes are quite good quality when data are not missing.

Other Station Types Common to SEKI and YOSE

RAWS Stations

As is noted elsewhere in this report, it is very clear that RAWS stations that are properly maintained provide very useful climate data. Their clear-cut delineation for what defines acceptable data, and the variation in inter-station relationships as these criteria are relaxed, shows the importance of following observational protocols when performing manual measurements. This conclusion is particularly relevant for temperature, and also for wind and humidity. It is just as clear that the lack of all-weather precipitation gauges on RAWS stations severely limits the usefulness of their precipitation records outside of the warm season. The stations were originally deployed primarily in support of fire applications, so summer precipitation was of greater interest when the stations were deployed. Most fire specialists now also recognize the importance of cool season precipitation to fire potential the following summer. However, the difficulty of making reliable, automated, unattended and unvisited, remote measurements of precipitation during an entire winter, when most of the precipitation is snow, is formidable. An ultrasonic snow depth sensor should be included on all stations that expect to see more than 6-12 inches of snow on the ground during a typical winter.

As a consequence of these correlations, we further corroborated an additional conclusion, namely that RAWS stations are very viable options for climate measurement, if the proper resources are set aside for maintenance and station care. At WRCC, we have witnessed many of the bad effects of insufficient maintenance on the quality of RAWS data. Conversely, when properly maintained, the sites can produce excellent climate records. RAWS data have an additional characteristic, in that in exchange for a modest annual maintenance fee, and loss of control over the data stream, the site host can leave the data management issues to others.

Figure 71. UC Santa Barbara research meteorological station at Emerald Lake in Sequoia National Park. The left image is a view of the station looking to the southeast and the right image is a view to the west with Emerald Lake in the background. *NPS photos from Sequoia and Kings Canyon National Parks Air Quality staff, taken in 2005.*

IV. Recommendations

Overall, this study resulted in both pleasant surprises and challenges. We were disappointed to discover the fair to poor quality of the COOP network, particularly in YOSE, both of the data itself and of some of the siting issues (SEKI COOP sites are better). We were encouraged by the manual ranger observations we obtained from Tuolumne Meadows, with high quality temperature and precipitation measurements. The RAWS network within the SIEN boundaries appears to be well-maintained, both in equipment and communications.

YOSE is much more instrumented than DEPO and SEKI, perhaps for obvious reasons of its popularity and high profile as a national park, or for water supply concerns of Hetch Hetchy's flows to the Bay Area, or because of the Tioga Pass road that transects the park from east to west, offering opportunities for instrumentation at many elevations—important for monitoring changes in hydroclimate and the freezing level. Tioga Pass (Highway 120) offers access to a number of microclimate regimes and areas of ecological importance, in part simply because it transects the park over the crest, but also because trailheads for many routes into the wilderness are located along the road. By contrast, very little of SEKI is readily accessible, and much of what cannot be reached easily is steep, rugged high elevation terrain.

DEPO, although relatively smaller, is in a unique setting, and in 2006, had a high quality station installed that we believe offers a bright future of bringing good quality climate data to the users. We recommend continuing upkeep of this station, and the collaboration with both a research institution (Scripps Institution of Oceanography) and a state agency (DWR) to ensure data quality, data archiving, and completeness. The data from the two sets of instruments are still going to separate locations, at CDWR and at Scripps, and these two should be merged more completely.

In SEKI, the COOP stations are at lower and middle elevations of the park, and while useful, much of the park area is unobserved climatologically. These stations may be considered mid-elevation as far as the Sierra Nevada range as a whole is concerned. The east side of the park reaches the highest heights of the lower 48 States, and the observational network could use some additions at high altitudes in this area. Unfortunately, there is not a convenient elevational transect already in place along which instrumentation can be placed, such as Tioga Pass in YOSE. In addition, there are few observation sites of any type in the middle portion of the park. Cedar Grove's COOP station closed decades ago, leaving just Grant Grove and Lodgepole / Giant Forest as the longest climate records in the park. Lodgepole and Giant Forest have different climates, but correlate very well for their overlap period, and can be used to reconstruct each other's records for longer periods. As it is, these are in the west side of the SEKI management unit. The northern reaches of KICA are virtually unobserved, as is the east side of SEQU and KICA. Figure 31 illustrates the distribution of observing sites in these parks. About the only sites within the central and eastern parts of SEKI are the CDWR sites. These now have significant length of record, and efforts should be made to ensure that the stations are well maintained.

In all parks, the high altitudes are under-observed. A new WRCC station on Mt. Warren, at 12,327 feet, comparable to Mt. Conness and a short distance east of the Yosemite boundary, has furnished very useful observations, and reiterated the challenges of operating high-altitude remote climate stations. A suite of instrumentation, including temperature, humidity, pressure and wind, on 3-5 more mountain top locations (perhaps utilizing existing relay tower sites), would be ideal. We suggest Gould Peak in SEKI and Mt. Hoffman in YOSE as two possible sites. We single these out because they have existing infrastructure, are considered disturbed and would thus be easier to justify in these areas of designated Wilderness than sites that are undisturbed. These sites are also relatively prominent, and provide backup for each other in the event of outages (which are likely). They have also been suggested previously by NPS personnel. Two to three additional sites, perhaps a little lower altitude (8000-10000 feet), would bracket the high elevation climates well in the SIEN. Recent hydroclimate studies have indicated that spring snowmelt can occur differently above and below about 9000 feet.

During the winter of 2010-2011, the station at Mt Warren suffered damage, reported by a US Forest Service technician that visited the site (a radio repeater station) by helicopter. We have not yet had a chance to assess the damage to this site, and develop a strategy for replacement, refurbishment, or a possible move to a nearby mountaintop (Tioga Crest is one such possibility).

We would not discourage any new stations from being installed at any location, but below are a few specific recommendations that we have identified for the SIEN. We see a lot of promise for continued quality climate observations in the Sierra Nevada Network.

Specific geographic recommendations

A. Tuolumne Meadows Ranger Station

This station has proven to be of high quality, with little missing data. The data were usable without any initial quality tests or checks. We highly recommend year-round manual daily temperature and precipitation, including snow, observations to continue at this location. If automated equipment were situated at Tuolumne Meadows Ranger Station, we would still strongly advocate continuation of the manual measurements as a very valuable baseline.

B. High Altitude Observation

We recommend multiple (for backup) high altitude sites, in part as a back-up to Mt. Warren in YOSE. Instruments in these environments are exposed to the most extreme weather, and can fail or lose communications quickly. One to two more high altitude sites in YOSE, and in SEKI, are recommended both for redundancy, but also to bracket the high elevation climate above tree line. A suggestion is to co-locate weather and climate observational equipment with existing towers in designated Wilderness areas to minimize wilderness impacts. In YOSE we suggest Mt. Hoffman as an obvious candidate for a long-term high elevation climate monitoring site. In SEKI, we suggest Gould Peak, which has existing antenna, and is about 1500 feet lower than the highest point in the High Sierra, Mount Whitney. SEKI is more rugged, inaccessible, and higher, and logistics pose a large problem for high elevation monitoring in the large area at high elevation. Such sites should be outfitted with a suite of instrumentation (minus precipitation), which includes temperature, humidity, barometric pressure and wind speed and direction. Given the harsh conditions, cheap backup sensors (such as Hobos) should be emplaced so that entire winters are not lost.

C. Remote Automated Weather Stations (RAWS)

The RAWS stations in the SIEN performed surprisingly well for the correlation analysis, and data quality proved to be adequate for this climatological analysis, especially for temperature. For precipitation, the unheated gauges do not provide accurate wintertime measurements. Such precipitation measurements are only useful for short periods in summer, such as for their original primary purpose in the fire program. In the summer season, the RAWS stations under the NPS purview appear to behave well, reflecting upon the good maintenance of equipment and communications. We recommend continuing the maintenance on these stations for a few reasons: 1) well maintained stations over a long period of time, with accompanying metadata, are critical for climate monitoring, 2) fire weather and fire climate needs in the region equally (if not more so) depend on these data, 3) they are, by definition, located in remote areas where little other weather or climate monitoring is conducted, and thus can provide better information about the SIEN. In addition, these stations report, and are archived, at hourly intervals in near-realtime, and also include wind information that is typically difficult to find in most other networks in the region.

In addition, we recommend the year-round operation of Rattlesnake RAWS in SEKI. This would provide better information for climate monitoring purposes in an area that is generally under observed. Seeing as how this station is primarily used for fire weather purposes, recent research has shown that antecedent weather conditions for seasons or years before a fire season can contribute to the knowledge of vegetation growth and density, soil and fuel moisture, and including drought conditions in the wet (winter) season. These factors can impact fire prediction for both occurrence of fire and fire severity. By "year-round" we mean that the station is not shut down in winter. As long as snow does not bury a station, very useful temperature, humidity, wind, and solar measurements can result. A sonic snow sensor is relatively inexpensive (less than $1 K). In general, we do not advocate winter precipitation measurements on fully automated platforms that do not have AC power or are otherwise unable to heat a gauge. Gauge heating takes far more power than does making a routine observation. A few heated gauges would be encouraged, if power requirements can be met.

D. California Cooperative Snow Survey (CCSS) Sites

Manual and automated snow measurement sites are integral for water supply forecasting, and, over time, can provide information on climate change impacts in the SIEN (e.g. Dettinger 2004; Stewart 2004). Even though high-tech snow sensors and snow pillows are now available, snow depth and water equivalent is a finicky observation and is best supplemented by manual measurements. Snow courses, the long-time manual snow measurements taken once a month January-May, are one way to do this. Automated networks (DWR's snow survey) are just now of long enough periods to be useful for climate purposes. As in all other networks, equipment maintenance and observational consistency are key to retaining the utility of these datasets for future analyses and understanding of climate in the parks. If and when these networks are augmented with soil moisture sensors, this would be a boon to climate and drought monitoring in the region. These sites have not always measured all hydrologic quantities simultaneously (precipitation, snow depth, and snow water equivalent), but increasingly they do.

Most of the focus with CCSS sites has been on "hydrologic" elements. Temperature, wind, humidity, and solar radiation, all important to snow budgets, have received less attention. In particular, there has been virtually no quality control of temperature measurements from these sites during their entire existence, and very little analysis of their temperature quality or characteristics. In addition, until recently, budget limitations have led to service intervals of as much as 3 to 4 years between visits for DWR automated sites. In the harsh conditions found in these locations, annual maintenance is highly desirable.

E. Climate Reference Network

This newly installed station (autumn 2007) has potential in contributing to the understanding of climate in the SIEN, and in particular, in YOSE. The CRN station at Crane Flat Lookout in Yosemite is equipped with some of the highest quality instrumentation and most reliable communications. At this time the maintenance of the CRN is provided by NOAA through a contractor, and we highly recommend that the SIEN continue to work with NOAA to the best of its ability to obtain the best quality data available for this station. A lot of effort has been put forth nationwide to establish the CRN, and its utility can only be demonstrated over time, as long data histories are developed. This station is also quite close to a RAWS station next to the Crane Lookout heliport, and some useful comparisons can be made there.

F. Devils Postpile Automated Site

This station was installed and has been in operation since 2006 by Devils Postpile National Monument, Sierra Nevada Network I&M program, California Department of Water Resources, Scripps Institution of Oceanography’s Climate Research Division, U.S. Geological Survey, and California Energy Commission. We feel it is in a well-sited location for climate and weather monitoring purposes. It was encouraging to learn that DEPO is using the station as an educational opportunity to teach visitors about climate in the national monument. The collaboration with DWR’s California Data Exchange Center (CDEC) is a good way to have real-time access to the data, making it much more beneficial to the weather and climate community, as well as visitors and potential visitors to the Monument. CDEC quality control efforts are minimal, however. It is our understanding that the Scripps group will perform more thorough quality control on a semi-annual basis (pers. comm. from M. Tyree). We have had sporadic discussions with Scripps about automatically ingesting data from their station into the WRCC system, where there are many ways of summarizing and visualizing the data, and ways to download to other applications.

G. SIEN Climate Focal Point

As another suggestion, perhaps an individual would be identified to serve as a “climate focal point” for the SIEN. The NWS has made similar such designations. The responsibilities of this person may encompass other duties, but such a position would include a specific mandate to monitor network daily quality, data transmission, completeness of climate records, pending and actual equipment needs, and interaction with a number of contractors and collaborators.

H. Department of Interior Climate Science Centers

As noted below, WRCC / DRI is one of the partner institutions in the newly created Southwest Climate Science Center at the University of Arizona in Tucson. This is one of eight such centers nationally. We see one of the roles of the NOAA Regional Climate Center Program as serving as a conduit to climate data and information that will be needed by the Climate Science Centers. This furnishes an excellent opportunity to build on prior efforts between WRCC and NPS nationwide to build user-friendly access techniques to reach climate data and information.

Many of the basic building blocks have been developed, and WRCC has this capacity internally. However, methods to extend this capability to partner agencies have been only partially completed.

V. Data Access

The Western Regional Climate Center (WRCC) at Desert Research Institute has archived all of the data sets analyzed for this report. A large part of the mission of WRCC is to provide data archiving and distribution; hence, this is the only location where RAWS data is archived historically (entire period of record), and as a NOAA Regional Climate Center we also store NOAA climate data sets such as COOP. The majority of our database is updated as near to real-time as possible: within an hour or a day of when the original observation was taken, if the observations can be transmitted through electronic means.

Some recent and ongoing projects at WRCC are designed to provide better data access for the NPS. Before this report was assembled, a website for Yosemite NP area climate monitoring was created at WRCC in coordination with Scripps Institution of Oceanography: http://www.yosemite.dri.edu/index.html This website includes only currently operating DWR snow survey, RAWS, SNOTEL and COOP stations. Similar web sites should exist for SEKI.

Another project for California climate monitoring (CalClim) was also begun in 2004: http://www.calclim.dri.edu. This website provides data access for DWR snow survey, RAWS, SNOTEL, COOP and other hourly reporting stations for the entire state of California.

A recent project at WRCC funded by NPS was designed to develop easy data access for all NPS I&M networks nationwide. The goal is a system that NPS users do not need to know programming or detailed data exchange protocols, but rather simply how to run a web application. Another goal was to provide a means by which NPS data can be loaded into a system which then provides storage, summarization, product generation, and data distribution, in a way that reduces some of the data management concerns of NPS personnel. This capability was tested and appeared to be working quite well. However, there was a need to develop an NPS interface, and the project personnel at NPS moved on to other activities.

WRCC has recently become a member of the new Department of Interior (DOI) Southwest Climate Science Center (SW-CSC). One role we envision is to utilize resources from that project to develop the capabilities for all DOI agencies that were mentioned in the previous paragraph. This will be a subject of active investigation.

The software used to generate the climate history of the five counties shown in the country time series presented earlier is part of a NOAA project to make monthly data available from 1895 through current, and can be accessed online at www.cefa.dri.edu/Westmap via the WRCC "projects" web page. This enables a user to select a desired combination of months, a desired climate element (precipitation, or max/min/mean temperature), and a range of years, and plot the time history for a spatial unit of interest. Currently those areas include states, counties, climate divisions, hydrographic units, and individual 4-km pixels. We could add administrative units such as NPS parks and monuments. The values are based on the PRISM gridded data set. This capability could be expanded nationwide.

The precipitation graphic used to illustrate the precipitation time history of the Sierra Nevada is from the California Climate Tracker at www.wrcc.dri.edu/monitor/cal-mon/index.html, and more specifically the frames version currently now accessible under "explore climate products" at www.wrcc.dri.edu/monitor/cal-mon/frames_version.html (see Abatzoglou et al (2009) for details about methodology. This lumps the entire Sierra Nevada into one unit, but is intended to show climate variability and trends across California for the last 114 years in a form understandable to politicians, the press, average citizens, and resource managers.

Access to RAWS data is provided through another set of web pages at WRCC (and for California is also included in the Calclim pages mentioned above), at www.raws.dri.edu/index.html. These pages give the ability to generate the wind roses shown in Figure 11, to generate other climatic summaries, to view station metadata (and photos when available), and to generate data listings. Data from about 2000 RAWS stations flow live into this archive, which now extends from about the middle 1980s.

Also, during this project, as part of a NOAA effort WRCC developed a tool to visualize the history of freezing levels for any point in North America from 1948 through the current month. This has great relevance to the highly three-dimensional SIEN park units. This web site can be reached at www.wrcc.dri.edu/cwd/products. This was used to generate the freezing level information in this report.

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Appendix A. Priority List of Weather and Climate Information Needs in the Sierra Nevada Network

Following is the list of Sierra Nevada Network weather and climate needs and objectives identified at the October 4, 2006, Climate Assessment Project Meeting. The meeting was held in El Portal at Yosemite Park Administrative Headquarters, and attended by a number of SIEN personnel from all four park units. The number of votes received during our rough prioritization process is indicated in parentheses.

Highest Priority

- Current and historic data on-line and a way to make it *accessible,* and easy to understand; one-stop shopping (like Yosemite map-link) (8)
- Identify core parameters to measure (all sites, and at benchmark sites) (6)
- Ensure adequate monitoring at high elevations (5)
- Higher resolution climate maps (PRISM) (5)
- Inform biological issues (forests, wildlife, vital signs) (4)
- To what degree do SEKI and YOSE serve as surrogates for each other? Identifying areas that might be changing sooner, could be used to inform areas that will change in the future. (3)
- Need for better precipitation measurements at all stations, especially snow measurements (need more instruments and better instruments) (3)
- Metadata (2)
- Need to know micro-site bias (2)

Medium to lower priority

- Would like to answer “Is the long-term climate changing in our parks?”
- Identify sites with missing data and data collection issues that may compromise data quality
- Know adequacy of historic and contemporary data (much discussion on historic, long-term “ranger data”) (1)
- Capture short-term and opportunistic data sets (i.e. fire, research projects). (Discussed that this was lower priority)

- Evaluate which stations are most important. Identify need for (or lack of need) for additional sites. (1)

- Need to know what is happening 6,000 ft or more above ground level for operational fire purposes.

- Need to know what is happening at 6,000 ft elevation-transitional zone for air currents.

- Weather and climate information to inform changes in forest dynamics. Stations near tree-line? (Also, identified as high priority as a component of ‘biological issues’)

- Inform vital signs monitoring (Also, identified as high priority as a component of ‘biological issues’)

- Evaluation of number of stations, evaluation of placement of stations (which are most important and need for additional sites)

- Compare synchronicity of current stations (to see if any station is redundant). The issues is different depending on what element you are most interested (e.g. wind, rain, temp … precipitation is hardest to measure). What might be a good wind measurement site could be a really poor precipitation measurement site. You can’t have everything.

- DEPO legacy ranger data (make digital)

- Ensure long-term maintenance and high data quality of new DEPO met station

- Evaluate Rainbow Falls as a location for a met station in DEPO (burned area?)

- Access to archived National Weather Service weather narratives/forecast discussions

- Monthly post-weather discussions and analyses

- Radiation measurements at benchmark sites (1)

- Evapotranspiration estimates

- Snowcover (remotely), correlated with on-the-ground snow measurements

- Local changes in snow cover and albedo

- Hydro and met data-gap at SEKI (8,000 feet)

- Making current and historic Tokopah data (SEQU) more accessible

- Document history of SEKI long-term sites (were they moved or not, e.g. Ash Mountain, Lodgepole, Giant Forest, Grant Grove)

- Kings Canyon is quite sparse (in terms of meteorological instrumentation)

- Collocate meteorological stations where we have paleo records (1)

- Meteorological data for transport models of contaminants (i.e. David Bradford's research)

- Biological Issues tied with climate change: chytrid, pikas, small mammals. (Also, identified as high priority as a component of 'biological issues')

- Data gaps in the Kern watershed?

- To what degree do SEKI and YOSE serve as surrogates for each other? Identifying areas that might be changing sooner, could be used to inform areas that will change in the future.

- Inform glacier research and monitoring

- Adding instrumentation to existing radio towers. For example, in Yosemite, there is one on Mt. Hoffman; in Sequoia, they have 6 or 7 (up to 12,000 feet elevation?) Get tower information to Kelly and Laura.

- Real-time access to data

- Data-gap at 4,000 feet elevation in Sequoia; also at elevation greater than 12,000 feet

- Addition of sensors to existing, year-round RAWS sites at SEKI

Appendix B. Metadata for COOP stations in and near the Sierra Nevada Network

Table B-1 is the result of an exercise to choose climate stations from the National Weather Service (NWS) Cooperative Station (COOP) Network, which provides daily data, for the correlation analysis. The starting point was the tables of Davey et al. (2007), which did not contain enough specific detail to determine the completeness of a station's record. Most of the stations were originally in metadata listings provided by the National Climatic Data Center (NCDC). In these listings many of those stations have no data at all, but were merely assigned a number for convenience. The stations with a number, but with no daily data, were generally not stations managed by NWS, but by other agencies. This was done at a time when the number of networks was much smaller than at present. The presence of a station with a COOP number does not always guarantee that an actual daily data record exists. Stations with no data are labeled "nodata."

Table B-1. Metadata for COOP stations in and near the Sierra Nevada Network parks. HPD= Hourly Precipitation Data.

COOP Number	Name	Lat	Long	Elev (M)	Source/ Data Status	Start	End	In Park?
41737	Chiquito Creek	37.500	-119.383	2223	COOP/ nodata	9/1/1961	9/30/1976	No
41844	Clover Meadows G.S.	37.533	-119.283	2135	COOP nodata	7/1/1948	11/30/1972	No
42756	Ellery Lake	37.936	-119.231	2940	COOP	11/1/1924	12/27/2006	No
43093	Florence Lake	37.274	-118.973	2233	COOP/ HPD	7/1/1948	Present	No
43369	Gem Lake	37.752	-119.140	2734	COOP/ precip	11/1/1924	12/27/2006	No
44442	Kaiser Meadows	37.300	-119.100	2779	COOP/ nodata	7/1/1948	9/30/1976	No
44881	Lee Vining	37.957	-119.119	2072	COOP	4/15/1988	Present	No
45280	Mammoth Lakes R.S.	37.648	-118.962	2379	COOP	12/1/1993	Present	No
45284	Mammoth Pass	37.617	-119.033	2861	COOP/ nodata	7/1/1948	9/30/1976	No
45288	Mammoth Pool	37.350	-119.317	1034	COOP/ nodata	7/23/1947	9/30/1976	No
45040	Logan Meadow							
45927	Mt. Givens	37.283	-119.083	2898	COOP/HPD	10/1/1963	4/1/1969	No
47510	Rock Creek	37.450	-118.733	2949	COOP/ nodata	7/1/1948	9/30/1976	No
47560	Rose Marie Meadow	37.317	-118.867	3050	COOP/ nodata	10/1/1953	9/30/1976	No
47606	Rush Creek Ranch	37.950	-119.067	1967	COOP	7/1/1948	10/31/1950	No
49063	Tuolumne Meadows	37.883	-119.350	2638	COOP nodata	7/1/1948	11/30/1972	No
49301	Vermilion Valley	37.367	-118.983	2294	COOP/ nodata	12/1/1946	9/30/1976	No

Table B-1. Metadata for COOP stations in and near the Sierra Nevada Network parks. HPD= Hourly Precipitation Data (continued).

COOP Number	Name	Lat	Long	Elev (M)	Source/ Data Status	Start	End	In Park?
40425	Badger Pass	37.667	-119.667	2227	COOP/ nodata	7/1/1948	6/30/1976	YOSE
40617	Beehive Meadow	38.000	-119.783	1983	COOP/ nodata	7/1/1948	9/30/1971	YOSE
45329	Grace Meadow	38.150	-119.600	2715	COOP/ nodata	7/1/1948	6/30/1973	YOSE
43939	Hetch Hetchy	37.961	-119.783	1180	COOP	10/1/1910	Present	YOSE
44015	Hodgdon Meadow	37.800	-119.867	1281	COOP/ nodata	6/1/1967	6/30/1978	YOSE
44679	Lake Eleanor	37.967	-119.883	1421	COOP/ nodata	10/19/1909	10/31/1957	YOSE
45614	Miguel Meadows	37.967	-119.833	1617	COOP/ nodata	11/1/1946	6/30/1948	YOSE
46549	Oshaughnessy Dam	37.950	-119.783	1220	COOP/ nodata	11/1/1946	5/5/1948	YOSE
46552	Ostrander Lake	37.633	-119.55	2623	COOP/ nodata	7/1/1948	9/30/1976	YOSE
46688	Paradise Meadow	38.050	-119.667	2349	COOP/ nodata	8/1/1948	9/30/1971	YOSE
48318	Snow Flat	37.833	-119.500	2654	COOP/ nodata	7/1/1948	9/30/1976	YOSE
48380	South Entrance Yosemite	37.508	-119.634	1566	COOP	7/1/1941	Present	YOSE
49063	Tuolumne Meadows	37.883	-119.350	2638	COOP/ nodata	7/1/1948	11/30/1972	YOSE
49481	Wawona	37.533	-119.667	1190	COOP	1/1/1934	7/31/1940	YOSE
49482	Wawona R.S.	37.540	-119.652	1215	COOP/ HPD	10/1/1940	6/15/2006	YOSE
049482	Wawoma R.S.	37.540	-119.652	1215	COOP	10/1/1940	9/30/1951	YOSE
49855	Yosemite Park Hq.	37.750	-119.590	1209	COOP	8/1/1906	Present	YOSE
40048	Ahwahnee	37.367	-119.717	708	COOP/ nodata	2/1/1957	3/31/1959	No
40049	Ahwahnee 2 NNW	37.374	-119.728	850	COOP/ nodata	12/1/1960	11/30/2005	No
40755	Big Creek PH 1	37.206	-119.242	1487	COOP/ Gap 1963-1998	6/1/1915	Present	No
40943	Bodie	38.212	-119.014	2551	COOP/ data from 19640901	2/1/1895	Present	No
41072	Bridgeport	38.258	-119.229	1972	COOP/ NCDC data from 19480701	10/1/1903	Present	No
41075	Bridgeport Dam	38.317	-119.217	1958	COOP	4/1/1925	6/30/1957	No

Table B-1. Metadata for COOP stations in and near the Sierra Nevada Network parks. HPD= Hourly Precipitation Data (continued).

COOP Number	Name	Lat	Long	Elev (M)	Source/ Data Status	Start	End	In Park?
41075	Bridgeport R.S.	38.251	-119.216	1963	COOP/ HPD 198112 to present	6/1/1950	Present	No
41187	Bumblebee Trailer P.A.	38.200	-120.000	1757	COOP/ nodata	2/1/1964	11/30/1964	No
41588	Catheys Vly. Bull Run Rch.	37.400	-120.050	436	COOP	7/1/1948	5/31/1977	No
41611	Cedar Point Ranch	37.467	-119.733	985	COOP	6/1/1959	6/30/1962	No
41630	Central Camp	37.350	-119.483	1635	COOP	12/1/1923	12/31/1948	No
41696	Cherry Valley Camp	38.000	-119.900	1373	COOP/ nodata	11/1/1946	6/22/1948	No
41697	Cherry Valley Dam	37.975	-119.916	1452	COOP	10/1/1955	Present	No
41737	Chiquito Creek	37.500	-119.383	2223	COOP/ nodata	9/1/1961	9/30/1976	No
41844	Clover Meadows G.S.	37.533	-119.283	2135	COOP/ nodata	7/1/1948	11/30/1972	No
41878	Coarsegold 1 SW	37.250	-119.705	680	COOP	2/6/1957	Present	No
41906	Cold Springs Chalet	38.167	-120.050	1751	COOP	2/1/1951	8/31/1953	No
41908	Coleville (5 SE)	38.513	-119.449	1696	COOP/ river	4/19/1983	Present	No
41910	Coleville 3 SE	38.533	-119.467	1617	COOP	2/1/1945	7/31/1946	No
41911	Coleville 4 SE	38.517	-119.467	1617	COOP	5/1/1949	1/31/1953	No
42173	Crocker Stn.	37.800	-119.900	1434	COOP	1/17/1904	10/31/1953	No
42465	Donnells Dam	38.333	-119.967	1476	COOP	6/1/1959	10/31/1960	No
42539	Dudleys	37.750	-120.100	915	COOP	8/1/1908	10/31/1976	No
42756	Ellery Lake	37.936	-119.231	2940	COOP	11/1/1924	12/27/2006	No
43069	Fish Camp	37.483	-119.633	1562	COOP	5/1/1971	3/31/1972	No
43369	Gem Lake	37.752	-119.140	2734	COOP/ precip	11/1/1924	12/27/2006	No
43666	Groveland	37.833	-120.217	854	COOP/ Gap 1917-1948	1/1/1905	12/31/1954	No
43669	Groveland 2	37.844	-120.226	853	COOP/ Gap 1952-2000	7/1/1948	Present	No
43672	Groveland R.S.	37.823	-120.098	959	COOP/ data 1955 to present	10/1/1906	Present	No
43954	Highland Lakes	38.500	-119.800	2638	COOP/ nodata	7/1/1961	9/30/1976	No
44148	Huckleberry Lake	38.100	-119.750	2379	COOP/ nodata	8/1/1948	9/30/1971	No
44176	Huntington Lake	37.228	-119.221	2140	COOP/ Gap 1962-1974	6/1/1915	Present	No

Table B-1. Metadata for COOP stations in and near the Sierra Nevada Network parks. HPD= Hourly Precipitation Data (continued).

COOP Number	Name	Lat	Long	Elev (M)	Source/ Data Status	Start	End	In Park?
44442	Kaiser Meadows	37.300	-119.100	2779	COOP/ nodata	7/1/1948	9/30/1976	No
48881	Lee Vining	37.957	-119.119	2072	COOP	4/15/1988	Present	No
45079	Long Barn 1 W	38.083	-120.150	1491	COOP/ nodata	9/1/1965	12/31/1978	No
45078	Long Barn Exp.	38.183	-120.017	1586	COOP/ Data 1948-1951	7/1/1948	2/28/1964	No
45160	Lower Kibbey Ridge	38.017	-119.883	1983	COOP/ nodata	1/1/1949	9/30/1971	No
45194	Lundy Lake	38.033	-119.217	2367	COOP/ nodata	1/1/1931	5/31/1940	No
45280	Mammoth Lakes R.S.	37.648	-118.962	2379	COOP	12/1/1993	Present	No
45284	Mammoth Pass	37.617	-119.033	2861	COOP/ nodata	7/1/1948	9/30/1976	No
45288 45040	Mammoth Pool	37.350	-119.317	1034	COOP/ nodata	7/23/1947	9/30/1976	No
45346	Mariposa	37.483	-119.967	613	COOP/ nodata 1896-1909	1/1/1893	9/18/1984	No
45352	Mariposa R.S.	37.495	-119.986	640	COOP	5/1/1953	Present	No
45400	Mather	37.881	-119.856	1375	COOP	10/9/1947	Present	No
45779	Mono Lake	38.000	-119.150	1966	COOP	5/1/1943	3/30/1988	No
45927	Mt. Givens	37.283	-119.083	2898	COOP/ HPD	10/1/1963	4/1/1969	No
46252	North Fork R.S.	37.231	-119.507	802	COOP	3/1/1904	Present	No
46325	Oakhurst	37.331	-119.653	680	COOP	10/1/1999	Present	No
46795	Penon Blanco	37.733	-120.267	854	COOP/ Fire?	5/1/1953	Present	No
46849	Pickel Meadows	38.350	-119.517	2074	COOP/ nodata	6/1/1959	9/30/1959	No
46893	Pinecrest Summit R.S.	38.187	-120.006	1707	COOP/ HPD	11/27/1964	Present	No
47270	Raymond	37.210	-119.908	288	COOP/ nodata	2/1/1957	Present	No
47273	Raymond 10 N	37.350	-119.867	390	COOP	2/21/1962	2/9/1966	No
47272	Raymond Whipple Ranch	37.367	-119.900	421	COOP/ No missing	8/1/1959	2/28/1962	No
47606	Rush Creek Ranch	37.950	-119.067	1967	COOP	7/1/1948	10/31/1950	No
47623	Saches Springs	38.100	-119.850	2410	COOP/ nodata	9/1/1948	9/30/1971	No
48171	Shields Ranch	38.533	-119.517	1684	COOP/ nodata?	1/1/1931	5/31/1946	No
48355	Sonora Junction	38.351	-119.450	2099	COOP/ HPD	9/1/1959	Present	No

Table B-1. Metadata for COOP stations in and near the Sierra Nevada Network parks. HPD= Hourly Precipitation Data (continued).

COOP Number	Name	Lat	Long	Elev (M)	Source/ Data Status	Start	End	In Park?
49193	Usona 2 N	37.483	-119.817	961	COOP/ HPD	3/1/1972	11/4/1980	No
49749	Wishon P.H.	37.150	-119.500	305	COOP/ nodata	12/1/1957	12/31/1978	No
40343	Ash Mtn.	36.491	-118.825	521	COOP/ 25 d missing	1/1/1927	Present	SEQU
40374	Atwell	36.467	-118.667	1976	COOP/ nodata	6/24/1948	10/1/1976	SEQU
41182	Bullfrog Lake	36.767	-118.400	3264	COOP/ nodata	7/1/1948	7/31/1955	KICA
41609	Cedar Grove	36.783	-118.667	1418	COOP/ summer only	12/15/1940	5/23/1963	KICA
41647	Chagoopa	36.500	-118.450	3154	COOP/ nodata	7/1/1964	11/30/1972	SEQU
42114	Crabtree Meadow	36.567	-118.350	3264	COOP/ nodata	7/1/1948	9/30/1976	SEQU
42577	Dusy Bench	37.100	-118.583	2888	COOP/ nodata	7/1/1948	11/30/1972	KICA
42653	East Vidette Meadow	36.733	-118.383	3172	COOP/ 1 day missing	4/28/1949	8/31/1964	KICA
43397	Giant Forest	36.567	-118.767	1955	COOP/ 16 d missing	6/6/1921	11/8/1968	SEQU
43398	Giant Forest Radio	36.567	-118.767	2028	COOP/ nodata	9/1/1965	9/30/1976	SEQU
43548	Granite Basin	36.867	-118.600	3050	COOP/ nodata	7/1/1948	8/31/1964	KICA
43551	Grant Grove	36.739	-118.963	2012	COOP	7/1/1940	Present	KICA
44012	Hockett Meadows	36.367	-118.650	2593	COOP/ nodata	8/1/1959	9/30/1976	SEQU
44920	Lewis Creek Kings Cn.	36.800	-118.683	1418	COOP/ nodata	11/1/1945	7/25/1961	KICA
45026	Lodgepole	36.604	-118.733	2053	COOP	11/1/1968	Present	SEQU
45028	Lodgepole Ranger Stn	36.600	-118.733	2044	COOP	2/22/1951	12/31/1955	SEQU
45680	Mineral King	36.433	-118.583	2434	COOP/ nodata	8/1/1956	7/31/1969	SEQU
45723	Mitchell Meadow	36.733	-118.717	3020	COOP/ nodata	8/1/1957	9/30/1976	SEQU
45832	Moraine Creek	36.717	-118.567	2696	COOP/ nodata	8/1/1964	9/30/1974	KICA
46767	Pear Lake	36.600	-118.667	2959	COOP/ nodata	8/1/1956	9/30/1969	SEQU
47259	Rattlesnake Creek	36.983	-118.717	3020	COOP/ nodata	6/1/1961	9/30/1976	SEQU
48510	State Lakes	36.933	-118.583	3142	COOP/ nodata	7/1/1955	9/30/1976	KICA

Table B-1. Metadata for COOP stations in and near the Sierra Nevada Network parks. HPD= Hourly Precipitation Data (continued).

COOP Number	Name	Lat	Long	Elev (M)	Source/ Data Status	Start	End	In Park?
48635	Sugarloaf Meadow	36.717	-118.667	2196	COOP/ nodata	7/1/1948	8/31/1957	KICA
49328	Vidette Meadow	36.750	-118.417	2898	COOP/ nodata	8/1/1964	9/30/1974	KICA
40425	Badger	36.629	-119.012	933	COOP/ nodata	7/1/1948	12/1/2006	No
40449	Balch Pwr. House	36.909	-119.088	524	COOP	2/1/1950	Present	No
40534	Barton Flat	36.817	-118.883	1147	COOP/ nodata	7/1/1961	9/30/1972	No
40596	Beartrap Meadow	36.683	-118.867	2074	COOP/ nodata	8/1/1959	9/30/1976	No
40755	Big Creek P.H. 1	37.206	-119.242	1487	COOP/ Gap 1963-1998	6/1/1915	Present	No
40767	Big Pine Creek	37.133	-118.483	3068	COOP/ nodata	7/1/1948	9/30/1976	No
40822	Bishop Arpt.	37.371	-118.358	1250	COOP/ 41 d missing	8/1/1930	Present	No
40819	Bishop Ck. Intake 2	37.248	-118.581	2485	COOP	10/1/1959	12/27/2006	No
40820	Bishop Creek	37.240	-118.599	2591	COOP/ nodata	1/1/1931	Present	No
40823	Bishop F.S.	37.368	-118.365	1252	COOP	11/21/1996	8/25/2005	No
40824	Bishop Union Carbide	37.367	-118.717	2864	COOP	5/1/1957	5/6/1970	No
41470	Camp Wishon	36.183	-118.667	1159	COOP	7/1/1948	11/30/1971	No
41821	Cliff Camp	37.000	-119.000	1882	COOP/ nodata	1/1/1931	12/31/1947	No
42069	Cottonwood Creek	36.483	-118.183	3099	COOP/ nodata	7/1/1948	9/30/1976	No
42492	Doublebunk Meadow	35.950	-118.600	1891	COOP/ nodata	8/1/1955	12/31/1972	No
42557	Dunlap	36.750	-119.117	592	COOP/ nodata	7/1/1937	1/31/1950	No
42559	Dunlap Shingle Mill	36.717	-119.117	610	COOP/ nodata	3/13/1948	8/25/1949	No
42577	Dusy Bench	37.100	-118.583	2888	COOP/ nodata	7/1/1948	11/30/1972	No
42591	Eagle Creek	35.983	-118.650	2028	COOP/ nodata	11/1/1964	9/30/1976	No
42922	Exeter Fauver Ranch	36.350	-119.067	134	COOP/ HPD	7/1/1948	9/1/1988	No
44116	Horse Corral Meadow	36.750	-118.767	2342	COOP/ nodata	7/1/1948	8/31/1959	No
44120	Hossack	36.183	-118.617	2166	COOP/ nodata	8/1/1959	9/30/1976	No

Table B-1. Metadata for COOP stations in and near the Sierra Nevada Network parks. HPD= Hourly Precipitation Data (continued).

COOP Number	Name	Lat	Long	Elev (M)	Source/ Data Status	Start	End	In Park?
44176	Huntington Lake	37.228	-119.221	2140	COOP/ Gap 1962-1974	6/1/1915	Present	No
44232	Independence	36.798	-118.204	1204	COOP/ Complete after 1925/ HPD too	1/1/1893	Present	No
44235	Independence Onion V	36.767	-118.333	2800	COOP/ HPD	12/1/1948	2/25/1971	No
44389	Johnsondale	35.967	-118.533	1427	COOP/ precip	11/1/1954	5/9/1979	No
44518	Kern River Intake 3	35.950	-118.483	1113	COOP/ precip	10/1/1952	9/1/1966	No
44520	Kern River PH 1	35.467	-118.783	296	COOP	1/1/1931	8/31/1991	No
44523	Kern River PH 3	35.783	-118.439	824	COOP	0701/1948	Present	No
44705	Lake Sabrina	37.213	-118.614	2763	COOP/ Gap 1954-1975	1/1/1925	12/27/2006	No
44890	Lemon Cove	36.382	-119.026	156	COOP/ 3 d missing	1/1/1899	Present	No
44957	Lindsay	36.203	-119.058	128	COOP	12/1/1913	Present	No
	Lone Pine Cottnwd. P.H.	36.443	-118.043	1155	COOP	7/1/1948	Present	No
	McKay Point	36.400	-119.050	137	COOP	10/1/1963	10/31/1964	No
	Meadow Brook	37.100	-118.833	2959	COOP	7/1/1948	8/31/1951	No
	Milo 5 NE	36.276	-118.768	945	COOP	1/1/1957	9/1/2006	No
	Miramonte Conserv. Camp	36.663	-119.083	916	COOP	1/1/1957	Present	No
	Monache Meadows	36.217	-118.167	2410	COOP	7/1/1948	9/30/1972	No
	Mt. Givens	37.283	-119.083	2898	COOP	10/1/1963	4/1/1969	No
	Mtn. Home	36.250	-118.717	1635	COOP	10/1/1962	9/30/1976	No
	Orange Cove	36.617	-119.300	131	COOP	6/1/1931	5/1/1991	No
	Peppermint Meadows	36.100	-118.500	1617	COOP	7/1/1948	8/31/1955	No
	Piedra	36.800	-119.383	177	COOP	3/1/1912	11/1/1964	No
	Pine Flat Dam	36.824	-119.336	186	COOP	11/1/1964	Present	No
	Porterville	36.068	-119.020	120	COOP	6/1/1902	6/30/2004	No
	Post Corral Meadow	37.117	-118.900	2507	COOP	9/1/1951	8/31/1959	No
	Quaking Aspen	36.117	-118.533	2196	COOP	7/1/1955	8/31/1972	No
	Quinn R.S.	36.333	-118.583	2532	COOP	7/1/1948	8/31/1959	No
	Rock Creek	37.450	-118.733	2949	COOP	7/1/1948	9/30/1976	No
	Rogers Camp	36.100	-118.633	1903	COOP	9/1/1964	9/30/1976	No
	Rose Marie Meadow	37.317	-118.867	3050	COOP	10/1/1953	9/30/1976	No
	Round Meadow	35.967	-118.350	2745	COOP	7/1/1948	8/31/1971	No

Table B-1. Metadata for COOP stations in and near the Sierra Nevada Network parks. HPD= Hourly Precipitation Data (continued).

COOP Number	Name	Lat	Long	Elev (M)	Source/ Data Status	Start	End	In Park?
	South Lake	37.168	-118.571	2920	COOP	12/1/1924	12/27/2006	No
	Springville 3 ENE	36.150	-118.767	445	COOP	2/1/1951	10/31/1953	No
	Springville 7 ENE	36.167	-118.700	753	COOP	10/1/1953	10/31/1974	No
	Springville R.S.	36.142	-118.811	320	COOP	7/1/1948	9/1/2006	No
	Springville Tule Hd.	36.193	-118.657	1241	COOP	1/1/1896	9/1/2006	No
	Statum Meadow	36.933	-118.917	2532	COOP	7/1/1948	8/31/1959	No
	Three Rivers 6 SE	36.368	-118.848	590	COOP	1/1/1957	Present	No
	Three Rivers Edison P.H. 2	36.467	-118.883	290	COOP	8/1/1909	6/7/1971	No
	Three Rivers Edison P.H. 1	36.465	-118.862	347	COOP	7/1/1948	Present	No
	Trout Meadows	36.200	-118.417	1906	COOP	7/1/1948	7/31/1955	No
	Tunnel R.S.	36.367	-118.283	2730	COOP	7/1/1948	9/30/1976	No
	Vermilion Valley	37.367	-118.983	2294	COOP	12/1/1946	9/30/1976	No
	Wet Meadow	36.350	-118.567	2730	COOP	8/1/1959	9/30/1976	No
	Wishon Dam	37.007	-118.984	1996	COOP	11/1/1966	11/30/2005	No
	Woodchuck Meadow	37.033	-118.900	2806	COOP	6/24/1955	10/7/1969	No
	Worth Bridge	36.050	-118.933	159	COOP	2/1/1957	1/1/1965	No

Appendix C. Metadata from Non-COOP Stations within the Sierra Nevada Network

The lists of non-COOP stations in Tables C-1, C-2, and C-3 are excerpted from Davey et al. (2007), and give basic information about weather and climate stations located within the parks of the Sierra Nevada Network (SIEN). A few stations are outside. Some stations are listed by climate monitoring network, and others are listed by the source from which the metadata were received. Abbreviations: NPS – National Park Service, RAWS (Remote Automated Weather Station), CARB (California Air Resources Board), CASTNet – Clean Air Status and Trends Network, DWR-A – California Department of Water Resources Automated Station, DWR-M – California Department of Water Resources Manual (usually a Snow Course), DRI – Desert Research Institute / Western Regional Climate Center, GPMP – NPS Gaseous Pollutant Monitoring Program, NADP – National Acid Deposition Program, POMS – Passive Ozone Monitoring System, MID – Merced Irrigation District, CWOP – Citizens Weather Observing Program, IMPROVE – Visibility measurements, CRN – NOAA Climate Reference Network, UCSB – University of California at Santa Barbara. Most station names are listed as maintained by the sponsoring organization. Stations may be active or inactive.

Table C-1. Metadata from non-COOP weather and climate stations within Devils Postpile National Monument.

Devils Postpile National Monument (DEPO)							
Name	**Lat.**	**Lon.**	**Elev. (m)**	**Source**	**Start**	**End**	**In Park?**
Devils Postpile	37.629	-119.085	2305	NPS	9/1/2006	Present	Yes
Devils Post Pile	37.630	-119.093	2304	RAWS	11/1/1993	8/31/2004	Yes

Table C-2. Metadata from non-COOP weather and climate stations within Sequoia and Kings Canyon National Parks.

Sequoia and Kings Canyon National Parks (SEKI)							
Name	**Lat.**	**Lon.**	**Elev. (m)**	**Source**	**Start**	**End**	**In Park?**
Sequoia & Kings Cyn. NP -- Ash Mtn	36.488	-118.827	561	CARB	1984	2001	Yes
Sequoia & Kings Cyn. NP -- Ash Mtn	36.489	-118.829	535	CARB	1/1/2000	Present	Yes
Sequoia NP – Lower Kaweah	36.562	-118.769	1900	CARB	4/1/1987	Present	Yes
Wolverton	36.601	-118.717	2130	CARB	1986	1999	Yes
Ash Mountain	36.489	-118.827	457	CASTNet	10/1/2001	Present	Yes
Lookout Point	36.429	-118.763	1225	CASTNet	2/1/1997	12/31/2004	Yes
Bishop Pass	37.100	-118.557	3414	DWR-A	1/1/1988	Present	Yes
Chagoopa Plateau	36.497	-118.442	3139	DWR-A	10/1/1986	Present	Yes
Charlotte Lake	36.797	-118.422	3170	DWR-A	10/1/1985	Present	Yes

Table C-2. Metadata from non-COOP weather and climate stations within Sequoia and Kings Canyon National Parks (continued).

Name	Lat.	Lon.	Elev. (m)	Source	Start	End	In Park?
Sequoia and Kings Canyon National Parks (SEKI)							
Crabtree Meadow	36.563	-118.345	3261	DWR-A	10/1/1985	Present	Yes
Farewell Gap	36.412	-118.583	2896	DWR-A	10/1/2000	Present	Yes
Giant Forest (USACE)	36.562	-118.765	2027	DWR-A	8/1/1988	Present	Yes
Mitchell Meadow	36.737	-118.712	3018	DWR-A	8/1/1988	Present	Yes
State Lakes	36.927	-118.574	3139	DWR-A	8/1/1988	Present	Yes
Upper Tyndall Creek	36.650	-118.397	3475	DWR-A	8/1/1988	Present	Yes
Hockett Meadows	36.382	-118.655	2590	DWR-M	3/1/1930	Present	Yes
Farewell Gap	36.412	-118.583	2896	DWR-M	4/1/1952	Present	Yes
White Chief	36.422	-118.592	2804	DWR-M	3/1/1970	12/31/1978	Yes
Mineral King	36.437	-118.587	2438	DWR-M	4/1/1946	Present	Yes
Giant Forest	36.570	-118.768	1950	DWR-M	2/1/1930	Present	Yes
Panther Meadow	36.588	-118.717	2621	DWR-M	3/1/1925	Present	Yes
Grant Grove	36.742	-118.963	2011	DWR-M	2/1/1930	Present	Yes
Rattlesnake Creek	36.982	-118.720	3017	DWR-M	4/1/1973	Present	Yes
Bench Lake	36.958	-118.445	3230	DWR-M	4/2/1973	Present	Yes
Junction Meadow	36.755	-118.438	2514	DWR-M	4/1/1932	12/31/1963	Yes
Emerald Lake	37.183	-118.762	3230	DWR-M	4/1/1944	Present	Yes
Colby Meadow	37.178	-118.720	2956	DWR-M	4/1/1944	Present	Yes
Bishop Pass	37.100	-118.557	3414	DWR-M	4/1/1930	Present	Yes
Charlotte Ridge	36.770	-118.415	3261	DWR-M	2/1/1955	Present	Yes
Bullfrog Lake	36.770	-118.398	3246	DWR-M	4/1/1932	Present	Yes
Vidette Meadow	36.758	-118.410	2895	DWR-M	4/1/1956	4/1/1996	Yes
Tyndall Creek	36.632	-118.392	3246	DWR-M	4/1/1949	Present	Yes
Bighorn Plateau	36.615	-118.377	3459	DWR-M	4/1/1949	Present	Yes
Sandy Meadows	36.572	-118.367	3246	DWR-M	4/1/1949	Present	Yes
Crabtree Meadow	36.563	-118.345	3261	DWR-M	4/1/1949	Present	Yes

Table C-2. Metadata from non-COOP weather and climate stations within Sequoia and Kings Canyon National Parks (continued).

Sequoia and Kings Canyon National Parks (SEKI)							
Name	**Lat.**	**Lon.**	**Elev. (m)**	**Source**	**Start**	**End**	**In Park?**
Guyot Flat	36.523	-118.348	3246	DWR-M	4/1/1949	Present	Yes
Rock Creek	36.497	-118.333	2926	DWR-M	4/1/1949	Present	Yes
Siberian Pass	36.473	-118.267	3322	DWR-M	4/1/1948	Present	Yes
Quinn Ranger Station	36.328	-118.573	2545	DWR-M	3/1/1930	Present	No
Ash Mountain (seki-am)	36.494	-118.829	610	GPMP	5/1/1991	12/1/1994	Yes
Grant Grove	36.740	-118.961	2012	GPMP	7/1/1993	12/31/1994	Yes
Lower Kaweah	36.566	-118.777	1890	GPMP	9/1/1988	Present	Yes
Elk Creek	36.513	-118.809	690	NPS	1/1/1983	12/31/2000	Yes
MEWSS[1]	36.554	-118.752	1920	NPS	1984	2000	Yes
Ash Mountain	36.491	-118.825	527	RAWS	12/1/2004	Present	Yes
Cedar Grove	36.788	-118.656	1439	RAWS	9/1/1999	Present	Yes
Milk Ranch	36.487	-118.780	1897	RAWS	8/1/1997	8/31/1999	Yes
Park Ridge	36.724	-118.943	2298	RAWS	7/1/1997	Present	Yes
Rattlesnake	36.407	-118.422	2621	RAWS	7/1/1992	Present	Yes
Sugarloaf	36.727	-118.675	2475	RAWS	7/1/1992	Present	Yes
Wolverton	36.445	-118.703	1597	RAWS	6/1/1996	Present	Yes
Emerald Lake	36.598	-118.674	2808	UCSB	8/1/1990	Present	Yes
Marble Fork	36.608	-118.685	2619	UCSB	8/1/1992	Present	Yes
M3	36.610	-118.647	3232	UCSB	3/1/1994	Present	Yes
Topaz Lake	36.625	-118.639	3221	UCSB	11/1/1995	Present	Yes

1. Mid-elevation weather station site

Table C-3. Metadata from non-COOP weather and climate stations within Yosemite National Park.

Yosemite National Park (YOSE)							
Name	Lat.	Lon.	Elev. (m)	Source	Start	End	In Park?
Yosemite NP-Merced River	37.743	-119.594	1220	CARB	M	Present	Yes
Yosemite NP-Turtleback Dome	37.711	-119.706	1611	CARB	5/1/1988	Present	Yes
Yosemite Village-Visitor Center	37.749	-119.587	1213	CARB	1/1/1976	Present	Yes
Turtleback Dome	37.713	-119.706	1605	CASTNet	10/1/1995	Present	Yes
K6IXA-2 Yosemite Park	37.723	-119.575	2469	CWOP	M	Present	Yes
Gin Flat TC Tower	37.767	-119.773	2149	DRI	10/1/2003	Present	Yes
Dana Meadows	37.897	-119.257	2987	DWR-A	10/1/1985	Present	Yes
Dog House Meadow	37.762	-119.785	1859	DWR-A	3/14/2005	Present	Yes
Gin Flat	37.767	-119.773	2149	DWR-A	10/1/1985	10/31/2002	Yes
Lower Kibbie Ridge	38.032	-119.877	2042	DWR-A	10/1/1985	Present	Yes
Merced Lake	37.738	-119.405	2225	DWR-A	10/24/2007	Present	Yes
Ostrander Lake	37.637	-119.550	2499	DWR-A	10/1/1988	Present	Yes
Paradise Meadow	38.047	-119.670	2332	DWR-A	10/1/1985	Present	Yes
Slide Canyon	38.092	-119.430	2804	DWR-A	10/1/1985	Present	Yes
Snow Flat	37.827	-119.497	2651	DWR-A	1/1/1995	10/27/1998	Yes
Tenaya Lake	37.838	-119.448	2484	DWR-A	10/1/1998	Present	Yes
Tioga Pass Entry Station	37.911	-119.257	3031	DWR-A	12/10/2001	Present	No
Tuolumne Mdws. (DWR)	37.873	-119.350	2621	DWR-A	10/1/1985	Present	Yes
Johnson Lake	37.568	-119.517	2591	DWR-M	2/1/1931	12/31/1941	Yes
Peregoy Meadows	37.667	-119.625	2133	DWR-M	2/1/1931	Present	Yes
Gin Flat	37.765	-119.773	2133	DWR-M	2/1/1930	Present	Yes
Cottonwood Meadows	37.908	-119.772	1828	DWR-M	3/1/1947	12/31/1949	Yes
Smith Meadows	37.917	-119.750	2011	DWR-M	4/1/1938	12/31/1949	Yes
Beehive Meadow	37.995	-119.780	1981	DWR-M	2/1/1930	Present	Yes
Sachse Springs	38.085	-119.837	2407	DWR-M	1/1/1948	Present	Yes
Ostrander Lake	37.637	-119.550	2499	DWR-M	4/1/1938	Present	Yes
Spotted Fawn	38.092	-119.758	2377	DWR-M	1/1/1948	Present	Yes
Vernon Lake	38.017	-119.717	2042	DWR-M	2/1/1947	Present	Yes
Paradise Meadow	38.047	-119.670	2332	DWR-M	2/1/1946	Present	Yes
Wilma Lake	38.083	-119.633	2438	DWR-M	2/1/1946	Present	Yes
Grace Meadow	38.150	-119.617	2712	DWR-M	2/1/1947	12/31/1968	Yes
Dana Meadows	37.897	-119.257	2987	DWR-M	1/1/1926	Present	Yes
Tuolumne Mdws. (DWR)	37.873	-119.350	2621	DWR-M	2/1/1930	Present	Yes
Tenaya Lake	37.838	-119.448	2484	DWR-M	2/1/1930	Present	Yes
Snow Flat	37.827	-119.497	2651	DWR-M	2/2/1930	Present	Yes

Table C-3. Metadata from non-COOP weather and climate stations within Yosemite National Park (continued).

Name	Lat.	Lon.	Elev. (m)	Source	Start	End	In Park?
Yosemite National Park (YOSE)							
Rafferty Meadows	37.837	-119.325	2865	DWR-M	4/1/1948	Present	Yes
Fletcher Lake	37.796	-119.343	3139	DWR-M	2/1/1930	4/1/1960	Yes
Merced River	37.743	-119.594	1219	GPMP	8/1/2002	12/31/2005	Yes
Turtleback Dome	37.713	-119.706	1605	IMPROVE	8/18/1988	9/30/2006	Yes
Yosemite at Wawona	31.508	-119.632	1510	MID	11/30/1998	Present	Yes
Yosemite at Yosemite Village	37.740	-119.589	1280	MID	11/30/1998	Present	Yes
Mobile 2 (Lake Tenaya)	37.838	-119.450	2487	POMS	6/28/2007	Present	Yes
School Yard	37.748	-119.592	1234	POMS	6/7/2006	Present	Yes
Tioga Pass	37.911	-119.259	3037	POMS	7/20/2005	9/22/2005	Yes
Yosemite Mobile	37.748	-119.592	1219	POMS	4/27/2007	6/27/2007	Yes
Crane Flat Lookout	37.762	-119.825	2025	RAWS	11/1/1991	Present	Yes
Gaylor Meadow	37.868	-119.318	2825	RAWS	8/1/1988	Present	Yes
Golden Gate NRA #2	37.806	-119.785	1829	RAWS	6/1/1994	10/31/1998	Yes
Mariposa Grove	37.513	-119.605	1951	RAWS	9/1/1988	Present	Yes
White Wolf	37.851	-119.650	2446	RAWS	8/1/1988	Present	Yes
Yosemite Village 12 W	37.759	-119.821	2018	CRN	12/19/2007	Present	Yes

Appendix D. General Considerations for Complete Climate Monitoring Network Design

When considering the installation of a new station or augmentation of an existing one, here are some points to consider for a number of the more commonly measured climatic elements. Of these, we consider air temperature, precipitation, humidity and wind to be core parameters.

Element-specific factors

A. Temperature. An open exposure with good air movement is much preferred. The most common measurement is about eye height, 1.5 to 2.0 meters. In snowy locations sensors should be 3-4 feet higher than the deepest expected snowpack in the next 50 years, or perhaps 2-3 times the depth of the average maximum annual depth. Sensors should be shielded from solar radiation, from above, from below (reflecting off snow), from sunrise/sunset horizontal input, and from vertical rock faces. They should be clamped tightly so as not to swivel away from level stacks of radiation plates. Nearby vegetation should be kept away from the sensors (several meters). Growing vegetation should be cut to original conditions. Small hollows and swales can cool tremendously at night and are best avoided. Side slopes, not on the very bottom of a valley, of perhaps a degree or two of angle, facilitate air movement and drainage, and in effect sample a large area during nighttime hours. Temperature can change substantially from moves of only a few feet. We have encountered many situations where flat and seemingly uniform conditions (like airport runways) appear to have different climate behaviors over distances of a few hundreds to tens of feet (differences of 10-20 degrees F). When snow is on the ground, these microclimatic differences can be much stronger, and differences of 5-10 degrees F can occur in the short distance between the thermometer and the snow surface on quiet evenings.

B. Precipitation (liquid). Quiet locations with vegetative or artificial shielding are preferred to reduce the influence of wind on the gauge's catch. Very windy locations should be avoided; wind should be minimized wherever possible. Wind effects on precipitation are much less for rain than for snow. Devices that "save" or store precipitation have advantages, but most gages are built to dump precipitation as it falls, or must be periodically emptied. Automated gages give both the amount and the timing. Simple backups that record only the total since the last visit have a certain attraction (for example, storage gages, or lengths of PVC pipe, perhaps with bladders on the bottom): does the total from an automated gage add up to the measured total in a simple bucket (with evaporation prevention, such as with mineral oil)? Overhanging foliage and drip from trees can alter precipitation totals and should be avoided.

C. Precipitation (frozen). Quiet locations, or shielding from wind, are a must. Undercatch is only about 5 percent for rain, but with winds of only 5-10 mph gages may catch only 30-70 percent of the actual snow falling, depending on density of the flakes. To achieve 100 percent catch of snow, the standard configuration is the one employed by the Climate Reference Network, the DFIR shield (Double Fence Intercomparison Reference), with 8-foot high vertical wooden slatted fences in two concentric octagons with diameters of 26 feet and 13 feet, and an inner Alter shield (flapping vanes). Numerous tests have shown this is the only way to achieve complete catch of snowfall (Yang et al. 2001). The DFIR is big and bulky; it is recommended that all precipitation gages have at least Alter shields on them. Sometimes on the westward slopes in fall and spring seasons snow can be heavy and fall more vertically. In colder locations or winter storms, light flakes will frequently fly in and then out of a gage. Clearings in forests are usually good sites. Snow blowing from trees that are too close can augment actual precipitation totals. Artificial shielding (vanes, etc) around gages in snowy locales should always be used if accurate totals are desired. Moving parts tend to freeze up. Capping of gages, or building up of snow around the rim of the gauge and over the opening, during heavy snowfall events is a common occurrence. When the cap becomes pointed, snow falls off onto the ground and is not recorded. Caps and plugs often will not fall into the tube until hours, days, or even weeks have passed, typically when an extended period of freezing or warmer temperatures, or sunlight, finally occurs. Liquid-based measurements (e.g., Snotel "rocket" gages) do not have the resolution (usually 0.1 inch rather than 0.01 inch) that tipping buckets and other gages do, but are known to be reasonably accurate in very snowy climates. Light events might not be recorded until enough of them add up to the next reporting increment. More expensive gages like Geonor (all weather gauge) can be considered, and could do quite well in many Californian settings; however they need to be emptied every 15 inches or so (20-inch capacity) until the new 36-inch capacity gage is offered for sale. Recently the NWS has been testing the new (and very expensive) Ott all-weather gage. Riming can be an issue in windy, foggy or cloudy environments below freezing, such as on mountaintops. Rime, dew, and other forms of atmospheric condensation are not considered to be precipitation, since they are caused by the gage itself.

D. Snow depth. Windswept areas tend to be blown clear. Conversely, certain vegetation can act as a snow fence and cause artificial drifts. Some amount of vegetation in the vicinity can help generally slow down the wind. The two most common brands of snow depth sensors are Judd and Campbell Scientific, with varied opinions on the superior model. Both use ultrasound, and look downward in a cone about 22 degrees in diameter. The ground should be maintained in such a manner that the zero point on the calibration scale does not change, and should be relatively clear of vegetation. The down side of automated snow depth sensors is that they represent a single spot in a landscape, whereas manual observations generally take an average of snow depths in an area (e.g. COOP standard procedure). The device itself can oftentimes create a minimum of snow depth below the sensor as compared to the surrounding area, particularly in the spring melt season.

E. Snow water equivalent. This is determined by the weight of snow on fluid-filled pads, about the size of a desk top, sometimes in groups of four, or in larger hexagons 6-8 feet in diameter. These require flat ground, some distance from nearby sources of windblown snow, and shielding which is "just right": not too close to shielding to act as a kind of snow fence, and not too far from shielding that blowing and drifting are a factor. Generally these require fluids with anti-freeze properties, and handling and replacement protocols.

F. Wind. Open exposure is needed. Small prominences or benches without blockage from certain sectors are preferred. A typical rule for trees is to stay back 10 tree-heights from all tree obstructions. Sites in long narrow valleys can obviously only exhibit two main wind directions. Gently rounded eminences are more favored. Any kind of local topographic steering of airflow should be avoided to the extent possible. In SEKI, isolated mountain tops or hill tops would be considered desirable. Sustained speeds and highest gusts (1 second) should be recorded. Averaging methodologies for both sustained winds and gusts can affect climate trends and should be recorded as metadata, and all such changes noted. Vegetation growth affects the vertical wind profile, and growth over a few years can lead to changes in mean wind speed even if the "real" wind does not change, so vegetation near the site (perhaps out to 50 meters radius) should be maintained in a quasi-permanent status (same height and spatial distribution). Wind devices can rime up and freeze, or spin out of balance. In severely rimed or windy climates, rugged anemometers such as those by Taylor are worth considering. These are expensive, but durable and can take substantial abuse. In exposed locations, plan for 100-150 mph winds, and be able to measure these. At a minimum, anemometers should be rated to 120-150 mph. The highest wind seen at Mount Warren thus far has been 186 mph in 2010.

G. Humidity. This is a relatively straightforward element. Close proximity to lakes or spray can affect readings, but in soggy locations bogs are like lakes draped over the landscape. Humidity readings are typically less accurate near 100 percent, and at low humidities in cold weather.

H. Solar radiation. An unobstructed horizon is best for incoming radiation measurement. This generally implies a flat plateau or summit. Only a pyranometer in a fairly flat location without nearby mountain peaks will record the direct beam contribution every day of the year. In many locations, trees or mountains will block part of the day, so locations deep in Yosemite Valley floor or Kings Canyon may not be ideal. This can also be problematic in the winter months when daylight hours are shortest and you are relying on solar power to operate the equipment. This has already been experienced by WRCC in operating the White Mountain Summit station, and others.

I. Soil temperature. If there is soil at the site, it is a good idea to measure soil temperature. If a single depth is recorded, 10 cm is the most preferred. Other common depths are 25 cm, 50 cm, 2 cm, and 100 cm. Biological activity in the soil will be proportional to temperature, with important threshold effects near freezing. This measurement has historically been omitted from observational platforms, but is becoming increasingly common due to its uniqueness and need for many scientific fields to know this information. NRCS SNOTEL and the DWR California Snow Survey are in the process of adding these sensors to their observational platforms.

J. Soil moisture. These are much more finicky than temperamental measurements, and take a degree of care to install. The soil should be characterized by a soil expert during installation. The readings can take some experience to interpret correctly. If accurate they are very useful.

K. Distributed observations. One can readily see that compromises must be struck among the above considerations in order to have all present on a single platform, because some of them are mutually exclusive. How big can a "site" be? Generally we like to keep the equipment footprint as small as practical, with all the components next to each other (less than 10-20 meters or so). Readings from one instrument are frequently used to help interpret readings from the remaining instruments, and collectively these constitute a package deal. What is a tolerable degree of separation? Some consideration can be given to locating a precipitation gage or snow pillow among protective vegetation, while the associated temperature, wind and humidity readings might be in a more open and exposed nearby location 20-50 meters away. Ideally, we would like to know the wind *right at* the precipitation gage, but a compromise involving a short split, and in effect a "distributed observation," could be entertained. There is no hard and fast rule, but we would suggest that the footprint of a site be kept to within about 50 meters. There are also constraints imposed by engineering and electrical factors that affect cable lengths, signal strength, and line noise; the shorter the better. Practical issues involve whether to trench to outlying instruments, or allow lines atop the ground, and associated problems with animals, people, weathering, and the like. Separating a precipitation gage by up to 100 meters or so from an instrument mast may be an acceptable compromise if other factors are not limiting.

K. Swap-out schedules. Instruments slowly degrade and a plan for replacing them with new, refurbished or recalibrated instruments should be in place. After about 5 years, a systematic swapping procedure should result in replacement of most of the sensors in a network. Certain parts, such as solar radiation sensors, are candidates for annual calibration or swap-out. Anemometers tend to degrade as bearings erode or electrical contacts become uneven. Noisy bearings are a tip-off, and a stethoscope might aid in hearing such rumbles. Increased internal friction affects the threshold starting speed; once spinning they tend to work. Increases in starting threshold speeds can create more zero winds, and thus reduce the reported mean wind speed, with no real change in the wind properties. A field calibration kit should be developed and taken along on all visits, routine or otherwise, to a site. Rain gages can be tested with drip testers during field visits. Protective conduit and tight water seals can prevent abrasion and moisture problems, although seals can keep moisture in as well as out. Bulletproof casings are sometimes employed in remote settings. A supply of spare parts, at least one of each, and more for less expensive or more delicate sensors, should be maintained. These also permit swapping out during field visits so that instruments can be calibrated in the relative luxury of the operational home. The larger the network, the more the need for a parts depot.

Long-term comparability and consistency

A. Consistency: Hold the biases constant. Every site has biases, problems and idiosyncracies of one sort or another. A good rule of thumb is to simply try to keep these biases constant through time. Since the goal is to track climate through time, keeping sensors, methodologies, and exposure constant will insure that the only measured change is truly in the climate system. This means leaving the site as it originally was, or performing maintenance to keep it that way. Once a site is installed, the goal should be to never move the site, even by a few feet, or allow any significant changes within 100-300 feet, for the next several decades.

Sites in or near rock outcroppings will likely have less vegetation disturbance or growth through the years. This is beneficial to prevent corrosion that can occur to the base of the station mounts in moist soils or vegetation.

Sites that will remain locally similar for some time are also preferable. For example, a site in the immediate vicinity of a glacier may become locally much more “balmy” and change rapidly as the ice withdraws, even if the ice is responding to regional climate over the last decade or two. In this case, a lightly vegetated prominence away from the direct influence of the ice (as through reflected solar radiation, or glacially induced winds), and at about the middle elevation of the ice, would be more appropriate.

B. Metadata. Since the climate of every site is affected by features in the immediate vicinity, it is vital to record this information for all time, and to repeatedly update through time with each service visit. Distances, angles, heights of vegetation, fine scale topography, condition of instruments, shielding discoloration, and other factors from within a meter to several kilometers should be noted. Systematic photography should be undertaken, and updated at least once every year or two. For the photographic methodology used to document Climate Reference Stations, see Redmond (2004).

The main purpose for climate stations is *tracking through time*. Anything that affects the interpretation of records through time needs to be noted and recorded for posterity. The important factors should be clear to a person who has never visited the site, or was not alive when the site was installed.

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