National Park Service
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Natural Resource Program Center
Fort Collins, Colorado

Weather and Climate Inventory National Park Service Northern Colorado Plateau Network

Natural Resource Technical Report NPS/NCPN/NRTR—2006/002

ON THE COVER
Hickman Bridge—Capitol Reef National Park

Weather and Climate Inventory
National Park Service
Northern Colorado Plateau Network

Natural Resource Technical Report NPS/NCPN/NRTR—2006/002
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Acronyms

AASC	American Association of State Climatologists
ACIS	Applied Climate Information System
ASOS	Automated Surface Observing System
ARCH	Arches National Park
AWOS	Automated Weather Observing System
BLCA	Black Canyon of the Gunnison National Park
BLM	Bureau of Land Management
BRCA	Bryce Canyon National Park
CANY	Canyonlands National Park
CARE	Capitol Reef National Park
CASTNet	Clean Air Status and Trends Network
CEBR	Cedar Breaks National Monument
CEMP	Community Environmental Monitoring Program
CLIM-MET	Climate Impact Meteorological Stations Network
CoAgMet	Colorado Agricultural Meteorological Network
COLM	Colorado National Monument
COOP	Cooperative Observer Program
CRN	Climate Reference Network
CURE	Curecanti National Recreation Area
DFIR	Double-Fence Intercomparison Reference
DINO	Dinosaur National Monument
DST	daylight savings time
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FOBU	Fossil Butte National Monument
FIPS	Federal Information Processing Standards
GMT	Greenwich Mean Time
GOES	Geostationary Operational Environmental Satellite
GOSP	Golden Spike National Historic Site
GPS	Global Positioning System
HOVE	Hovenweep National Monument
I&M	NPS Inventory and Monitoring Program
LST	local standard time
NABR	Natural Bridges National Monument
NADP	National Atmospheric Deposition Program
NCPN	Northern Colorado Plateau Inventory and Monitoring Network
NCDC	National Climatic Data Center
NetCDF	Network Common Data Form
NOAA	National Oceanic and Atmospheric Administration
NPS	National Park Service
NRCS	Natural Resources Conservation Service
NRCS-SC	Natural Resources Conservation Service snowcourse network
NWS	National Weather Service
PISP	Pipe Spring National Monument

PRISM	Parameter Regression on Independent Slopes Model
RAWS	Remote Automated Weather Station Network
RCC	regional climate center
SAO	Surface Airways Observation Network
Surfrad	Surface Radiation Budget Network
SNOTEL	Natural Resources Conservation Service Snowfall Telemetry Network
TICA	Timpanogos Cave National Monument
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
UTC	Coordinated Universal Time
WBAN	Weather Bureau Army Navy
WMO	World Meteorological Organization
WRCC	Western Regional Climate Center
ZION	Zion National Park

Executive Summary

Climate drives many of the environmental processes in the Northern Colorado Plateau Inventory and Monitoring Network (NCPN). Climate variations are responsible for short and long-term changes in ecosystem fluxes of energy and matter and they have profound effects on underlying geomorphic and biogeochemical processes. Future changes in climate will, in turn, have tremendous impacts on these processes. Monitoring climate facilitates interpretation of other vital sign measurements. Efforts to manage various native plant and animal species in the NCPN, and the control of invasive species such as cheatgrass (*Bromus tectorum*) and *Tamarix* (in riparian areas), are very sensitive to both short-term and long-term climate variations. The region covered by NCPN is vulnerable to drought and other interannual climate variations, highlighting the region's sensitivity to possible future climate changes. Because of its influence on the ecology of NCPN parks and the surrounding area, climate was identified as a high-priority vital sign for NCPN and climate is one of the 12 basic inventories to be completed for all Inventory and Monitoring Parks.

Because of the importance of climate to almost every aspect of both ecology and park management, this project was initiated to inventory past and present climate monitoring efforts. For the NCPN, the primary objectives for climate and weather monitoring are 1) to provide monthly and annual summaries of climatic elements in NCPN park units and 2) to identify extremes of climatic conditions for common elements (precipitation and temperature) and other elements where sufficient data are available. In this report, we provide the following information:

- Overview of broad-scale climatic factors and zones important to NCPN park units.
- Inventory of weather and climate station locations in and near NCPN park units.
- Results of an inventory of metadata on each weather station, including affiliations for weather-monitoring networks, types of measurements recorded at these stations, and information about the actual measurements (length of record, etc.).
- Initial evaluation of the adequacy of coverage for existing weather stations and recommendations for improvements in monitoring weather and climate.

The climate backdrop of the NCPN is complex. Spatial climate variability within NCPN is heavily influenced by topography. Mean annual temperature ranges from about 20°C near Zion National Park down to almost 0°C in most of the alpine areas. Precipitation is generally proportional to elevation. Mean annual precipitation ranges from just under 200 mm near Capitol Reef National Park (CARE) to almost 2000 mm in the mountains near Timpanogos Cave National Monument (TICA). A spatial pattern of primary interest in NCPN is the northwestern boundary of the summertime monsoon event, which runs through the NCPN region. Parks to the south and east of this boundary (e.g., Natural Bridges National Monument) have precipitation maxima during the summer months, while parks to the north and west of this boundary (e.g., TICA) have precipitation maxima during the winter months. Winter precipitation in the region is sensitive to climate indices such as the El Niño Southern Oscillation and the Pacific Decadal Oscillation. This is particularly true in southern portions of NCPN, where El Niño

conditions and/or positive phases of the Pacific Decadal Oscillation generally lead to wetter winters. Recent droughts have stressed native vegetation and water resources in the NCPN, increasing the region's vulnerability to wildfires and invasions of alien plant species.

This report builds on the substantial information that has already been compiled by the NCPN network regarding past and present weather and climate monitoring efforts in the NCPN. Through a search of national databases and inquiries to National Park Service staff, we identified 41 weather and climate stations within the park units of the NCPN. Some of the national-scale weather and climate station networks that are represented within the NCPN park units are:

- National Weather Service Cooperative Observer Program (27 stations),
- Remote Automated Weather Station (6 stations),
- United States Department of Agriculture Natural Resources Conservation Service (2 stations),
- Climate Reference Network (2 stations), and
- Clean Air Status and Trends Network (1 station).

Many of the park units within the NCPN are well-sampled by weather and climate stations. These include TICA, Dinosaur National Monument (DINO), and most of the park units in southwestern Utah. In these areas, it is important that a high priority be placed on the retention and maintenance of existing weather and climate stations, especially those with the longest periods of record. The majority of these weather and climate stations that have been identified within NCPN do have satisfactory metadata and data records.

There are, however, some park units in the NCPN for which the current coverage of weather and climate stations is quite sparse, particularly for automated weather stations. These park units include Colorado National Monument (COLO), Golden Spike National Historic Site (GOSP), and Hovenweep National Monument (HOVE). In most of these park units, it could be useful to work together with the Bureau of Land Management, to install a Remote Automated Weather Station (RAWS) in or near each of these park units. This is particularly true in light of the high importance placed on monitoring fire behavior in this semi-arid region.

Acknowledgements

This work was supported and completed under Task Agreement H8R07010001 with the Great Basin Cooperative Ecosystem Studies Unit. We would like to acknowledge very helpful assistance from various National Park Service personnel associated with the Northern Colorado Plateau Inventory and Monitoring Network. Particular thanks are extended to Steve Garman, John Gross, and Margaret Beer. We would also like to acknowledge Grant Kelly, Heather Angeloff, and Greg McCurdy, all from the Western Regional Climate Center, for their useful assistance. Portions of the work also were supported by the Western Regional Climate Center under the auspices of the National Oceanic and Atmospheric Administration.

1.0. Introduction

Weather and climate are key drivers of ecosystem structure and function. Global- and regional-scale climate variations do have a tremendous impact on natural systems (Chapin et al. 1996; Schlesinger 1997; Jacobson et al. 2000; Bonan 2002). Long-term patterns in temperature and precipitation provide first-order constraints on potential ecosystem structure and function (Whitford 2002). Secondary constraints are realized from the intensity and duration of individual weather events, and additionally, from seasonality and interannual climate variability. These constraints influence the fundamental properties of ecological systems, such as soil-water relationships, plant-soil processes, nutrient cycling, as well as disturbance rates and intensity. These properties, in turn, influence the life-history strategies supported by a climate regime (Neilson 1987; Garman et al. 2004).

Given the importance of climate, it is one of 12 basic inventories to be completed by the National Park Service (NPS) Inventory and Monitoring Program (I&M) network (I&M 2006). As primary environmental drivers for the other vital signs, weather and climate patterns present various practical and management consequences and implications for the NPS (Oakley et al. 2003). Most park units observe weather and climate elements as part of their overall mission. The lands under NPS stewardship provide many excellent locations for monitoring climate conditions.

It is essential that park units within the Northern Colorado Plateau Inventory and Monitoring Network (NCPN) have an effective climate-monitoring system in place to track climate changes and to aid in management decisions relating to these changes. The two primary objectives for climate- and weather-monitoring in the NCPN are as follows (Garman et al. 2004; O'Dell et al. 2005):

A. Provide monthly and annual summaries of climatic elements in NCPN park units.
B. Identify extremes of climatic conditions for common elements (precipitation and temperature) and other elements where sufficient data are available (e.g. wind speed and direction, solar radiation, fuel temperature and moisture).

The purpose of this report is to determine the current status of weather and climate monitoring in the NCPN (Figure 1.1, Table 1.1). In this report, we provide the following informational elements:

- Overview of broad-scale climatic factors and zones important to NCPN park units.
- Inventory of locations for known weather/climate stations in and near NCPN park units.
- Results of metadata inventory for each station, including weather-monitoring network affiliations, types of recorded measurements, and information about actual measurements (length of record, etc.).
- Initial evaluation of the adequacy of coverage for existing weather stations and recommendations for improvements in monitoring weather and climate.

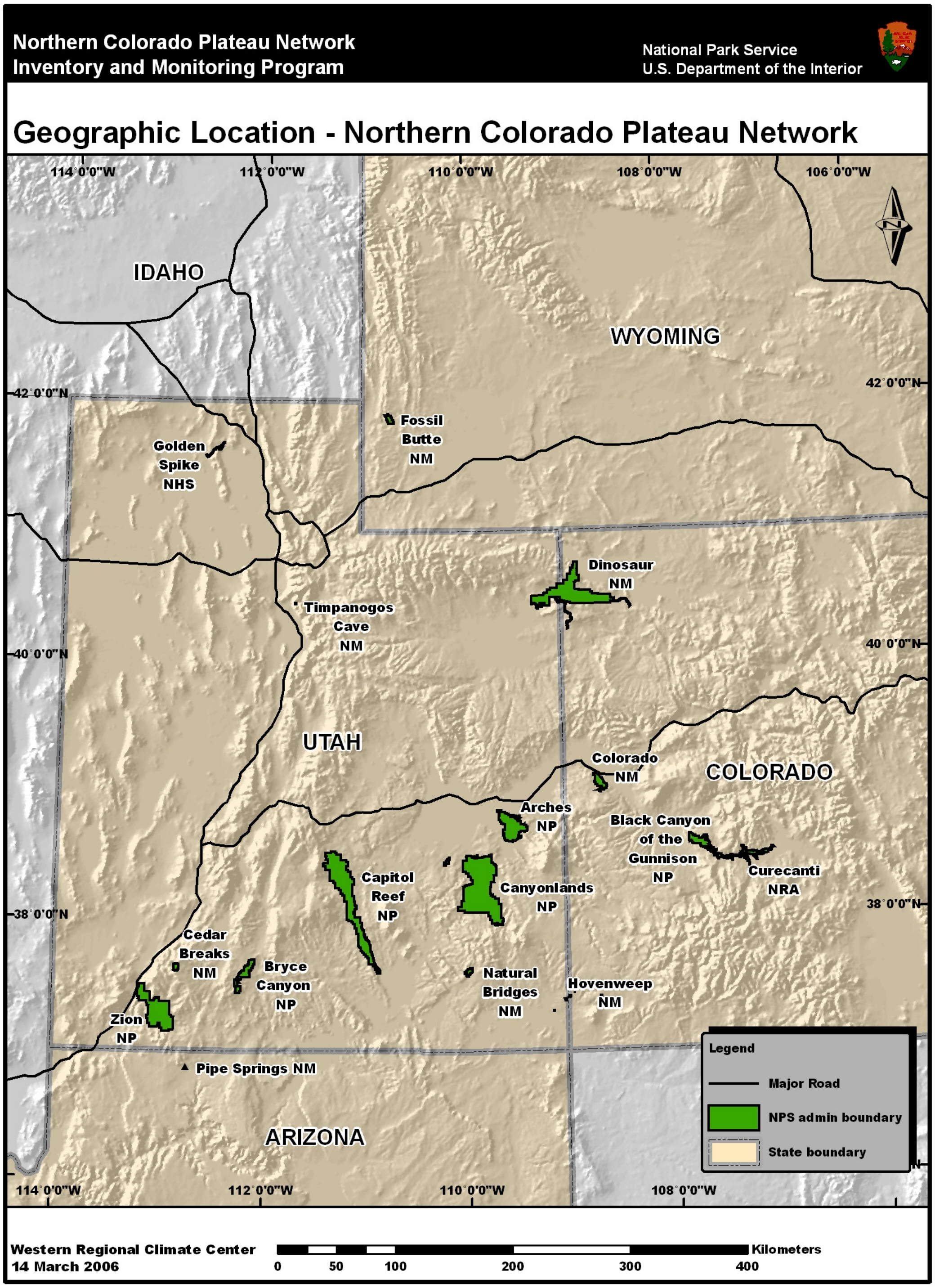


Figure 1.1. Map of the Northern Colorado Plateau Inventory and Monitoring Network (NCPN).

Table 1.1. Park units in NCPN.

Acronym	Name
ARCH	Arches National Park
BLCA	Black Canyon of the Gunnison National Park
BRCA	Bryce Canyon National Park
CANY	Canyonlands National Park
CARE	Capitol Reef National Park
CEBR	Cedar Breaks National Monument
COLM	Colorado National Monument
CURE	Curecanti National Recreation Area
DINO	Dinosaur National Monument
FOBU	Fossil Buttes National Monument
GOSP	Golden Spike National Historic Site
HOVE	Hovenweep National Monument
NABR	Natural Bridges National Monument
PISP	Pipe Spring National Monument
TICA	Timpanogos Cave National Monument
ZION	Zion National Park

1.1. Network Terminology

Before proceeding, it is important to stress that this report discusses the idea of "networks" in two different ways. Modifiers are used to distinguish between NPS I&M networks and weather/climate station networks. See Appendix B for a full definition of these terms.

1.1.1. Weather/Climate Station Networks

Most weather and climate measurements are made not from isolated stations but from stations that are part of a network operated in support of a particular mission. The limiting case is a network of one station, where measurements are made by an interested observer or group. Larger networks usually have more and better inventory data and station-tracking procedures. Some national weather/climate networks are associated with the National Oceanic and Atmospheric Administration (NOAA), including the National Weather Service (NWS) Cooperative Observer Program (COOP). Other national networks include the interagency Remote Automated Weather Station Network (RAWS) and the U.S. Department of Agriculture/Natural Resources Conservation Service (USDA/NRCS) Snowfall Telemetry (SNOTEL) and snowcourse networks. Usually a single agency, but sometimes a consortium of interested parties, will jointly support a particular weather/climate network.

1.1.2. NPS I&M Networks

Within the NPS, the system for monitoring various attributes in the participating park units (about 270–280 in total) is divided into 32 NPS I&M networks. These networks are collections of park units grouped together around a common theme, typically geographical.

1.2. Weather versus Climate Definitions

It is also important to distinguish whether the primary use of a given station is for weather purposes or for climate purposes. Weather station networks are intended for near-real-time usage, where the precise circumstances of a set of measurements are typically less important. In these cases, changes in exposure or other attributes over time are not as critical. Climate networks, however, are intended for long-term tracking of atmospheric conditions. Siting and exposure are critical factors for climate networks, and it is vitally important that the observational circumstances remain essentially unchanged over the duration of the station record. Some climate networks can be considered hybrids of weather/climate networks. These hybrid climate networks can supply information on a short-term "weather" time scale and a longer-term "climate" time scale.

In this report, "weather" generally refers to current (or near-real-time) atmospheric conditions, while "climate" is defined as the complete ensemble of statistical descriptors for temporal and spatial properties of atmospheric behavior (see Appendix B). Climate and weather phenomena shade gradually into each other and are ultimately inseparable.

1.3. Purpose of Measurements

Climate inventory and monitoring climate activities should be based on a set of guiding fundamental principles. Any evaluation of weather/climate monitoring programs begins with asking the following question:

- What is the purpose of weather and climate measurements?

Evaluation of past, present, or planned weather/climate monitoring activities must be based on the answer to this question.

Weather and climate data and information constitute a prominent and widely requested component of the NPS I&M networks (I&M 2006). Within the context of the NPS, the following services constitute the main purposes for recording weather and climate observations:

- Provide measurements for real-time operational needs and early warnings of potential hazards (landslides, mudflows, washouts, fallen trees, plowing activities, fire conditions, aircraft and watercraft conditions, road conditions, rescue conditions, fog, restoration and remediation activities, etc.).
- Provide visitor education and aid interpretation of expected and actual conditions for visitors while they are in the park and for deciding if and when to visit the park.
- Establish engineering and design criteria for structures, roads, culverts, etc., for human comfort, safety, and economic needs.
- Consistently monitor climate over the long-term to detect changes in environmental drivers affecting ecosystems, including both gradual and sudden events.
- Provide retrospective data to understand *a posteriori* changes in flora and fauna.
- Document for posterity the physical conditions in and near the park units, including mean, extreme, and variable measurements (in time and space) for all applications.

The last three items in the preceding list are pertinent primarily to the NPS I&M networks; however, all items are important to NPS operations and management. Most of the needs in this list overlap heavily. It is often impractical to operate separate climate measuring systems that also cannot be used to meet ordinary weather needs, where there is greater emphasis on timeliness and reliability.

1.4. Design of Climate-Monitoring Programs

Determining the purposes for collecting measurements in a given weather/climate monitoring program will guide the process of identifying weather/climate stations suitable for the monitoring program. The context for making these decisions is provided in Chapter 2 where background on the NCPN climate is presented. However, this process is only one step in evaluating and designing a climate-monitoring program. This process includes the following additional steps:

- Define park- and network-specific monitoring needs and objectives.
- Identify locations and data repositories of existing and historic stations.
- Acquire existing data when necessary or practical.
- Evaluate the quality of existing data.
- Evaluate the adequacy of coverage of existing stations.
- Develop a protocol for monitoring the weather and climate, including the following:
    - Standardized summaries and reports of weather/climate data.
    - Data management (quality assurance and quality control, archiving, data access, etc.).
- Develop and implement a plan for installing or modifying stations, as necessary.

Throughout the design process, there are various factors that require consideration in evaluating weather and climate measurements. Many of these factors have been summarized by Dr. Tom Karl, director of the NOAA National Climatic Data Center (NCDC), and widely distributed as the "Ten Principles for Climate Monitoring" (Karl et al. 1996; NRC 2001). These principles are presented in Appendix A, and the guidelines are embodied in many of the comments made throughout this report. The most critical factors are presented here. In addition, an overview of requirements necessary to operate a climate network is provided in Appendix C, with further discussion in Appendix E.

1.4.1. Need for Consistency

A principal goal in climate monitoring is to detect and characterize slow and sudden changes in climate through time. This is of less concern for day-to-day weather changes, but it is of paramount importance for climate variability and change. There are many ways whereby changes in techniques for making measurements, changes in instruments or their exposures, or seemingly innocuous changes in site characteristics can lead to apparent changes in climate. Safeguards must be in place to avoid these false sources of temporal "climate" variability if we are to draw correct inferences about climate behavior over time from archived measurements.

For climate monitoring, consistency through time is vital, counting at least as important as absolute accuracy. Sensors record only what is occurring at the sensor—this is all they can detect. It is the responsibility of station or station network managers to ensure that observations are representative of the spatial and temporal climate scales that we wish to record.

1.4.2. Metadata

Changes in instruments, site characteristics, and observing methodologies can lead to apparent changes in climate through time. It is therefore vital to document all factors that can bear on the interpretation of climate measurements and to update the information repeatedly through time. This information ("metadata," data about data) has its own history and set of quality-control issues that parallel those of the actual data. There is no single standard for the content of climate metadata, but a simple rule suffices:

- Observers should record all information that could be needed in the future to interpret observations correctly without benefit of the observers' personal recollections.

Such documentation includes notes, drawings, site forms, and photos, which can be of inestimable value if taken in the correct manner. That stated, it is not always clear to the metadata provider *what is important* for posterity and *what will be important* in the future. It is almost impossible to "over document" a station. Station documentation is greatly underappreciated and is seldom thorough enough (especially for climate purposes). Insufficient attention to this issue often lowers the present and especially future value of otherwise useful data.

The convention followed throughout climatology is to refer to metadata as information about the measurement process, station circumstances, and data. The term "data" is reserved solely for the actual weather and climate records obtained from sensors.

1.4.3. Maintenance

Inattention to maintenance is the greatest source of failure in weather/climate stations and networks. Problems begin to occur soon after sites are deployed. A regular visit schedule must be implemented, where sites, settings (e.g., vegetation), sensors, communications, and data flow are checked routinely (once or twice a year at a minimum) and updated as necessary. Parts must be changed out for periodic recalibration or replacement. With adequate maintenance, the entire instrument suite should be replaced or completely refurbished about once every five to seven years.

Simple preventative maintenance is effective but requires much planning and skilled technical staff. Changes in technology and products require retraining and continual re-education. Travel, logistics, scheduling, and seasonal access restrictions can consume major amounts of time and budget but are absolutely necessary. Without such attention, data gradually become less credible and then often are misused or not used at all.

1.4.4. Automated versus Manual Stations

Historic stations often have depended on manual observations and many continue to operate in this mode. Manual observations frequently produce excellent data sets. Sensors and data are simple and intuitive, well tested, and relatively cheap. Manual stations have much to offer in certain circumstances and can be a source of both primary and backup data. However, methodical consistency for manual measurements is a constant challenge, especially with a mobile work force. Operating manual stations takes time and needs to be done on a regular schedule, though sometimes the routine is welcome.

Nearly all newer stations are automated. Automated stations provide better time resolution, increased (though imperfect) reliability, greater capacity for data storage, and improved accessibility to large amounts of data. The purchase cost for automated stations is higher than for manual stations. A common expectation and serious misconception is that an automated station can be deployed and left to operate on its own. In reality, automation does not eliminate the need for people but rather changes the type of person that is needed. Skilled technical personnel are needed and must be readily available, especially if live communications exist and data gaps are not wanted. Site visits are needed at least annually and spare parts must be maintained. Typical annual costs for sensors and maintenance are $1500–2500 per station per year.

1.4.5. Communications

With manual stations, the observer is responsible for recording and transmitting station data. Data from automated stations, however, can be transmitted quickly for access by research and operations personnel, which is a highly preferable situation. A comparison of communication systems for automated and manual stations shows that automated stations generally require additional equipment, more power, higher transmission costs, attention to sources of disruption or garbling, and backup procedures (e.g. manual downloads from data loggers).

Automated stations are capable of functioning normally without communication and retaining many months of data. At such sites, however, alerts about station problems are not possible, large gaps can accrue when accessible stations quit, and the constituencies needed to support such stations are smaller and less vocal. Two-way communications permit full recovery from disruptions, ability to reprogram data loggers remotely, and better opportunities for diagnostics and troubleshooting. In virtually all cases, two-way communications are much preferred to all other communication methods. However, two-way communications require considerations of cost, signal access, transmission rates, interference, and methods for keeping sensor and communication power loops separate. Two-way communications are frequently impossible (no service) or impractical, expensive, or power consumptive. Two-way methods (cellular, land line, radio, Internet) require smaller up-front costs as compared to other methods of communication and have variable recurrent costs, starting at zero. Satellite links work everywhere (except when blocked by trees or cliffs) and are quite reliable but are one-way and relatively slow, allow no re-transmissions, and require high up-front costs ($3–4K) but no recurrent costs. Communications technology is changing constantly and requires vigilant attention by maintenance personnel.

1.4.6. Quality Assurance and Quality Control

Quality control and quality assurance are issues at every step through the entire sequence of sensing, communication, storage, retrieval, and display of environmental data. Quality assurance is an umbrella concept that covers all data collection and processing (start-to-finish) and ensures that credible information is available to the end user. Quality control has a more limited scope and is defined by the International Standards Organization as "the operational techniques and activities that are used to satisfy quality requirements." The central problem can be better appreciated if we approach quality control in the following way.

- Quality control is the evaluation, assessment, and rehabilitation of imperfect data by utilizing other imperfect data.

The quality of the data only decreases with time once the observation is made. The best and most effective quality control, therefore, consists in making high-quality measurements from the start and then successfully transmitting the measurements to an ingest process and storage site. Once the data are received from a monitoring station, a series of checks with increasing complexity can be applied, ranging from single-element checks (self-consistency) to multiple-element checks (inter-sensor consistency) to multiple-station/single-element checks (inter-station consistency). Suitable ancillary data (battery voltages, data ranges for all measurements, etc.) can prove extremely useful in diagnosing problems.

There is rarely a single technique in quality control procedures that will work satisfactorily for all situations. Quality-control procedures must be tailored to individual station circumstances, data access and storage methods, and climate regimes.

The fundamental issue in quality control centers on the tradeoff between falsely rejecting good data (Type I error) and falsely accepting bad data (Type II error). We cannot reduce the incidence of one type of error without increasing the incidence of the other type. In weather and climate data assessments, Type I errors are deemed far less desirable than Type II errors.

Not all observations are equal in importance. Quality-control procedures are likely to have the greatest difficulty evaluating the most extreme observations, where independent information usually must be sought and incorporated. Quality-control procedures involving more than one station usually involve a great deal of infrastructure with its own (imperfect) error-detection methods, which must be in place before a single value can be evaluated.

1.4.7. Standards

Although there is near-universal recognition of the value in systematic weather and climate measurements, these measurements will have little value unless they conform to accepted standards. There is not a single source for standards for collecting weather and climate data nor a single standard that meets all needs. Measurement standards have been developed by the American Association of State Climatologists (AASC 1985), U.S. Environmental Protection Agency (EPA 1987), World Meteorological Organization (WMO 1983; 2005), Finklin and Fischer (1990), National Wildfire Coordinating Group (2004), and the RAWS program (Bureau of Land Management [BLM] 1997). Variations to these measurement standards also have been offered by instrument makers (e.g., Tanner 1990).

1.4.8. Who Makes the Measurements?

The lands under NPS stewardship provide many excellent locations to host the monitoring of climate by the NPS or other collaborators. These lands are largely protected from human development and other land changes that can impact observed climate records. Most park units historically have observed weather/climate elements as part of their overall mission. Many of these measurements come from station networks managed by other agencies, with observations taken or overseen by NPS personnel, in some cases, or by collaborators from the other agencies. National Park Service units that are small, lack sufficient resources, or lack sites presenting adequate exposure may benefit by utilizing weather/climate measurements collected from nearly stations.

2.0. Climate Background

Ecosystem processes in arid environments such as those in the NCPN are strongly governed by climate characteristics (Comstock and Ehleringer 1992; Miller and Thomas 2004; Garman et al. 2004). It is therefore essential to understand the climate characteristics of the NCPN. These characteristics are discussed in this chapter.

2.1. Climate and the NCPN Environment

Interannual climate variations, along with historical fire patterns, have influenced disturbance rates and patterns in the NCPN and thus play a major role in the development of vegetation communities in this area (Van Devender and Spaulding 1979; Evenden et al. 2002; Garman et al. 2004; O'Dell et al. 2005). Fuel moisture and temperature in conjunction with lightning events drive the occurrence and effects of wildfire in the pinyon pine systems (Swetnam and Baisan 1994). The NCPN has a significant number of endemic plant species, partly due to its unique past and present climate characteristics (Welsh 1978). These biotic communities are adversely affected by the spread of invasive species such as cheatgrass (*Bromus tectorum;* Mack 1981; Billings 1990) and saltcedar (*Tamarix;* Shafroth et al. 2005). Populations of both native and invasive plant and animal species in the NCPN are very sensitive to both short- and long-term climate variations. Drought conditions can increase insect and pathogen infestation rates (Swetnam and Baisan 1994; Floyd et al. 2000), and increase the susceptibility of sites to exotic-plant invasion. Extreme drought conditions in recent years have had adverse impacts on the NCPN region's vegetation characteristics and hydrology.

Local precipitation and temperature patterns determine soil-water availability, which greatly influences ecosystem responses in the xeric NCPN (Miller and Thomas 2004). Intensity, duration, and timing of precipitation all determine soil-water recharge rates. These in turn determine primary production and attendant secondary production, and hydrological properties of riparian and spring-seep systems. High-intensity, short-duration summer precipitation contributes little to soil-water storage in much of the NCPN due to high evapotranspiration rates that occur during the summer (Garman et al. 2004; O'Dell et al. 2005). Increases in precipitation intensity and duration, however, can lead to pulses in soil-water availability, and immediate or delayed vegetative responses. Researchers working in other dryland systems have found 1-3 yr lags in the response of above-ground net primary production to precipitation (Lauenroth and Sala 1992; Oesterheld et al. 2001; Wiegand et al. 2004). Similar precipitation-production lags have been hypothesized for the dryland systems of the NCPN (Miller and Thomas 2004). Systems at higher elevations have cooler summer temperatures and are less sensitive to precipitation intensity and duration. The Colorado Plateau is a cool desert. Winter precipitation typically occurs in the form of snow, even at the lower elevations. Gradual snowmelt from winter precipitation provides deeper infiltration into the soil (West 1988), and largely contributes to available soil water in the NCPN.

Monsoonal storms are an important source of summer precipitation in the southeastern region of the NCPN. The northwest boundary of the summer monsoon generally lies in the NCPN (Mitchell 1976; Peterson 1994). About two-thirds of the Colorado Plateau is southeast of this boundary and is characterized by winter and summer precipitation maxima; winter precipitation dominates the northwestern portion of the Plateau (Evenden et al. 2002). Park units located near the monsoonal boundary exhibit high interannual variability in precipitation due to interannual variations in the strength of the monsoonal flow. Effects from changes in global circulation patterns may be seen sooner in the NCPN compared to other regions, as these climate changes may manifest themselves through summer precipitation pattern changes such as displacements of the monsoonal boundary from its average position (Ehleringer et al. 2000; Williams and Ehleringer 2000).

Climate variability and change will likely have significant impacts on the landscape of the NCPN. Responses of ecosystems to global warming have been postulated, and likely will vary among ecosystems (Shaver et al. 2000). Warming trends may increase primary production in ecosystems with low annual temperatures, such as the montane and alpine regions of NCPN. Conversely, production may decrease in mesic and xeric environments, such as the lower elevations of NCPN, where temperatures already correspond to peak production. Interactions among processes also may constrain realized change in system structure. In dryland systems, increased evapotranspiration may effectively offset temperature-driven increases in plant production (Saleska et al. 1999).

Understanding the role of climate as a forcing agent for other vital signs is therefore critical to NCPN monitoring. Observed changes in vital signs may be in response to multiple factors, such as anthropogenic stressors or variation in climatic conditions. Untangling the effects of intrinsic climatic variability and change will provide useful insights into regional trends in environmental change.

2.2. Spatial Variability

The climate characteristics of the NCPN are influenced by the mountain ranges that are in and near the NCPN, along with local topographic factors (West 1988; Garman et al. 2004). Based on interpolated estimates of precipitation, over 65 percent of the NCPN land area averages less than 300 mm of precipitation annually (Evenden et al. 2002; Garman et al 2004). Mean annual precipitation is highest in the Uinta Range and the northern Wasatch Range, where mean annual precipitation totals approach 2000 mm (Figure 2.1). Much lower totals are characteristic of the surrounding basins. The driest conditions occur in Western Utah and the Colorado Plateau, where mean annual precipitation in some locations averages between 100 and 200 mm per year. Mean annual precipitation for NCPN park units ranges from just under 200 mm at Capitol Reef National Park (CARE) to over 950 mm near Timpanogos Cave National Monument (TICA).

The Colorado Plateau is a cool desert. As a result, much of the wintertime precipitation comes in the form of snow, even at lower elevations (Garman et al. 2004). Snowmelt is a primary source of groundwater recharge and available soil water in the NCPN (West 1988). Winter precipitation is driven largely by orographic processes (West 1988). The Sierra Nevada and the Cascades, along with the mountain ranges in the Great Basin, intercept much of the winter moisture that comes into the NCPN primarily from the west. Therefore, much of the NCPN lies in a cumulative winter rainshadow from these mountain ranges during the winter months. This is illustrated by the fact that much of the NCPN, including parks such as CARE, has mean annual precipitation under 300 mm (Evenden et al. 2002; See Figure 2.1). Higher-altitude parks such as

TICA and Bryce Canyon National Park (BRCA) are more exposed to winter moisture and thus tend to have higher mean annual precipitation totals.

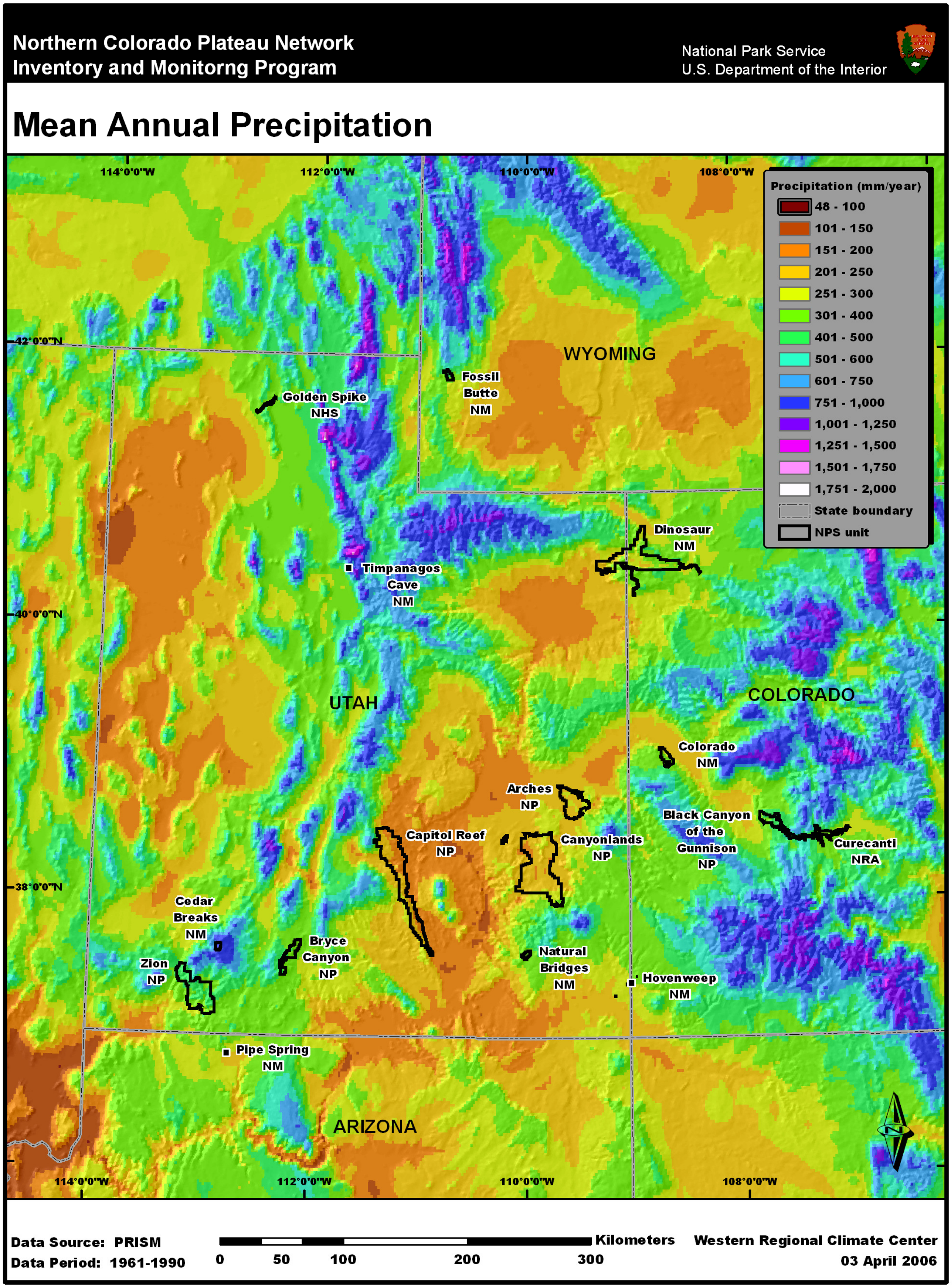


Figure 2.1. Mean annual precipitation, 1961-1990, within the NCPN region.

Precipitation during the summer months (Figure 2.2) is characterized primarily by convective storms, although higher elevations can also receive stratiform precipitation. In particular, storms associated with the southwestern monsoon are an important source of summer precipitation in southeastern portions of NCPN (Higgins et al. 1998; Garman et al. 2004). The northern boundary of the monsoon generally runs through southeastern Utah and west-central Colorado (Mitchell 1976; Peterson 1994). The portions of southeastern NCPN that are strongly influenced by the southwestern monsoon have a primary summer peak in precipitation. This pattern can be clearly seen, for example, at Canyonlands National Park (CANY) and Natural Bridges National Monument (NABR; Figure 2.3). Meanwhile, the northern portions of the NCPN, in places such as TICA (Figure 2.4), tend to only exhibit the wintertime peak in precipitation (Evenden et al. 2002).

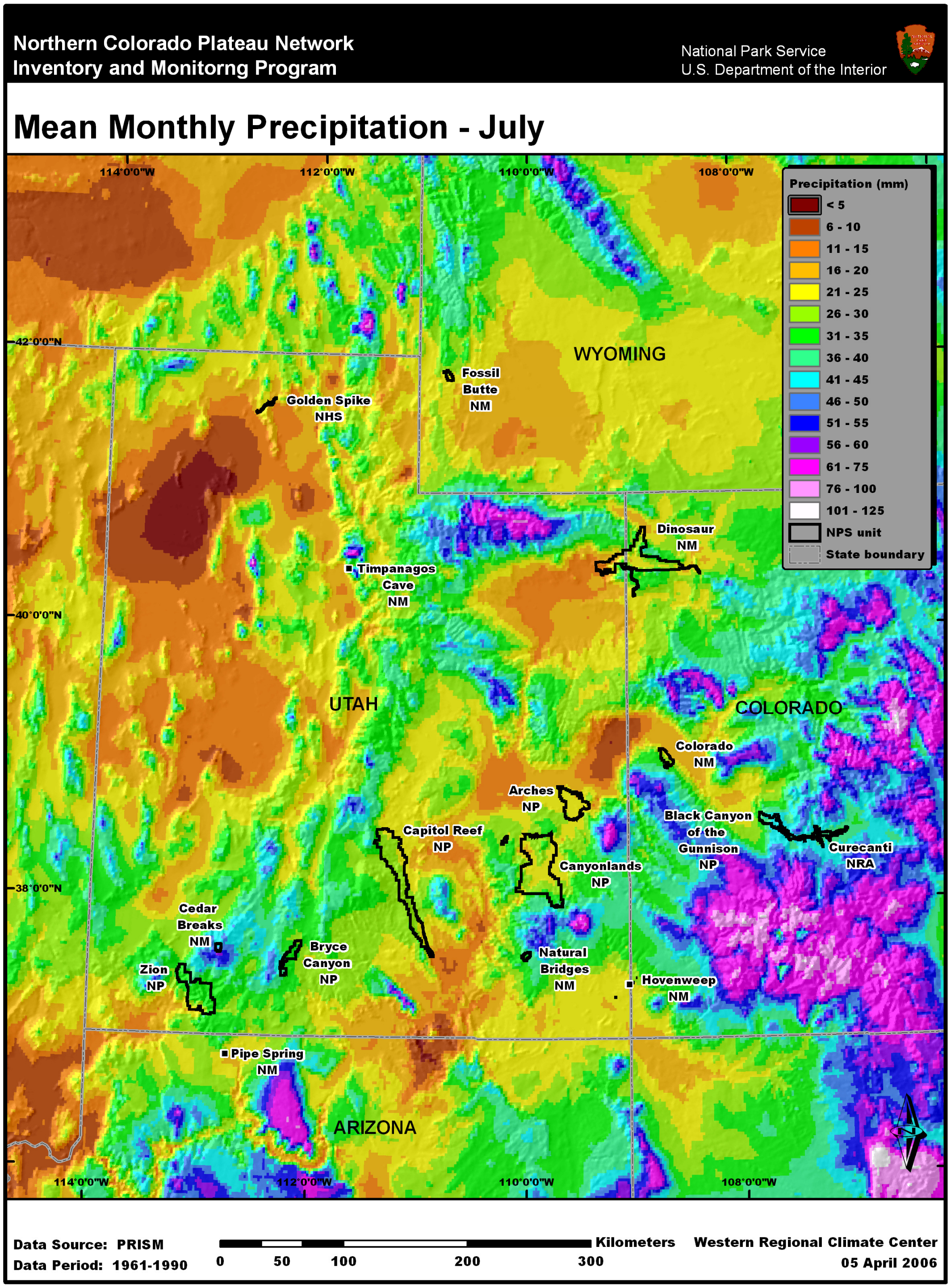
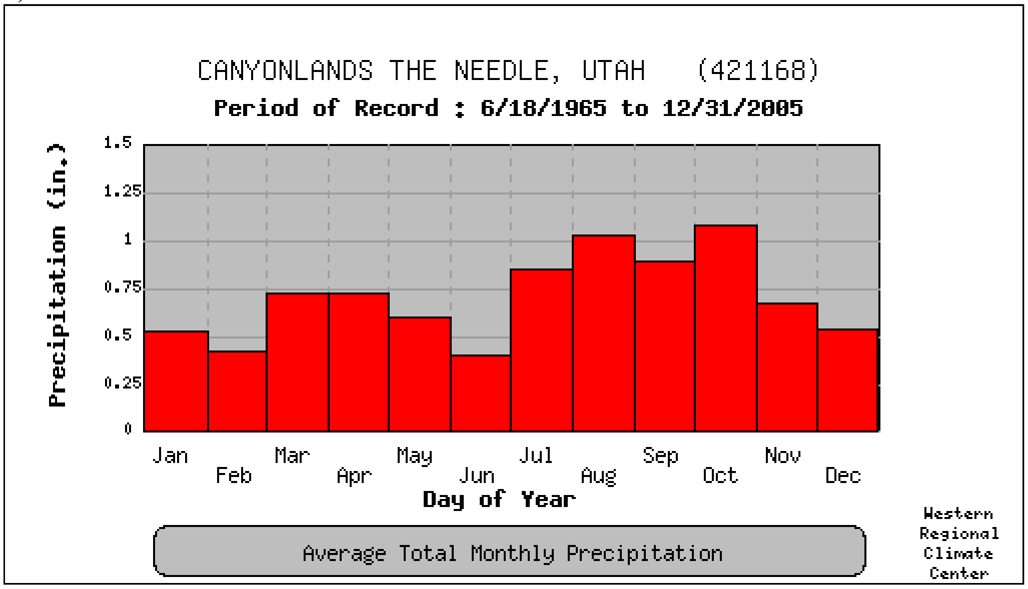


Figure 2.2. Mean July precipitation, 1961-1990, within the NCPN region.

a)



b)

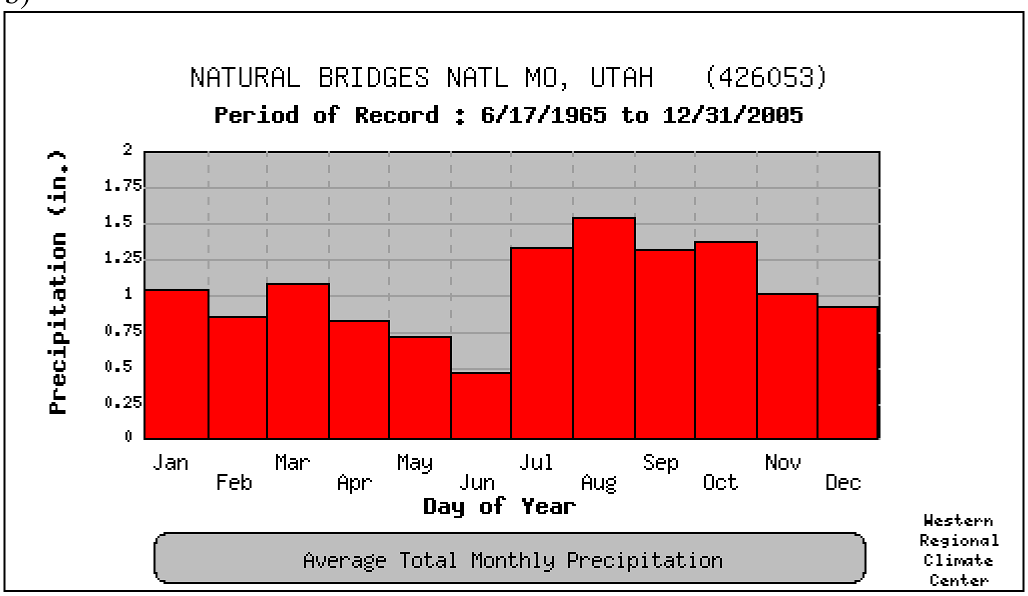


Figure 2.3. Mean monthly precipitation at CANY and NABR.

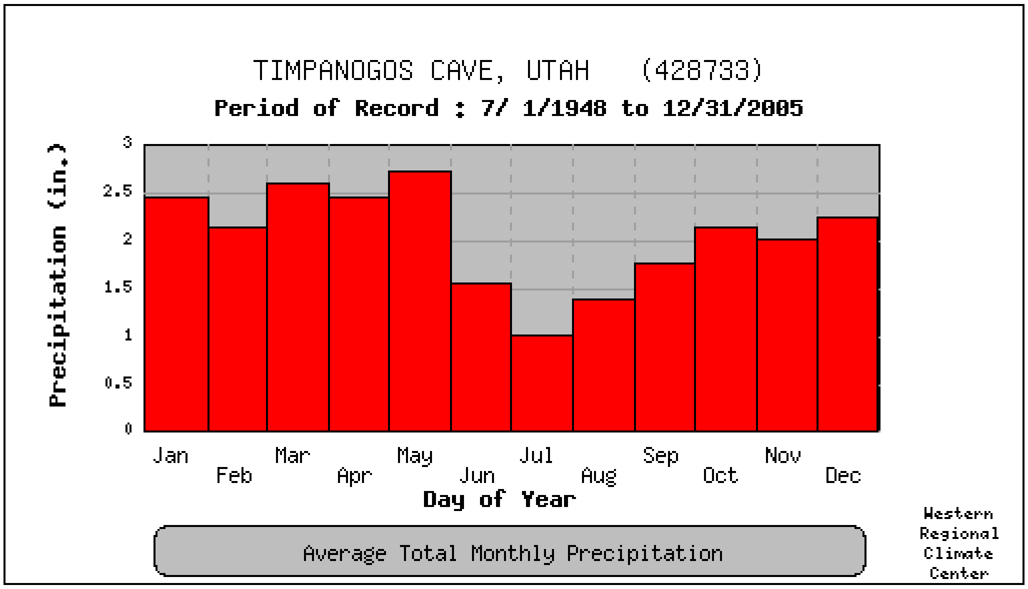


Figure 2.4. Mean monthly precipitation at TICA.

Mean annual temperatures in the NCPN are strongly influenced by topography (Figure 2.5). The coolest locations are in the Rocky Mountains, which occupy the very northern and eastern portions of the NCPN. These regions have mean annual temperatures that are generally under 0°C. Compared to other mountains in the NCPN, the Rocky Mountains are more influenced by wintertime continental air masses originating in Canada and they also have more frequent convective events during the summer months. January minimum temperatures are consistently below -20°C in these areas (Figure 2.6). Some of the mountain valleys, such as Curecanti National Recreation Area (CURE), have wintertime temperatures that in rare instances have dipped as low as -40°C. Temperatures generally increase to the south and west. The warmest portions of the NCPN are found in the Colorado River Canyon in southeastern Utah, and near Zion National Park (ZION) in southwestern Utah. In these regions, mean annual temperatures are just over 15°C (Figure 2.5). Summertime daily maximum temperatures in the southern portions of the NCPN regularly top 35°C (Figure 2.7) and can reach over 45°C.

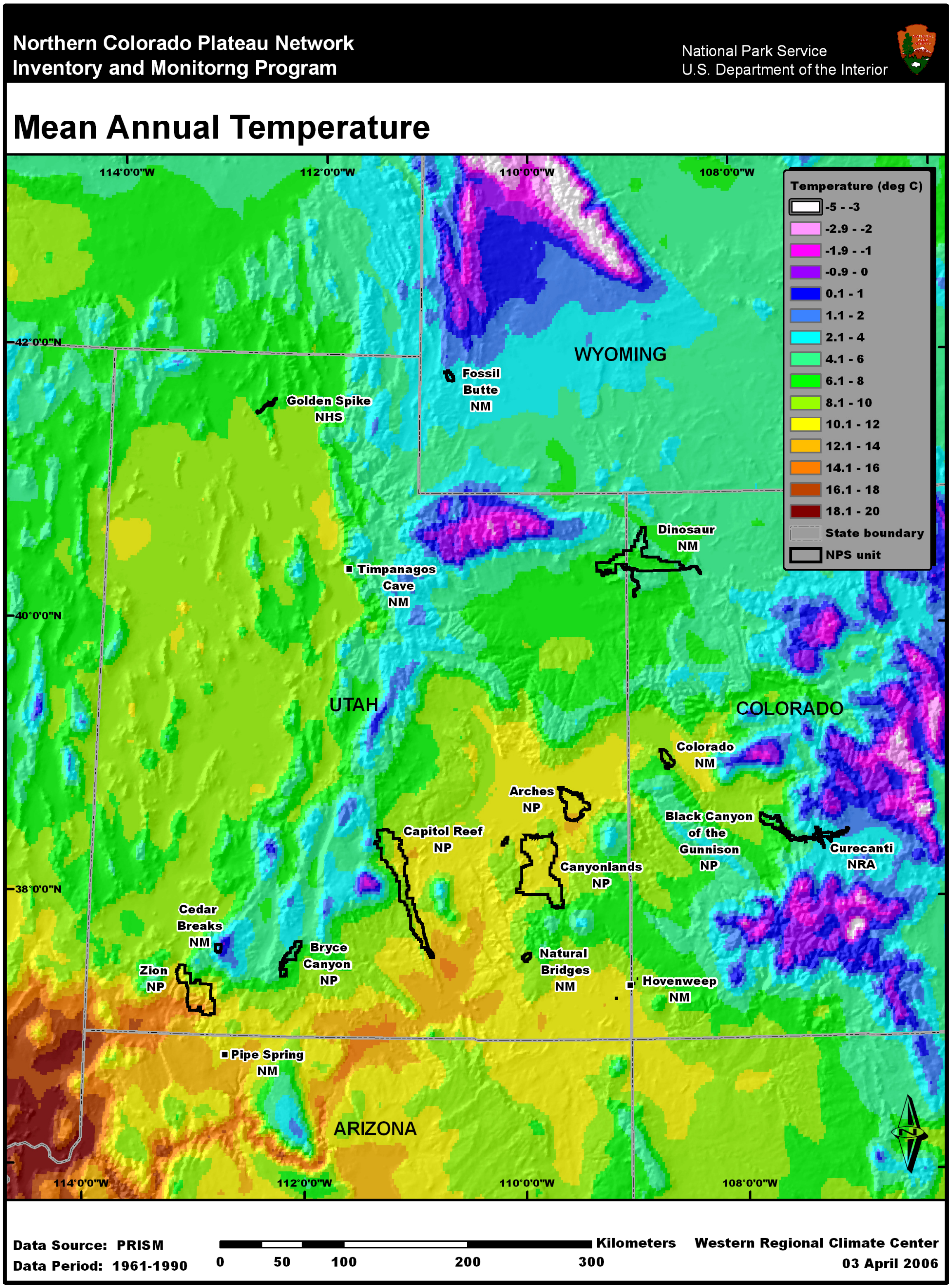


Figure 2.5. Mean annual temperature, 1961-1990, within the NCPN region.

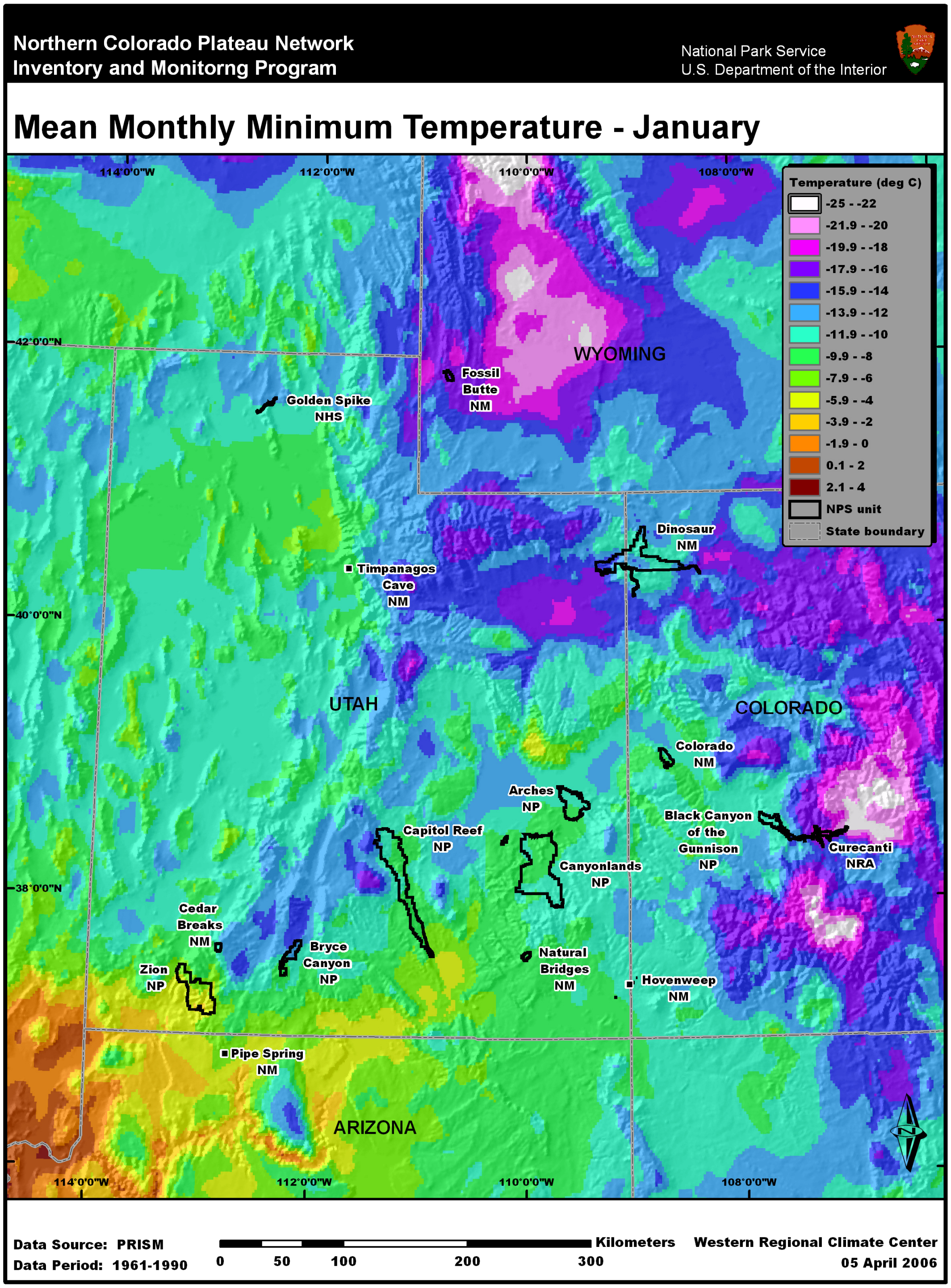


Figure 2.6. Mean January minimum temperature, 1961-1990, within the NCPN region.

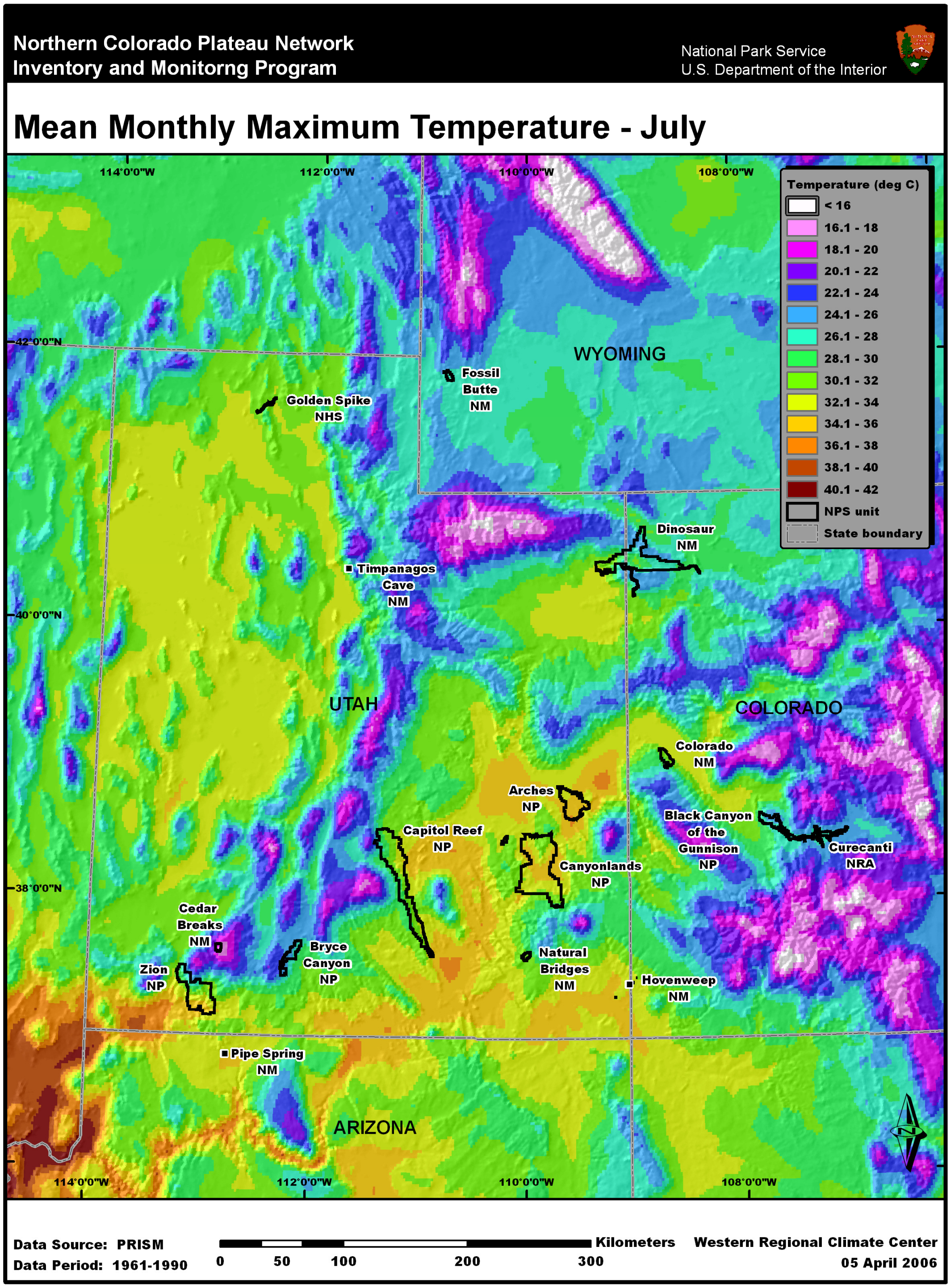


Figure 2.7. Mean July maximum temperature, 1961-1990, within the NCPN region.

2.3. Temporal Variability

Climate constantly fluctuates, on a variety of temporal scales. Paleoclimatic records (Van Devender and Spaulding 1979; Spaulding and Graumlich 1986) and current instrumental climate records have demonstrated the NCPN's climate variability at multiple time scales (Cayan et al. 1998). Links have been found between Pacific Basin climate indices, such as the El Niño Southern Oscillation and the Pacific Decadal Oscillation (Mantua et al. 1997; Mantua 2000), and precipitation patterns in the western United States (Mock 1996; Cayan et al. 1998). These variations have also been tied to fire activity in the region (Swetnam and Baisan 1994; Floyd et al. 2000). Relative wetness has been linked to El Niño events, especially in the southern portions of the Colorado Plateau (e.g. Redmond and Koch 1991; Cayan et al. 1998). An example of this was during the winter of 1982-1983. During this El Niño event, portions of the Colorado Plateau received over twice their normal winter precipitation.

Variations in annual mean temperature from the NCPN show that the most prominent feature is a steady rise in temperature starting in the 1970s. This signal is less pronounced in western Colorado (Figure 2.8) yet is especially pronounced in southeast Utah and the northern Wasatch Range (Figure 2.9a and 2.9b, respectively), where observed temperatures have warmed by as much as 1.7°C (3°F) since the 1970s.

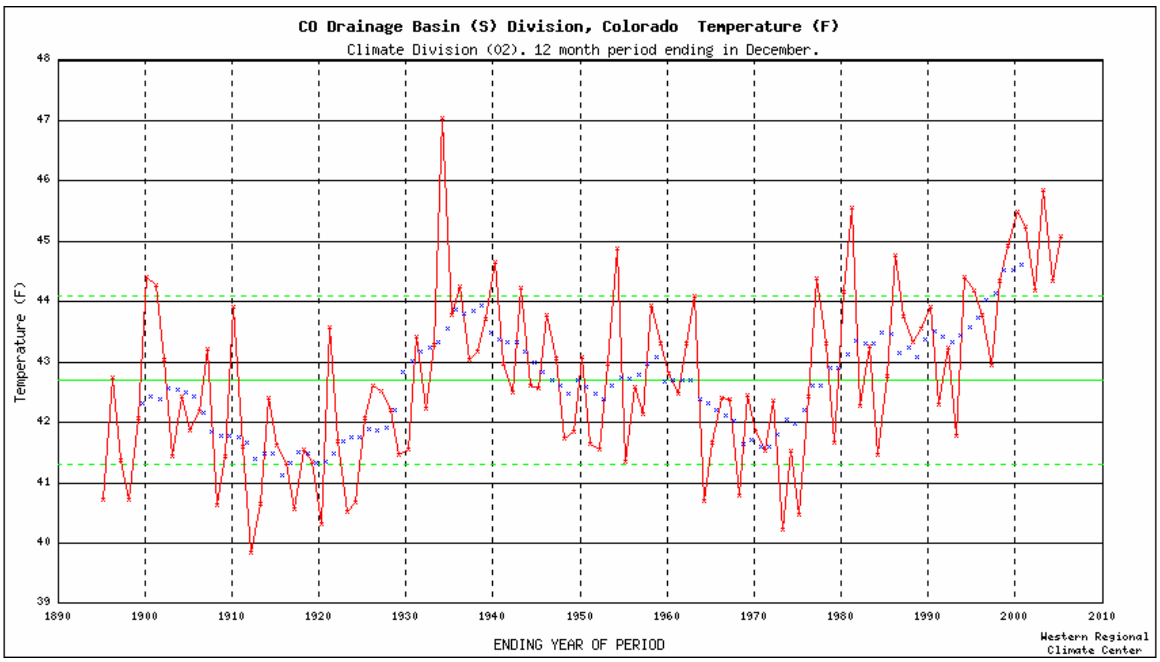
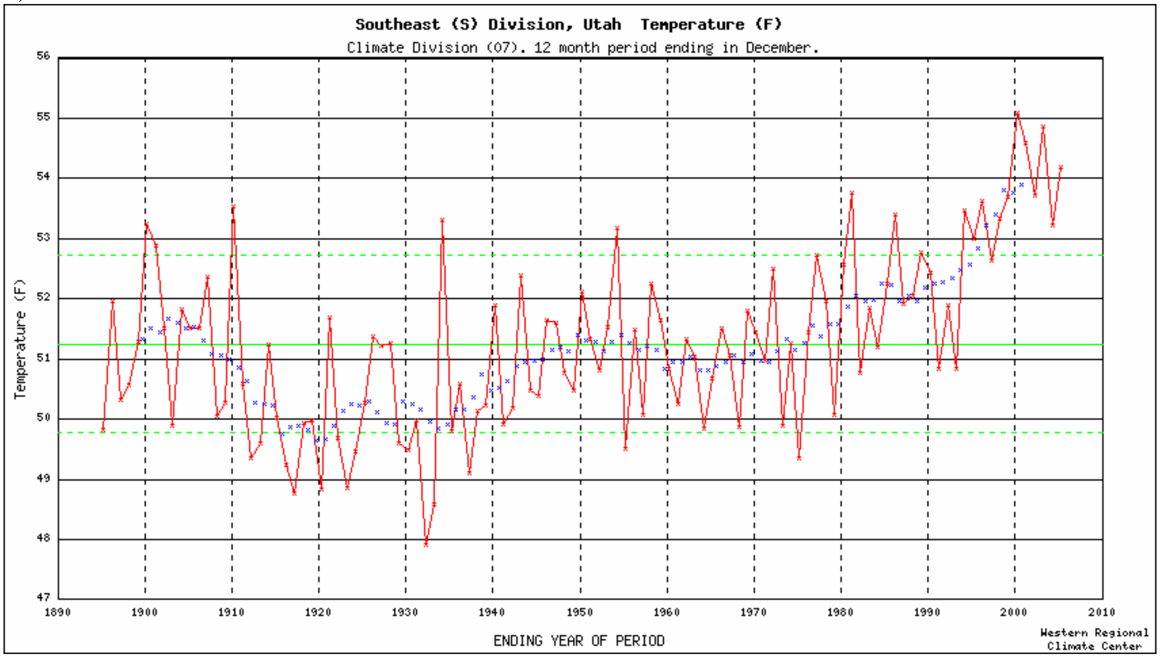


Figure 2.8. Colorado Drainage Basin (S) Division 12-month average temperature ending in December (red), 10-year running mean (blue), mean (green), and plus/minus one standard deviation (green dotted line), 1895-2005.

a)



b)

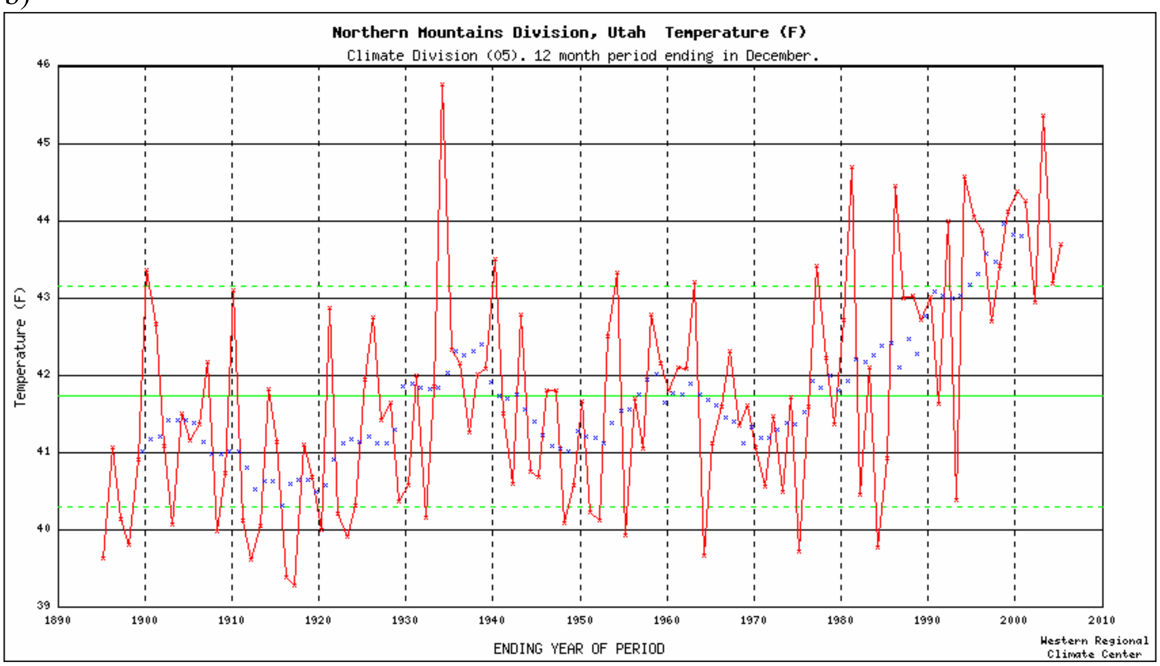
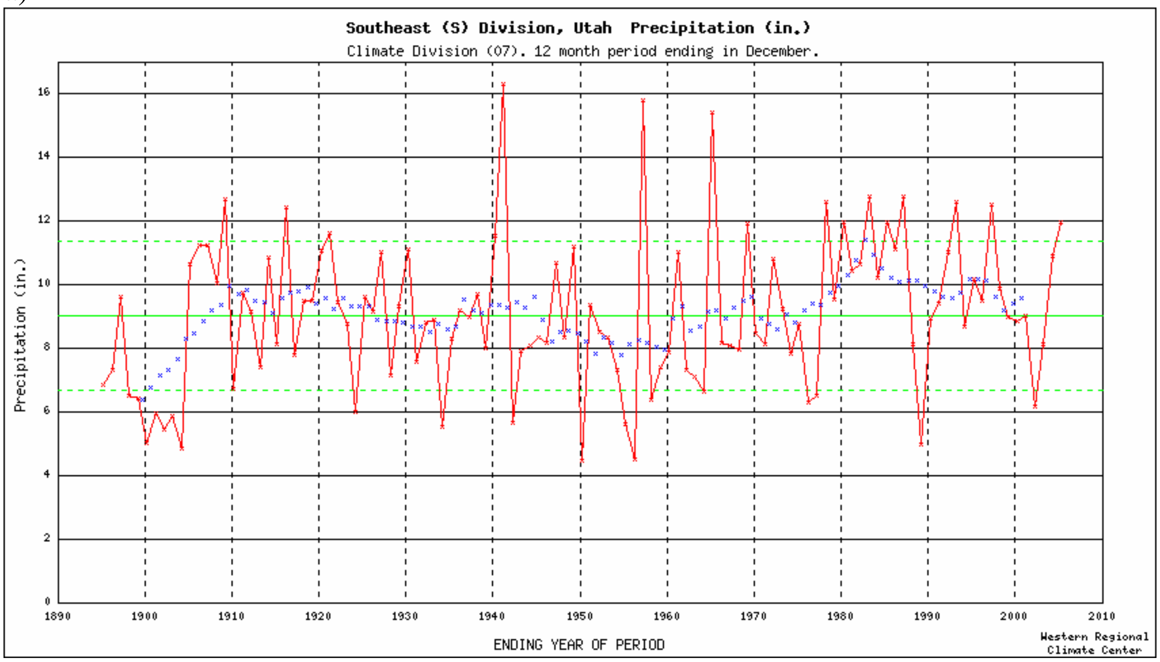


Figure 2.9. Twelve-month average temperature ending in December (red), 10-year running mean (blue), mean (green), and plus/minus one standard deviation (green dotted line), 1895-2005, for southeastern Utah (a) and for the northern Wasatch Range (b).

Variations in mean annual precipitation for the NCPN (Figure 2.10) generally show that there is no systematic trend, but wet and dry spells are readily apparent. General dry conditions are readily apparent in the 1930s and the 1950s. Generally wetter conditions had prevailed in the latter part of the twentieth century in most locations across the NCPN, up until the severe droughts of 1999-2004 and 2005-2006. Some of these decadal variations may be associated with variations in the Pacific Decadal Oscillation. Wetter conditions are apparent in 1982-1983 and

1997-1998 and are partly due to the wetter winters that were associated with El Niño events during these years. In contrast, the recent multi-year drought of 1999-2004 was at least partly associated with dry winters due to an extended period of weak to moderate La Niña conditions that occurred during this time.

a)



b)

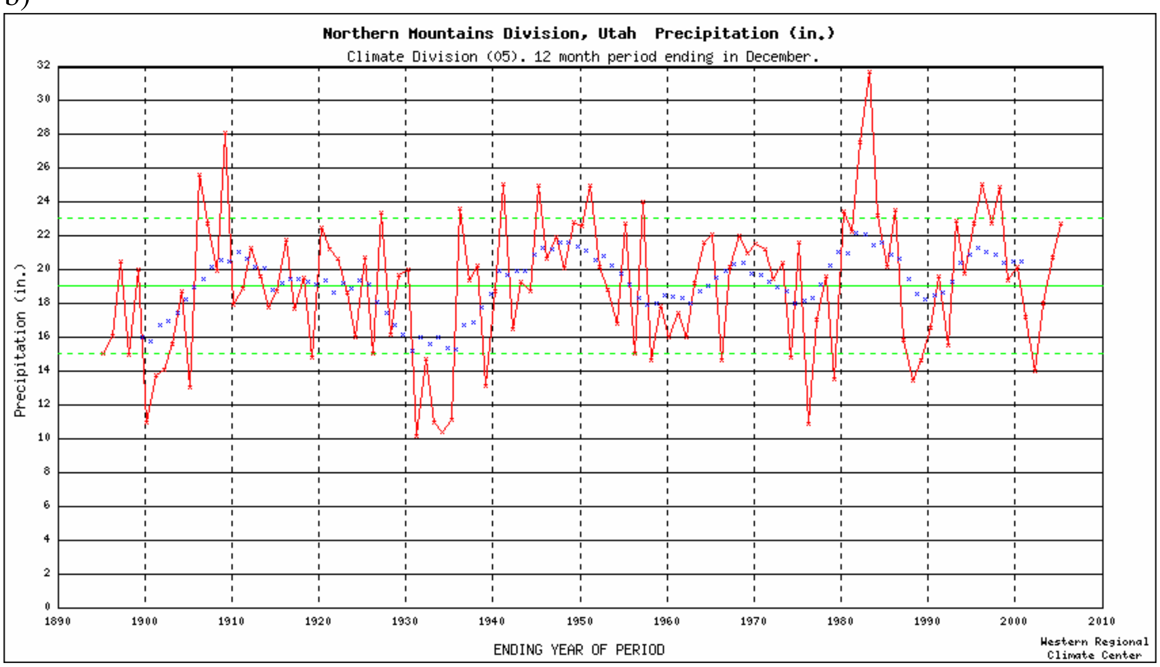


Figure 2.10. Twelve-month average precipitation ending in December (red), 10-year running mean (blue), mean (green), and plus/minus one standard deviation (green dotted line), 1895-2005, for southeastern Utah (a) and for the northern Wasatch Range (b).

2.4. Parameter Regression on Independent Slopes Model (PRISM)

The climate maps presented here were generated using the Parameter Regression on Independent Slopes Model (PRISM). This model was developed to address the extreme spatial and elevation gradients exhibited by the climate of the western United States (Daly et al. 1994; 2002; Gibson et al. 2002; Doggett et al. 2004). The maps produced through PRISM have undergone rigorous evaluation in the western U.S.. Originally, this model was developed to provide climate information at scales matching available land-cover maps to assist in ecologic modeling. The PRISM technique accounts for the scale-dependent effects of topography on mean values of climate elements. Elevation provides the first-order constraint for the mapped climate fields, with slope and orientation (aspect) providing second-order constraints. The model has been enhanced gradually to address inversions, coast/land gradients, and climate patterns in small-scale trapping basins. Monthly climate fields are generated by PRISM to account for seasonal variations in elevation gradients in climate elements. These monthly climate fields then can be combined into seasonal and annual climate fields. Since PRISM maps are grid maps, they do not replicate point values but rather, for a given grid cell, represent the grid-cell average of the climate variable in question at the average elevation for that cell. The model relies on observed surface and upper-air measurements to estimate spatial climate fields.

3.0. Methods

Having discussed the climatic characteristics of NCPN, we now present the procedures that were used to obtain information for weather/climate stations within NCPN. This information was obtained from various sources, as mentioned in the following paragraphs. Retrieval of station metadata constituted a major component of this work.

3.1. Metadata Retrieval

A key component of station inventories is determining the kinds of observations that have been conducted over time, by whom, and in what manner; when each type of observation began and ended; and whether these observations are still being conducted. Metadata about the observational process (Table 3.1) generally consist of a series of vignettes that apply to time intervals and, therefore, constitute a *history* rather than a single snapshot. An expanded list of relevant metadata fields for this inventory is provided in Appendix D. This report has relied on metadata records from three sources: (a) Western Regional Climate Center (WRCC), (b) NPS personnel, and (c) other knowledgeable personnel, such as state climate office staff.

Table 3.1. Primary metadata fields with explanations, as appropriate, for the inventory of weather/ climate stations within NCPN.

Metadata Field	Notes
Station name	Station name associated with network listed in "Climate Network."
Latitude	Numerical value (units: see coordinate units).
Longitude	Numerical value (units: see coordinate units).
Coordinate units	Latitude/longitude (units: decimal degrees, degree-minute-second, etc.).
Datum	Datum used as basis for coordinates: WGS 84, NAD 83, etc.
Elevation	Elevation of station above mean sea level (m).
Slope	Slope of ground surface below station (degrees).
Aspect	Azimuth that ground surface below station faces.
Climate division	NOAA climate division where station is located. Climate divisions are NOAA-specified zones sharing similar climate and hydrology characteristics.
Country	Country where station is located.
State	State where station is located.
County	County where station is located.
Weather/climate network	Primary weather/climate network the station belongs to (RAWS, Clean Air Status and Trends Network [CASTNet], etc.).
NPS unit code	Four-letter code identifying park unit where station resides.
NPS unit name	Full name of park unit.
NPS unit type	National park, national monument, etc.
UTM zone	If UTM is the only coordinate system available.
Location notes	Useful information not already included in "station narrative."
Climate variables	Temperature, precipitation, etc.
Installation date	Date of station installation.
Removal date	Date of station removal.

Metadata Field	Notes
Station photograph	Digital image of station.
Photograph date	Date photograph was taken.
Photographer	Name of person who took the photograph.
Station narrative	Anything related to general site description; may include site exposure, characteristics of surrounding vegetation, driving directions, etc.
Contact name	Name of the person involved with station operation.
Organization	Group or agency affiliation of contact person.
Contact type	Designation that identifies contact person as the station owner, observer, maintenance person, data manager, etc.
Position/job title	Official position/job title of contact person.
Address	Address of contact person.
E-mail address	E-mail address of contact person.
Phone	Phone number of contact person (and extension if available).
Contact notes	Other information needed to reach contact person.

The initial metadata sources for this report were stored at WRCC. This regional climate center (RCC) acts as a working repository of many western climate records, including the main networks outlined in this section. Live and periodic ingests from all major national and western weather/climate networks are maintained at WRCC. These networks include the COOP network, the Surface Airways Observation Network (SAO) jointly operated by NOAA and the Federal Aviation Administration (FAA), the NOAA upper-air observation network, NOAA data buoys, the RAWS network, the SNOTEL network, and various smaller networks. The WRCC is expanding its capability to ingest information from other networks as resources permit and usefulness dictates. This center has relied heavily on historic archives (in many cases supplemented with live ingests) to assess the quantity (not necessarily quality) of data available for NPS I&M network applications.

This report has relied primarily on metadata stored in the Applied Climate Information System (ACIS), a joint effort among RCCs and other NOAA entities. Metadata for NCPN weather/climate stations identified from the ACIS database are available in file "NCPN_from_ACIS.tar.gz" (see Appendix G). Historic metadata pertaining to major climate- and weather-observing systems in the United States are stored in ACIS where metadata are linked to the observed data. A distributed system, ACIS is synchronized among the RCCs. Mainstream software is utilized, including Postgress, Python™, and Java™ programming languages; CORBA®-compliant network software; and industry-standard, nonproprietary hardware and software. Metadata and data for all major national climate and weather networks have been entered into the ACIS database. The available metadata from many smaller networks also have been entered but in most cases the data from these smaller networks have not yet been entered. Data sets are in the NetCDF (Network Common Data Form) format, but the design allows for integration with legacy systems, including non-NetCDF files (used at WRCC) and additional metadata (added for this project). The ACIS also supports a suite of products to visualize or summarize data from these data sets. National climate-monitoring maps are updated daily using the ACIS data feed. The developmental phases of ACIS have utilized metadata supplied by the NCDC and NWS with many tens of thousands of entries, screened as well as possible for duplications, mistakes, and omissions.

In addition to obtaining NCPN weather/climate station metadata from ACIS, metadata were also obtained from NPS staff at the NCPN office in Moab, Utah. The metadata provided from the NCPN office are available in the attached file "NCPN.mdb" (Appendix G). Note that there is some overlap between the metadata provided from NCPN and the metadata obtained from ACIS. We have also relied on information supplied at various times in the past by BLM, NPS, NCDC, NWS, and the state climate offices of Colorado, Utah, and Wyoming (Table 3.2).

Table 3.2. Sources of weather and climate metadata for NCPN.

Name	Position	Phone Number	Email Address
Robert Gillies	Utah State Climatologist	(435)797-2664	rgillies@nr.usu.edu
Steve Gray	Wyoming State Climatologist	(307)766-6659	stateclim@wrds.uwyo.edu
Nolan Doesken	Colorado State Climatologist	(970)491-8545	nolan@ccc.atmos.colostate.edu

Two types of information have been used to complete the climate station inventory for NCPN.

- Station inventories: Information about observational procedures, latitude/longitude, elevation, measured elements, measurement frequency, sensor types, exposures, ground cover and vegetation, data-processing details, network, purpose, and managing individual or agency, etc.

- Data inventories: Information about measured data values including completeness, seasonality, data gaps, representation of missing data, flagging systems, how special circumstances in the data record are denoted, etc.

This is not a straightforward process. Extensive searches are typically required to develop historic station and data inventories. Both types of inventories frequently contain information gaps and often rely on tacit and unrealistic assumptions. Sources of information for these inventories frequently are difficult to recover or are undocumented and unreliable. In many cases, the actual weather/climate data available from different sources are not linked directly to metadata records. To the extent that actual data can be acquired (rather than just metadata), it is possible to cross-check these records and perform additional assessments based on the amount and completeness of the data.

Certain types of weather/climate networks that possess any of the following attributes have not been considered for inclusion in the inventory:

- Private networks with proprietary access and/or inability to obtain or provide sufficient metadata.
- Private weather enthusiasts (often with high-quality data) whose metadata are not available and whose data are not readily accessible.
- Unofficial observers supplying data to the NWS (lack of access to current data and historic archives; lack of metadata).
- Networks having no available historic data.
- Networks having poor-quality metadata.
- Networks having poor access to metadata.

- Real-time networks having poor access to real-time data.

Previous inventory efforts at WRCC have shown that for the weather networks identified in the preceding list, in light of the need for quality data to track weather and climate, the resources required and difficulty encountered in obtaining metadata or data are prohibitively large.

3.2. Criteria for Locating Stations

To identify stations for each park unit in NCPN, we first identified the centroid for each park unit. The centroid is defined as the average latitude and longitude of vertices defining the boundary of the park unit. We then calculated the diagonal distance of the park-unit bounding box (a box defined by the maximum and minimum latitude and longitude for the park unit). Next we identified all weather and climate stations, past and present, whose distances from the centroid were less than twice the diagonal distance of the park-unit bounding box. From these stations, we then selected only those that were located in NCPN park units or within 40 km of a NCPN park-unit boundary. We selected a 40-km buffer in an attempt to include the airport sites in the communities surrounding the NCPN park units.

The station locator maps presented in Chapter 4 were designed to show clearly the spatial distributions of all major weather/climate station networks in NCPN. We recognize that other mapping formats may be more suitable for other specific needs.

4.0. Station Inventory

An objective of this report is to show the locations of weather/climate stations for the NCPN region in relation to the boundaries of the NPS park units within NCPN. A station does not have to be within park boundaries to provide useful data and information for a park unit.

4.1. Climate and Weather Networks

Most stations in the NCPN region are associated with at least one of ten major weather/climate networks (Table 4.1). Brief descriptions of each weather/climate network are provided below (see Appendix F for greater detail).

Table 4.1. Weather/climate networks represented within NCPN.

Acronym	Name
Avalanche	USDA/USFS Avalanche Network
CASTNet	Clean Air Status and Trends Network
CEMP	Community Environmental Monitoring Program
COOP	NWS Cooperative Observer Program
CRN	NOAA Climate Reference Network
NRCS-SC	USDA/NRCS snowcourse Network
POMS	Portable Ozone Monitoring System
RAWS	Remote Automated Weather Station Network
SAO	NWS Surface Airways Observation Program
SNOTEL	USDA/NRCS Snowfall Telemetry Network

4.1.1. USDA/USFS Avalanche Network (Avalanche)

The United States Forest Service (USFS) administers a collection of weather stations run by various state- and local-level avalanche centers throughout the western U.S. Data record lengths vary greatly between sites, with sites having anywhere from a few years of data to several decades of data. These stations are typically found at mountain locations such as ski areas or mountain passes. Measured meteorological elements include temperature, precipitation, wind, and humidity.

4.1.2. Clean Air Status and Trends Network (CASTNet)

This network is primarily an air-quality monitoring network managed by the EPA. Standard hourly weather and climate elements are measured and include temperature, wind, humidity, solar radiation, soil temperature, and sometimes moisture. These elements are intended to support interpretation of air-quality parameters that also are measured at CASTNet sites. Data records at CASTNet sites are generally one–two decades in length.

4.1.3. Community Environmental Monitoring Program (CEMP)

The CEMP network has 26 monitoring stations. Most CEMP sites have operated since 1999. These sites are intended primarily to monitor airborne levels of manmade radioactivity from activities at the Nevada Test Site. This program is a joint effort between the Nevada Operations office of the Department of Energy and the Desert Research Institute. Standard meteorological elements are measured including temperature, precipitation, wind, barometric pressure, humidity, and solar radiation.

4.1.4. NWS Cooperative Observer Program (COOP)

The COOP network has been a foundation of the U.S. climate program for decades. Manual measurements are made by volunteers and consist of daily maximum and minimum temperatures, observation-time temperature, daily precipitation, daily snowfall, and snow depth. When blended with NWS measurements, the data set is known as SOD, or "Summary of the Day." The quality of data from COOP sites ranges from excellent to modest.

4.1.5. NOAA Climate Reference Network (CRN)

The CRN is intended as a reference network for the United States that meets the requirements of the Global Climate Observing System. Up to 115 CRN sites are planned for installation, but the actual number of installed sites will depend on available funding. Temperature and precipitation are the primary meteorological elements are measured. Wind, solar radiation, and ground surface temperature are also measured. Data from the CRN are intended for use in operational climate-monitoring activities and to place current climate patterns in historic perspective.

4.1.6. Portable Ozone Monitoring System (POMS)

The POMS network is operated by the NPS Air Resources Division. Sites are intended primarily for short-term (1-5 years) monitoring of near-surface atmospheric ozone levels in remote locations. Measured meteorological elements include temperature, precipitation, wind, relative humidity, and solar radiation.

4.1.7. Remote Automated Weather Station Network (RAWS)

The RAWS network is administered through many land management agencies, particularly the BLM and the Forest Service. Hourly meteorology elements are measured and include temperature, wind, humidity, solar radiation, barometric pressure, fuel temperature, and precipitation (when temperatures are above freezing). The fire community is the primary client for RAWS data. These sites are remote and data typically are transmitted via GOES (Geostationary Operational Environmental Satellite). Some sites operate all winter. Most data records for RAWS sites began during or after the mid-1980s.

4.1.8. NWS/FAA Surface Airways Observation Network (SAO)

These stations are located usually at major airports and military bases. Almost all SAO sites are now automated. The hourly data measured at these sites include temperature, precipitation, humidity, wind, pressure, sky cover, ceiling, visibility, and current weather. Most data records begin during or after the 1940s, and these data are generally of high quality.

4.1.9. USDA/NRCS Snowfall Telemetry (SNOTEL) Network

The USDA/NRCS maintains a network of automated snow-monitoring stations known as SNOTEL. The network was implemented originally to measure daily precipitation and snow water content. Many modern SNOTEL sites now record hourly data, with some sites now recording temperature and snow depth. Most data records began during or after the mid-1970s.

4.1.10. USDA/NRCS snowcourse network (NRCS-SC)

The USDA/NRCS maintains another network of snow-monitoring stations in addition to SNOTEL. These sites are known as snowcourses. These are all manual sites, measuring only snow depth and snow water content one–two times per month during the months of January to June. Data records for these snowcourses often extend back to the 1920s or 1930s, and the data are generally of high quality. Many of these sites have been replaced by SNOTEL sites, but several hundred snowcourses are still in operation.

In addition to the major networks mentioned above, there are various networks that are operated for specific purposes by specific organizations or governmental agencies or scientific research projects. These networks could be present within NCPN but have not been identified in this report. Some of the commonly used networks include the following:

- NOAA upper-air stations
- National Atmospheric Deposition Program (NADP)
- Federal and state departments of transportation
- National Science Foundation Long-Term Ecological Research Network
- U.S. Department of Energy Surface Radiation Budget Network (Surfrad)
- U.S. Geological Survey (USGS) hydrologic stations
- Park-specific-monitoring networks and stations
- Other research or project networks having many possible owners

We are aware of four weather stations associated with the USGS Southwest Climate Impact Meteorological Stations network (CLIM-MET) in and near CANY. Two of these stations are inside CANY. Virginia Park is located in south-central CANY, while Needles is at the Needles Visitor Center. The other two CLIM-MET stations, Corral and Dugout Ranch are just outside the east boundary of CANY. We are also aware of weather and climate stations, near the NCPN park units in Colorado, which are associated with CoAgMet (Colorado Agricultural Meteorological Network). These stations are not included in the following station lists because the accessibility and quality of data for these stations could not be verified at the time of this report. We anticipate that any stations identified from these networks will be added to the final versions of the metadatabase files accompanying this report.

Weather stations associated with the CLIM-MET network are operated under the American Drylands Project. This project investigates the connection between climate properties and geologic processes in the southwestern U.S. Climate data from this project are being input into regional climate models that simulate future climatic conditions for the region.

The CoAgMet network is a weather monitoring network originally started in the early 1990s by the Agricultural Research Service branch of the USDA and the Plant Pathology extension service at Colorado State University. Data are managed by the Colorado Climate Center. Measured elements include temperature, precipitation, wind, relative humidity, solar radiation, and soil temperature.

4.2. Station Lists

Lists of stations have been compiled for the NCPN (Table 4.2). A station does not have to be within the boundaries to provide useful data and information regarding the park unit in question. Some might be physically *within* the administrative or political boundaries, whereas others might be just outside, or even some distance away, but would be *nearby* in behavior and representativeness. What constitutes "useful" and "representative" are questions whose answers vary according to application, type of element, period of record, procedural or methodological observation conventions, and the like.

Table 4.2. Weather/climate stations in or near NCPN park units. Each listing includes station name and weather/climate network associated with station; location, and elevation; start/end dates of station operation; and flag to indicate if station is located inside park boundaries. Missing entries are indicated by "M".

Name	Network	Lat.	Lon.	Elev. (m)	Start	End	In Park?
Arches National Park – ARCH							
Arches NP Hqs	COOP	38.616	-109.619	1259	5/22/1980	Present	YES
Castle Valley	COOP	38.651	-109.399	1440	7/1/1978	Present	NO
Castleton	COOP	38.600	-109.333	1781	11/1/1963	7/26/1978	NO
Cisco	COOP	38.967	-109.317	1321	9/1/1952	9/22/1967	NO
Cisco 11 S	COOP	38.811	-109.293	1256	9/30/1986	Present	NO
Cisco 14 SSE	COOP	38.797	-109.194	1277	2/22/1986	3/14/2001	NO
Dewey	COOP	38.813	-109.300	1256	9/1/1967	6/16/2004	NO
Thompson	COOP	38.967	-109.717	1554	5/1/1911	1/1/1995	NO
Moab Canyonland AP	SAO	38.755	-109.754	1390	10/2/1964	Present	NO
Moab Grand County AP	SAO	38.500	-109.450	1502	6/1/1955	10/12/1964	NO
Black Canyon of the Gunnison National Monument – BLCA							
Black Canyon Gunnison	COOP	38.555	-107.687	2484	10/9/2003	Present	YES
Montrose 11 ENE	COOP	38.544	-107.693	2560	7/25/2004	Present	YES
Montrose 11 ENE	CRN	38.544	-107.693	2561	7/25/2004	Present	YES
Black Canyon Gunnison	POMS	38.580	-107.717	734	6/11/2003	10/11/2005	YES
Black Canyon	RAWS	38.543	-107.687	2609	6/1/1997	Present	YES
Cimarron	COOP	38.444	-107.559	2102	9/1/1951	Present	NO
Montrose 1	COOP	38.483	-107.883	1764	1/1/1905	11/1/1982	NO
Montrose No 2	COOP	38.486	-107.879	1763	10/1/1895	Present	NO

Name	Network	Lat.	Lon.	Elev. (m)	Start	End	In Park?
Olathe	COOP	38.617	-107.983	1635	4/1/1941	7/31/1955	NO
Olathe 4 SSW	COOP	38.550	-108.000	1706	6/1/1983	10/1/1985	NO
Montrose Basic	SAO	38.500	-107.850	1768	6/1/1970	1/1/1993	NO
Montrose Regional AP	SAO	38.505	-107.898	1755	8/1/1947	Present	NO
Bryce Canyon National Park – BRCA							
Bryce Canyon NP	COOP	37.633	-112.183	2425	3/1/1933	12/31/1978	YES
Bryce Canyon NP Hqrs	COOP	37.641	-112.169	2412	6/1/1959	Present	YES
Bryce Canyon	NRCS-SC	37.617	-112.167	2438	1/1/1935	Present	YES
Agua Canyon – Bryce Canyon NP	RAWS	37.522	-112.271	2438	6/1/1990	Present	YES
Bryce Canyon	RAWS	37.642	-112.172	2394	1/1/2003	Present	YES
Agua Canyon	SNOTEL	37.517	-112.267	2713	10/1/1994	Present	YES
Alton	COOP	37.440	-112.482	2146	5/1/1915	Present	NO
Cougar Creek	COOP	37.450	-112.267	2608	9/1/1965	9/30/1976	NO
East Fork Creek	COOP	37.483	-112.300	2489	9/1/1965	8/31/1973	NO
Hatch	COOP	37.648	-112.433	2100	6/1/1915	Present	NO
Hatch Sevier River	COOP	37.651	-112.430	2097	7/1/1978	Present	NO
Henrieville	COOP	37.567	-112.000	1833	3/1/1963	4/18/1979	NO
Kodachrome Basin Par	COOP	37.521	-111.987	1771	4/1/1979	Present	NO
Tropic	COOP	37.626	-112.081	1914	1/1/1893	11/1/1999	NO
Widtsoe 3 NNE	COOP	37.875	-111.973	2298	3/1/1912	Present	NO
Assay – Hatch 10SW	RAWS	37.517	-112.556	2469	6/1/1983	Present	NO
Tom Best Spring	RAWS	37.817	-112.117	2286	6/1/1998	Present	NO
Bryce Canyon AP	SAO	37.706	-112.146	2312	9/1/1945	Present	NO
Long Valley Jct.	SNOTEL	37.490	-112.510	2243	M	M	NO
Canyonlands National Park – CANY							
Island In The Sky	CASTNet	38.459	-109.821	551	7/1/1992	Present	YES
Canyonlands The Neck	COOP	38.460	-109.821	1807	6/1/1965	Present	YES
Canyonlands-The Needle	COOP	38.151	-109.782	1523	6/1/1965	Present	YES
Buckboard Flat	COOP	37.867	-109.450	2745	10/1/1957	12/31/1974	NO
Hanksville 25 SE	COOP	38.094	-110.407	1183	10/11/1985	11/1/2001	NO
Hans Flat RS	COOP	38.255	-110.180	2012	10/2/1980	Present	NO
Hite Marina	COOP	37.867	-110.400	1125	9/1/1958	8/10/1977	NO
Hite Marina Store	COOP	37.883	-110.383	1204	10/1/1987	10/1/1996	NO
Hite Ranger Station	COOP	37.875	-110.388	1219	8/1/1977	Present	NO
La Sal Mountain Uppe	COOP	38.483	-109.267	2867	7/1/1958	12/31/1974	NO
Monticello 2 E	COOP	37.874	-109.308	2078	4/1/1902	Present	NO
Buckboard Flat	NRCS-SC	37.867	-109.450	2743	1/1/1930	Present	NO
Lasal Mountain-Lower	NRCS-SC	38.483	-109.283	2682	1/1/1931	Present	NO
Big Indian Valley - Lasal 6S	RAWS	38.224	-109.278	2121	9/1/1987	Present	NO
Crow Knolls	RAWS	38.930	-109.980	1646	11/1/1983	6/20/1991	NO
Gooseberry - Blanding 22NW	RAWS	37.817	-109.767	2608	5/1/1985	6/30/1985	NO
North Long Point	RAWS	37.855	-109.839	2646	8/1/1997	Present	NO
Camp Jackson	SNOTEL	37.800	-109.480	2621	M	M	NO
Lasal Mountain	SNOTEL	38.490	-109.260	3002	M	M	NO
Capital Reef National Park – CARE							
Capitol Reef NP	COOP	38.292	-111.262	1676	8/1/1938	Present	YES
Aquarius Guard Stn	COOP	38.200	-111.583	2684	10/1/1966	9/30/1975	NO
Bears Ears Lower	COOP	37.583	-109.883	2098	9/1/1960	9/30/1976	NO
Bears Ears Upper	COOP	37.617	-109.867	2471	9/1/1960	9/30/1976	NO
Blacks Flat Um Creek	COOP	38.683	-111.600	2867	7/1/1956	12/31/1974	NO
Bluebell Knoll	COOP	38.167	-111.517	3440	7/1/1974	9/30/1976	NO

Name	Network	Lat.	Lon.	Elev. (m)	Start	End	In Park?
Bobs Hole	COOP	38.217	-111.467	2745	10/1/1966	7/31/1973	NO
Boulder	COOP	37.905	-111.420	2036	6/1/1954	Present	NO
Bullfrog 8 N	COOP	37.630	-110.728	1225	5/1/1998	12/7/2005	NO
Bullfrog Basin Marina	COOP	37.518	-110.726	1171	10/22/1999	Present	NO
Clayton Guard Stn	COOP	37.967	-111.833	3056	9/1/1973	9/30/1975	NO
Elk Ridge Kigalia	COOP	37.650	-109.833	2593	7/1/1961	9/30/1976	NO
Emery 15 SW	COOP	38.767	-111.450	2330	6/1/1979	6/30/1986	NO
Escalante River Mouth	COOP	37.317	-110.900	1220	4/1/1951	10/31/1955	NO
Fish Lake RS	COOP	38.552	-111.723	2707	11/1/1949	Present	NO
Forty Mile Dance Hall	COOP	37.367	-111.083	1327	6/1/1954	9/30/1976	NO
Hanksville 25 SE	COOP	38.094	-110.407	1183	10/11/1985	11/1/2001	NO
Lake Powell Yacht Club	COOP	37.650	-110.700	1219	9/1/1987	1/1/1998	NO
Loa	COOP	38.406	-111.643	2155	1/1/1893	Present	NO
Mount Dutton	COOP	38.017	-112.217	3142	8/1/1968	9/30/1976	NO
Oak Draw Sawmill	COOP	38.067	-111.367	3309	11/1/1966	7/31/1974	NO
Sandy Ranch	COOP	38.100	-111.050	1615	8/1/1963	11/1/1988	NO
Shifting Sands Ranch	COOP	38.067	-111.067	1673	11/17/1988	10/1/1992	NO
Widtsoe Escalante 3	COOP	37.833	-111.883	2940	7/1/1956	12/31/1974	NO
Fish Lake	NRCS-SC	38.500	-111.767	2652	1/1/1931	Present	NO
Johnson Valley	NRCS-SC	38.617	-111.483	2697	1/1/1955	Present	NO
Barney Reservoir - Escalante 15 SE	RAWS	37.613	-111.421	1679	6/1/1991	2/28/1997	NO
Kane Gulch – Blanding 23WSW	RAWS	37.526	-109.894	2012	6/1/1991	Present	NO
Larb Hollow	RAWS	38.134	-111.318	2576	11/1/2003	Present	NO
Bullfrog Basin	SAO	37.530	-110.720	1165	3/1/1967	Present	NO
Bullfrog Marina	SAO	37.500	-110.700	1158	7/14/1970	Present	NO
Hanksville	SAO	38.371	-110.715	1313	1/1/1946	Present	NO
Black Flat U.M. Ck.	SNOTEL	38.690	-111.590	2865	M	M	NO
Donkey Reservoir	SNOTEL	38.210	-111.470	2987	M	M	NO
Widstoe #3	SNOTEL	37.840	-111.890	2896	M	M	NO
Cedar Breaks National Monument – CEBR							
Cedar Breaks NM	COOP	37.617	-112.833	3148	10/1/1958	8/31/1967	YES
Cedar Breaks Storage	COOP	37.617	-112.833	3123	7/1/1948	7/31/1974	YES
Blowhard Mtn Radar	COOP	37.593	-112.864	3260	6/1/1964	Present	NO
Brian Head	COOP	37.693	-112.847	2978	1/12/1991	Present	NO
Webster Flat	COOP	37.583	-112.900	2830	7/1/1956	5/31/1973	NO
Brian Head	NRCS-SC	37.683	-112.850	3048	1/1/1965	Present	NO
Susc Ranch	NRCS-SC	37.600	-112.917	2499	1/1/1966	Present	NO
Webster Flat	SNOTEL	37.590	-112.900	2804	M	M	NO
Colorado National Monument – COLM							
Colorado Natl Monument	COOP	39.101	-108.734	1762	3/1/1940	Present	YES
Fruita	COOP	39.164	-108.734	1373	1/1/1893	Present	NO
Fruita 1 SE	COOP	39.133	-108.733	1369	8/1/1948	7/1/1982	NO
Glade Park Store	COOP	39.000	-108.750	2135	8/1/1966	5/7/1975	NO
Grand Junction	COOP	39.067	-108.567	1409	1/1/1899	12/31/1947	NO
Grand Junction 6 ESE	COOP	39.042	-108.466	1451	3/1/1962	Present	NO
Grand Junction Hwy	COOP	39.054	-108.566	1387	8/1/1948	Present	NO
Little Dolores	COOP	38.933	-108.850	2044	7/1/1955	8/31/1966	NO
Little Dolores 5 NE	COOP	39.050	-108.850	1946	10/1/1961	8/10/1966	NO
Grand Jct. Walker Field	SAO	39.134	-108.540	1481	3/1/1946	Present	NO
Curecanti National Recreation Area – CURE							
Blue Mesa Dam	COOP	38.457	-107.333	2295	6/1/1962	Present	YES
Blue Mesa Lake	COOP	38.467	-107.168	2316	9/1/1967	Present	YES

Name	Network	Lat.	Lon.	Elev. (m)	Start	End	In Park?
Sapinero 8 E	COOP	38.483	-107.183	2355	10/1/1948	12/31/1965	YES
Almont East River	COOP	38.664	-106.848	2441	5/11/1986	Present	NO
Almont Taylor River	COOP	38.664	-106.845	2442	3/6/1986	Present	NO
Bone Mesa	COOP	38.817	-107.633	0	1/1/2001	Present	NO
Cochetopa Creek	COOP	38.446	-106.761	2438	6/1/1909	Present	NO
Cochetopa Creek	COOP	38.433	-106.767	2439	11/1/1955	12/31/1956	NO
Crested Butte	COOP	38.874	-106.976	2698	6/1/1909	Present	NO
Gunnison 1 WSW	COOP	38.542	-106.949	2335	10/16/1986	Present	NO
Gunnison 3 SW	COOP	38.525	-106.968	2329	7/1/1893	Present	NO
Hotchkiss	COOP	38.800	-107.700	1647	1/1/2001	10/31/1962	NO
Lake City	COOP	38.025	-107.315	2643	5/1/1905	Present	NO
Paonia 1 S	COOP	38.867	-107.583	1807	5/29/1930	5/9/1957	NO
Paonia 1 SW	COOP	38.852	-107.624	1701	5/9/1957	Present	NO
Powderhorn	COOP	38.267	-107.100	2467	8/1/1964	5/4/1973	NO
Ridgway	COOP	38.140	-107.759	2195	11/16/1983	Present	NO
Rogers Mesa	COOP	38.800	-107.783	1662	1/1/2001	11/30/1963	NO
Sapinero 9 W	COOP	38.467	-107.467	2837	1/1/1931	12/31/1946	NO
Somerset 1 E	COOP	38.933	-107.450	1915	8/24/1983	3/1/1994	NO
Somerset 2 E	COOP	38.926	-107.434	1852	7/1/1976	Present	NO
Somerset Bridge	COOP	38.933	-107.467	1830	8/1/1948	12/31/1954	NO
Wilcox Ranch	COOP	38.917	-107.517	1799	8/1/1948	8/23/1983	NO
Keystone	NRCS-SC	38.867	-107.033	3036	1/1/1961	Present	NO
Huntsman Mesa	RAWS	38.332	-107.089	2865	5/1/1991	Present	NO
Jay	RAWS	38.842	-107.736	1890	7/1/1984	Present	NO
Los Pinos Creek	RAWS	38.213	-106.758	2926	5/1/1991	6/30/1997	NO
Gunnison A	SAO	38.600	-106.917	2378	10/1/1970	2/14/1991	NO
Gunnison County Arpt	SAO	38.550	-106.917	2337	4/1/1946	Present	NO
Dinosaur National Monument – DINO							
Dinosaur National Mon.	COOP	40.433	-109.300	1549	1/10/1941	4/30/1958	YES
Dinosaur Natl Mon.	COOP	40.244	-108.972	1804	8/1/1948	Present	YES
Dinosaur Quarry Area	COOP	40.438	-109.304	1463	12/1/1915	Present	YES
Round Top Mountain	COOP	40.433	-108.917	2617	6/1/1953	Present	YES
Dinosaur NM	POMS	40.437	-109.305	446	5/1/2005	Present	YES
Dinosaur NM	RAWS	40.509	-108.911	1817	7/1/1998	Present	YES
Harpers Corner	RAWS	40.510	-109.048	1859	7/1/1993	6/30/1997	YES
Allen's Ranch	COOP	40.900	-109.153	1673	8/17/1962	11/1/2001	NO
Black Canyon	COOP	40.717	-109.700	3023	9/1/1967	9/30/1976	NO
Bonanza	COOP	40.017	-109.183	1661	3/16/1938	6/1/1993	NO
Bonanza 3 S	COOP	39.979	-109.178	1506	12/11/1986	Present	NO
Bonanza Pumping Stn	COOP	40.033	-109.117	1739	5/1/1960	6/10/1966	NO
Browns Park Refuge	COOP	40.863	-109.023	1713	5/3/1997	2/1/2002	NO
Browns Park Refuge	COOP	40.801	-108.917	1632	4/1/1966	Present	NO
Browns Park Store	COOP	40.784	-108.854	1695	5/22/2003	Present	NO
Dinosaur 2 E	COOP	40.244	-108.968	1852	7/21/2004	Present	NO
Greystone	COOP	40.617	-108.667	2074	3/1/1937	1/1/1963	NO
Hiawatha	COOP	40.983	-108.617	2166	9/1/1953	11/30/1958	NO
Jarvie Ranch	COOP	40.899	-109.179	1680	1/5/2002	Present	NO
Jensen	COOP	40.364	-109.345	1448	3/16/1925	Present	NO
Jensen 6 NE	COOP	40.426	-109.235	1451	7/24/1986	Present	NO
Kings Cabin Upper	COOP	40.717	-109.550	2663	7/1/1956	12/31/1974	NO
La Point	COOP	40.400	-109.800	1693	5/1/1946	8/26/1971	NO
Maeser 9 NW	COOP	40.560	-109.664	1963	5/1/1983	Present	NO
Massadona 3 E	COOP	40.284	-108.602	1887	10/18/1985	Present	NO
Maybell	COOP	40.516	-108.095	1801	6/1/1958	Present	NO
Maybell 3 ESE	COOP	40.503	-108.029	1806	10/29/1986	Present	NO

Name	Network	Lat.	Lon.	Elev. (m)	Start	End	In Park?
Rangely 1 E	COOP	40.089	-108.772	1612	6/1/1950	Present	NO
Sunbeam 12 W	COOP	40.547	-108.424	1740	4/21/1986	Present	NO
Sunbeam 7 SW	COOP	40.500	-108.267	1787	4/1/1927	12/31/1951	NO
Vernal 3 SE	COOP	40.433	-109.500	1583	4/23/1970	11/30/1973	NO
Vernal 4 NW	COOP	40.483	-109.583	1720	4/24/1970	10/25/1972	NO
Vernal Arpt	COOP	40.440	-109.510	1603	1/1/1948	Present	NO
Vernal RS	COOP	40.450	-109.533	1626	7/1/1953	Present	NO
Vernal Taylor Farm	COOP	40.433	-109.533	1635	5/27/1976	10/1/1979	NO
Vernal USU Res Farm	COOP	40.433	-109.517	1604	5/9/1974	3/1/1976	NO
Dinosaur 2 E	CRN	40.245	-108.968	1848	M	M	NO
Diamond Rim	RAWS	40.617	-109.243	1676	11/1/1983	Present	NO
Dragon Road	RAWS	39.915	-108.888	1920	7/1/1998	Present	NO
Kings Point - Dutch John 16ESE	RAWS	40.861	-109.102	1728	9/1/1985	Present	NO
Ladore	RAWS	40.739	-108.835	1798	6/1/1987	Present	NO
Little Mountain - Vernal 10NW	RAWS	40.540	-109.650	1999	M	M	NO
Miners Draw – Jensen 13W	RAWS	40.376	-109.085	2478	10/1/1987	9/30/1997	NO
Rangely	RAWS	40.170	-108.790	1976	7/1/1984	5/31/1998	NO
Yampa Plateau - Jensen 7SSE	RAWS	40.283	-109.290	2134	2/1/1984	Present	NO
Vernal Airport	SAO	40.427	-109.553	1667	8/1/2003	Present	NO
Vernal Muni AP SPCL	SAO	40.467	-109.533	1612	1/1/1973	3/31/1982	NO
King's Cabin	SNOTEL	40.710	-109.550	2661	M	M	NO
Trout Creek	SNOTEL	40.730	-109.670	2865	M	M	NO
Fossil Butte National Monument – FOBU							
Fossil Butte	COOP	41.833	-110.767	2067	8/1/1990	Present	YES
Frontier 23 NNW (DCP	COOP	42.117	-110.717	2273	12/9/1986	11/2/2005	NO
Kelley RS	COOP	42.250	-110.800	2501	10/1/1963	9/30/1977	NO
Kemmerer	COOP	41.783	-110.533	2120	11/1/1902	6/1/1990	NO
Kemmerer 2 N	COOP	41.817	-110.533	2111	7/21/1986	Present	NO
Kemmerer 3 WNW (DCP)	COOP	41.800	-110.583	2127	11/26/1985	11/2/2005	NO
Kemmerer Hwy Dept	COOP	41.733	-110.683	2111	1/25/1984	Present	NO
Kemmerer Muni Ap	COOP	41.825	-110.559	2220	4/1/1994	Present	NO
Randolph	COOP	41.663	-111.186	1911	5/1/1982	Present	NO
Sage 4 NNW	COOP	41.867	-111.000	1892	1/1/1923	8/31/2001	NO
Willow Springs	COOP	41.871	-110.496	2182	6/13/2001	Present	NO
Chausse	RAWS	42.174	-111.117	1975	8/1/1985	5/31/1997	NO
Potato Creek	RAWS	42.127	-111.042	2170	8/1/1985	10/31/1988	NO
Punp	RAWS	42.259	-110.808	2560	9/1/2002	10/31/2002	NO
Kemmerer Municipal Ap	SAO	41.824	-110.557	2220	4/1/1947	Present	NO
Hams Fork	SNOTEL	42.150	-110.683	2390	10/1/1985	Present	NO
Kelly R.S.	SNOTEL	42.250	-110.800	2493	M	M	NO
Golden Spike National Historic Site – GOSP							
Bear River Bay	COOP	41.300	-112.267	1283	5/1/1969	3/1/1997	NO
Bear River Refuge	COOP	41.467	-112.267	1284	8/4/1937	3/1/1984	NO
Blue Creek	COOP	41.900	-112.500	1479	2/18/1896	6/30/1953	NO
Bothwell	COOP	41.717	-112.250	1321	7/1/1946	3/31/1960	NO
Brigham City	COOP	41.483	-112.033	1324	3/1/1899	6/7/1974	NO
Brigham City Waste P	COOP	41.524	-112.044	1289	6/1/1974	Present	NO
Corinne	COOP	41.548	-112.111	1289	2/2/1896	Present	NO
Cutler Dam UP&L	COOP	41.833	-112.056	1308	1/1/1980	Present	NO
Garland 1 NE	COOP	41.756	-112.152	1323	4/1/1909	3/3/2000	NO

Name	Network	Lat.	Lon.	Elev. (m)	Start	End	In Park?
Midlake	COOP	41.217	-112.633	1287	12/1/1968	10/27/1981	NO
Plymouth	COOP	41.872	-112.149	1362	1/1/1940	Present	NO
Promontory	COOP	41.258	-112.492	1285	10/1/1981	7/22/1997	NO
Saline	COOP	41.217	-112.483	1290	6/1/1966	5/14/1969	NO
Snowville	COOP	41.967	-112.717	1390	1/1/1893	10/1/1991	NO
Thiokol Propulsion F S	COOP	41.720	-112.426	1402	6/1/1962	Present	NO
Tremonton	COOP	41.711	-112.164	1314	1/1/1931	Present	NO
Brigham City Airport	SAO	41.552	-112.062	1288	11/1/1933	Present	NO
Cutler	WBAN	41.833	-112.050	1309	11/1/1934	12/31/1938	NO
Locomotive Springs	WBAN	41.717	-112.917	1290	3/1/1933	9/30/1942	NO
Plymouth	WBAN	41.867	-112.167	1348	12/1/1938	6/30/1944	NO
Tremonton	WBAN	41.733	-112.150	1326	2/1/1946	10/31/1949	NO
Hovenweep National Monument – HOVE							
Hovenweep NM	COOP	37.386	-109.075	1588	12/1/1955	Present	YES
Aneth Plant	COOP	37.256	-109.329	1395	8/1/1959	Present	NO
Atkinson Ranch	COOP	37.600	-108.883	0	8/1/1948	11/30/1949	NO
Cedar Point	COOP	37.716	-109.083	2060	4/1/1946	Present	NO
Cortez	COOP	37.344	-108.593	1875	4/1/1911	Present	NO
Dove Creek	COOP	37.767	-108.912	2086	12/6/2002	Present	NO
Pleasant View 1 W	COOP	37.588	-108.784	2091	11/1/1949	Present	NO
Yellow Jacket 2 W	COOP	37.521	-108.756	2091	5/1/1962	12/5/2002	NO
Yellow Jacket 4 NE	COOP	37.559	-108.664	2158	12/5/2002	Present	NO
Cortez Montezuma Co Ap	SAO	37.303	-108.628	1803	8/1/1949	Present	NO
Natural Bridges National Monument – NABR							
Natural Bridges N M	COOP	37.609	-109.977	1981	6/1/1965	Present	YES
Pipe Spring National Monument – PISP							
Fredonia	COOP	36.963	-112.526	1439	3/1/1906	Present	NO
Kanab	COOP	37.039	-112.519	1506	12/1/1899	Present	NO
Pipe Springs Natl Mon	COOP	36.859	-112.739	1500	6/1/1963	Present	NO
Ryan Station	COOP	36.683	-112.350	1922	3/1/1952	7/31/1955	NO
Gunsight	RAWS	36.704	-112.583	1609	9/1/1994	Present	NO
Timpanogos Cave National Monument – TICA							
Timpanogos Cave	Avalanche	40.441	-111.706	2438	M	M	YES
Timpanogos Cave	COOP	40.445	-111.708	1750	12/1/1946	Present	YES
62nd South Pumping S	COOP	40.633	-111.833	1354	10/1/1963	10/31/1968	NO
Alpine	COOP	40.464	-111.771	1545	1/1/1894	Present	NO
Alta	COOP	40.591	-111.637	2661	3/17/1905	Present	NO
Alta Rustler Peak	COOP	40.583	-111.633	2715	7/1/1950	7/31/1967	NO
Argenta	COOP	40.642	-111.680	2128	1/1/1967	Present	NO
Barney Canyon	COOP	40.600	-112.133	1952	9/1/1963	2/28/1971	NO
Bartholomew Powerhou	COOP	40.167	-111.500	1566	9/1/1956	10/1/1995	NO
Bingham Canyon	COOP	40.533	-112.150	1861	12/1/1940	10/3/1974	NO
Bingham Canyon 2 NE	COOP	40.567	-112.133	1714	10/1/1974	8/31/1985	NO
Conrad Ranch	COOP	40.333	-111.517	1719	2/1/1963	1/1/1990	NO
Cottonwood Weir	COOP	40.624	-111.787	1512	5/1/1917	Present	NO
Deer Creek Dam	COOP	40.405	-111.529	1606	3/1/1939	Present	NO
Draper	COOP	40.533	-111.833	1412	10/1/1963	10/1/1968	NO
Draper Point Of Mtn	COOP	40.488	-111.899	1372	9/1/1985	Present	NO
Dutchman Guard Stn	COOP	40.533	-111.600	2306	7/1/1956	12/31/1974	NO
Emigration Creek	COOP	40.750	-111.813	1486	6/15/2002	4/14/2004	NO
Fairfield	COOP	40.270	-112.094	1487	9/1/1950	Present	NO
Fairfield Caa Ap	COOP	40.350	-112.050	1514	12/1/1942	7/31/1950	NO
Geneva Steel	COOP	40.283	-111.733	1388	1/1/1953	2/28/1960	NO
Geneva Steel 2	COOP	40.300	-111.733	1388	2/1/1960	7/29/1982	NO

Name	Network	Lat.	Lon.	Elev. (m)	Start	End	In Park?
Granite	COOP	40.600	-111.783	1586	7/1/1958	Present	NO
Granite Mountain Vau	COOP	40.567	-111.767	1784	11/1/1966	12/31/1969	NO
Heber	COOP	40.502	-111.419	1716	1/14/1893	Present	NO
Herriman	COOP	40.517	-112.033	1525	10/1/1963	7/23/1965	NO
Hobble Creek	COOP	40.150	-111.417	1464	7/1/1948	12/31/1949	NO
Hobble Creek Summit	COOP	40.183	-111.367	2263	7/1/1956	12/31/1974	NO
Hog Hollow Summit	COOP	40.483	-111.833	1787	10/1/1963	2/28/1971	NO
Hogum Fork	COOP	40.567	-111.717	1967	9/1/1963	9/30/1976	NO
Kearns	COOP	40.667	-112.000	1360	10/1/1963	10/31/1968	NO
Lambs Canyon	COOP	40.717	-111.650	2086	10/1/1962	10/31/1968	NO
Lambs Canyon 2	COOP	40.717	-111.617	2257	10/1/1969	5/31/1973	NO
Little Dell Basin	COOP	40.783	-111.683	1781	11/1/1960	10/31/1967	NO
Little Dell Bullochs	COOP	40.750	-111.633	2025	8/1/1961	6/30/1967	NO
Lower American Fork	COOP	40.433	-111.750	1537	1/1/1914	7/31/1957	NO
Lower Mill Creek Pow	COOP	40.700	-111.783	1513	12/1/1913	11/12/1970	NO
Midvale	COOP	40.600	-111.917	1324	10/1/1911	2/23/1972	NO
Mill Creek Canyon	COOP	40.700	-111.667	2123	9/1/1963	9/30/1975	NO
Mill Creek Gaging St	COOP	40.700	-111.717	1922	7/1/1953	3/31/1958	NO
Mountain Dell Dam	COOP	40.750	-111.722	1652	1/5/1920	Present	NO
Murdock Powerhouse	COOP	40.600	-111.400	1821	10/1/1949	8/31/1959	NO
Olmstead P H	COOP	40.316	-111.654	1469	2/1/1977	Present	NO
Orem Treatment Plant	COOP	40.277	-111.737	1375	7/29/1982	Present	NO
Park City	COOP	40.670	-111.508	2080	8/12/1992	Present	NO
Park City 3 SW	COOP	40.615	-111.513	2685	10/15/1997	Present	NO
Park City G C	COOP	40.661	-111.519	2100	3/1/1896	Present	NO
Park City Meadows	COOP	40.683	-111.500	2056	9/1/1978	5/31/1980	NO
Park City Summit Hou	COOP	40.633	-111.533	2827	10/1/1968	4/30/1978	NO
Park Cty Nornda Mine	COOP	40.633	-111.500	2393	6/18/1980	4/6/1982	NO
Parleys Summit	COOP	40.750	-111.617	2147	6/1/1953	10/31/1956	NO
Parleys Summit Scs	COOP	40.767	-111.617	2315	7/1/1956	12/31/1974	NO
Pleasant Grove	COOP	40.369	-111.733	1437	9/1/1946	Present	NO
Point Of Mtn Disp	COOP	40.483	-111.900	1420	4/1/1989	1/1/1997	NO
Provo Ap	COOP	40.217	-111.717	1370	12/1/1943	4/1/1982	NO
Provo BYU	COOP	40.246	-111.651	1393	9/9/1980	Present	NO
Provo Radio Kayk	COOP	40.217	-111.667	1363	4/1/1952	2/9/1977	NO
Red Butte 1	COOP	40.767	-111.833	1498	11/6/1911	7/31/1965	NO
Red Butte 2	COOP	40.783	-111.800	1656	11/1/1941	9/30/1976	NO
Red Butte 3	COOP	40.783	-111.783	1754	7/1/1948	6/30/1954	NO
Red Butte 4	COOP	40.800	-111.767	1891	7/1/1948	10/31/1974	NO
Red Butte 5	COOP	40.783	-111.800	1678	7/1/1948	6/30/1954	NO
Riverton	COOP	40.517	-111.983	1421	7/1/1965	10/1/1968	NO
Salt Lake City	COOP	40.767	-111.883	1312	7/1/1952	6/30/1953	NO
Salt Lake City	COOP	40.767	-111.900	1315	7/1/1952	6/30/1953	NO
Salt Lake City E Bench	COOP	40.736	-111.817	1478	5/1/1990	1/19/2005	NO
Salt Lake City Subur	COOP	40.700	-111.917	1293	1/23/1950	12/31/1978	NO
Salt Lake Triad Ctr	COOP	40.771	-111.896	1305	3/1/1973	Present	NO
Sandy	COOP	40.553	-111.853	1294	10/15/1997	Present	NO
Sandy Big Cottonwood	COOP	40.619	-111.780	1521	3/1/1997	Present	NO
Sandy Little Cottonwood	COOP	40.579	-111.798	1548	4/1/1997	Present	NO
Silver Lake Brighton	COOP	40.601	-111.584	2664	7/3/1915	Present	NO
Snake Creek Powerhou	COOP	40.545	-111.504	1832	12/1/1913	Present	NO
Snowbird	COOP	40.583	-111.667	2471	6/1/1977	4/30/1979	NO
Snyderville	COOP	40.704	-111.537	1969	9/18/1991	Present	NO
Spanish Fork 1 S	COOP	40.100	-111.667	1409	6/1/1950	8/31/1969	NO
Spanish Fork P H	COOP	40.080	-111.604	1439	7/1/1909	Present	NO

Name	Network	Lat.	Lon.	Elev. (m)	Start	End	In Park?
Sundance	COOP	40.391	-111.577	2018	10/1/1995	Present	NO
Timpanogos Divide 4	COOP	40.433	-111.617	2481	7/1/1948	12/1/1996	NO
Twin Peaks	COOP	40.283	-111.300	2867	11/1/1966	7/31/1973	NO
Univ Of Utah	COOP	40.767	-111.833	1463	1/1/1949	4/30/1990	NO
Upper Amercn Fork Ph	COOP	40.438	-111.724	1625	9/1/1957	Present	NO
Utah Lake Lehi	COOP	40.360	-111.897	1371	6/1/1904	Present	NO
Washington Grove	COOP	40.750	-111.717	1693	12/1/1941	10/31/1952	NO
Wheeler Farm	COOP	40.637	-111.862	1335	10/1/1995	4/1/2000	NO
Alta Central	NRCS-SC	40.583	-111.633	2682	1/1/1984	Present	NO
Brighton Cabin	NRCS-SC	40.600	-111.583	2652	1/1/1961	Present	NO
Hobble Creek Summit	NRCS-SC	40.183	-111.383	2262	1/1/1936	Present	NO
Killyon Canyon	NRCS-SC	40.800	-111.700	1920	1/1/1986	Present	NO
Lambs Canyon	NRCS-SC	40.717	-111.617	2256	1/1/1969	Present	NO
Mill Creek	NRCS-SC	40.700	-111.683	2118	1/1/1974	Present	NO
Mill D-South Fork	NRCS-SC	40.650	-111.650	2256	1/1/1935	Present	NO
Buckley Mtn (Baer #11)	RAWS	40.205	-111.585	2787	7/1/2002	Present	NO
Pleasant Grove	RAWS	40.431	-111.750	1585	6/1/1997	Present	NO
Salt Lake City Municipal 2 Air	SAO	40.619	-111.993	1403	4/1/1995	Present	NO
Brighton	SNOTEL	40.600	-111.610	2667	M	M	NO
Mill-D North	SNOTEL	40.650	-111.630	2731	M	M	NO
Parley's Summit	SNOTEL	40.760	-111.610	2286	M	M	NO
Timpanogos Divide	SNOTEL	40.430	-111.610	2481	M	M	NO
Zion National Park – ZION							
Lava Point	COOP	37.383	-113.033	2406	5/1/1953	Present	YES
Zion Nat Park East Gat	COOP	37.248	-112.873	1707	3/23/1999	Present	YES
Zion National Park	COOP	37.208	-112.984	1234	1/1/1904	Present	YES
Zion Canyon	RAWS	37.205	-112.978	1189	11/1/2002	Present	YES
Cedar City	CEMP	37.666	-113.073	1818	8/1/1999	Present	NO
Castle Valley	COOP	37.667	-112.733	2922	7/1/1956	5/31/1973	NO
Cedar City	COOP	37.708	-113.144	1856	2/15/2000	Present	NO
Cedar City 5E	COOP	37.656	-112.992	1966	3/1/1983	Present	NO
Cedar City College R	COOP	37.583	-112.933	2483	11/1/1951	9/30/1976	NO
Cedar City Powerhous	COOP	37.683	-113.083	1732	11/1/1905	12/31/1961	NO
Cedar City Steam Pla	COOP	37.667	-113.033	1830	12/1/1961	2/28/1983	NO
Colorado City	COOP	36.994	-112.972	1527	7/1/1950	Present	NO
Duck Creek RS	COOP	37.517	-112.700	2611	7/1/1956	12/31/1974	NO
Duck Creek Village	COOP	37.525	-112.663	2554	9/1/1978	Present	NO
La Verkin	COOP	37.203	-113.269	981	4/1/1950	Present	NO
Leeds 4 NE	COOP	37.617	-113.300	1159	1/1/1931	12/31/1939	NO
Long Flat	COOP	37.517	-113.400	2440	9/1/1958	12/31/1974	NO
New Harmony	COOP	37.484	-113.313	1605	6/13/1911	Present	NO
Orderville	COOP	37.272	-112.639	1664	3/1/1910	Present	NO
Summit	COOP	37.801	-112.933	1829	11/1/1951	Present	NO
Yankee Reservoir	COOP	37.750	-112.783	2654	9/1/1958	12/31/1974	NO
Birch Crossing	NRCS-SC	37.750	-112.833	2469	1/1/1965	Present	NO
Tall Poles	NRCS-SC	37.717	-112.833	2682	1/1/1965	Present	NO
Yankee Reservoir	NRCS-SC	37.750	-112.767	2652	1/1/1942	Present	NO
Lava Point	RAWS	37.392	-113.039	2347	7/1/1995	Present	NO
White Reef - Hurricane 5W	RAWS	37.216	-113.378	1049	9/1/1987	Present	NO
Cedar City Municipal AP	SAO	37.709	-113.094	1703	8/1/1946	Present	NO
Colorado City Muni AP	SAO	36.960	-113.014	1486	8/16/2002	Present	NO
Castle Valley	SNOTEL	37.750	-112.740	2920	M	M	NO
Harris Flat	SNOTEL	37.490	-112.590	2377	M	M	NO

Name	Network	Lat.	Lon.	Elev. (m)	Start	End	In Park?
Kolob	SNOTEL	37.530	-113.050	2819	M	M	NO
Long Flat	SNOTEL	37.510	-113.400	2438	M	M	NO
Midway Valley	SNOTEL	37.560	-112.840	2987	M	M	NO
Andersons Ranch	WBAN	37.283	-113.283	1732	11/1/1934	12/31/1937	NO
Cedar City A	WBAN	37.683	-113.067	1791	6/1/1899	12/31/1937	NO

4.3. Station Locations

The major weather/climate networks in NCPN (discussed in Section 4.1) typically have ten or more stations in each park unit (Table 4.3). Most of these stations are COOP stations. The greatest numbers of weather/climate stations are located in and near TICA.

Table 4.3. Number of stations near (in) NCPN park units, by park unit and weather/climate network.

Network	ARCH	BLCA	BRCA	CANY	CARE	CEBR	COLM	CURE
Avalanche	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)
CASTNet	**0**(0)	**0**(0)	**0**(0)	**1**(1)	**0**(0)	**0**(0)	**0**(0)	**0**(0)
CEMP	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)
CRN	**0**(0)	**1**(1)	**0**(0)	**0**(0)	**1**(1)	**0**(0)	**0**(0)	**0**(0)
COOP	**8**(1)	**9**(2)	**11**(2)	**10**(2)	**24**(1)	**5**(2)	**8**(1)	**23**(3)
NRCS-SC	**0**(0)	**0**(0)	**1**(1)	**2**(0)	**2**(0)	**2**(0)	**0**(0)	**1**(0)
POMS	**0**(0)	**1**(1)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)
RAWS	**0**(0)	**1**(1)	**4**(2)	**4**(0)	**3**(0)	**0**(0)	**0**(0)	**3**(0)
SAO	**2**(0)	**2**(0)	**1**(0)	**0**(0)	**3**(0)	**0**(0)	**1**(0)	**2**(0)
SNOTEL	**0**(0)	**0**(0)	**2**(1)	**2**(0)	**3**(0)	**1**(0)	**0**(0)	**0**(0)

Network	DINO	FOBU	GOSP	HOVE	NABR	PISP	TICA	ZION
Avalanche	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**1**(1)	**0**(0)
CASTNet	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)
CEMP	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**1**(0)
CRN	**1**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)
COOP	**34**(6)	**11**(1)	**16**(0)	**9**(1)	**1**(1)	**4**(0)	**84**(1)	**20**(3)
NRCS-SC	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**7**(0)	**3**(0)
POMS	**1**(1)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)
RAWS	**10**(2)	**3**(0)	**0**(0)	**0**(0)	**0**(0)	**1**(0)	**2**(0)	**3**(1)
SAO	**2**(0)	**1**(0)	**1**(0)	**1**(0)	**0**(0)	**0**(0)	**1**(0)	**2**(0)
SNOTEL	**2**(0)	**2**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**4**(0)	**5**(0)

4.3.1. Northern Park Units

There are relatively few weather or climate stations in and near the FOBU and GOSP park units (Figure 4.1). There are no weather stations within GOSP. The nearest station to GOSP is the “Thiokol Propulsion F S” COOP station. This station is currently active and its digital data record, which extends back to 1962, is quite complete. The nearest automated station is the SAO station at Brigham City Airport.

Besides this SAO site, the longest digital data records are indicated at the Tremonton, Plymouth, and Corinne COOP stations (Table 4.2). Data at the Tremonton COOP are only reliable since 1979. The Corinne station has operated since 1896, with data gaps in the mid-1960s and from the late 1990s to present. The data from the Plymouth COOP site have been very unreliable.

There is only one COOP station inside FOBU (Figure 4.1). This COOP site ("Fossil Butte") has only been active since 1990; however, its data record is largely complete. While there are some RAWS and SNOTEL sites 50 km to the north and west of FOBU, the nearest automated station to FOBU is the Kemmerer Municipal Airport SAO site, about 20 km east of FOBU. This SAO site has a digital data record extending back to 1947, which is the longest such record of the stations around FOBU. Of the currently active stations, the longest digital data record for COOP stations within 40 km of FOBU is from the Randolph COOP, which started in 1982.

In contrast to the previous two park units, TICA has many weather and climate stations in its vicinity. Most of these are COOP sites. There are two stations within the boundaries of TICA. These are a USFS Avalanche station and a COOP station at park headquarters. Both sites are named "Timpanogos Cave". The COOP station started in 1946 and its data record is quite complete. There is a RAWS site, called "Pleasant Grove", which is just outside the western boundary of TICA and has been operating since 1997, with high-quality real-time data.

Most of the weather and climate stations in the vicinity of DINO (Figure 4.1) are RAWS and COOP sites. West of DINO, there is a SAO site currently in operation at the main airport in Vernal, Utah, along with several COOP sites and 2 SNOTEL sites in the Uinta Mountains.

Inside the park boundaries of DINO, we have identified nine weather and climate stations (Table 4.2), seven of which are currently in operation. Three of these are automated sites, while the rest are manual COOP sites. The automated weather and climate stations currently operating in DINO include a NPS POMS station, a RAWS station, and a CRN site. The NPS POMS site is on the west edge of DINO, while the RAWS station ("Dinosaur N.M.") is located near the Yampa River, just east of the confluence of the Yampa and Green Rivers. This RAWS site has been operating since the late 1990s. A second RAWS site inside DINO ("Harpers Corner") was in operation during the mid-1990s. Two manual COOP stations currently operating in DINO are "Dinosaur Natl Monu" and "Dinosaur Quarry Area". Of these two stations, "Dinosaur Quarry Area" has operated longer, starting in 1915 (Table 4.2), and has more reliable data.

There are useful stations outside DINO as well, both for long-term climate records and for near-real-time weather conditions in the region around DINO. Two stations outside DINO that have periods of record greater than 50 years are the "Jensen" (1925-present) and "Vernal Airport" (1948-present) COOP sites. The data from both of these sites are quite complete. The SAO site at Vernal Airport is a useful station for real-time weather conditions in the region.

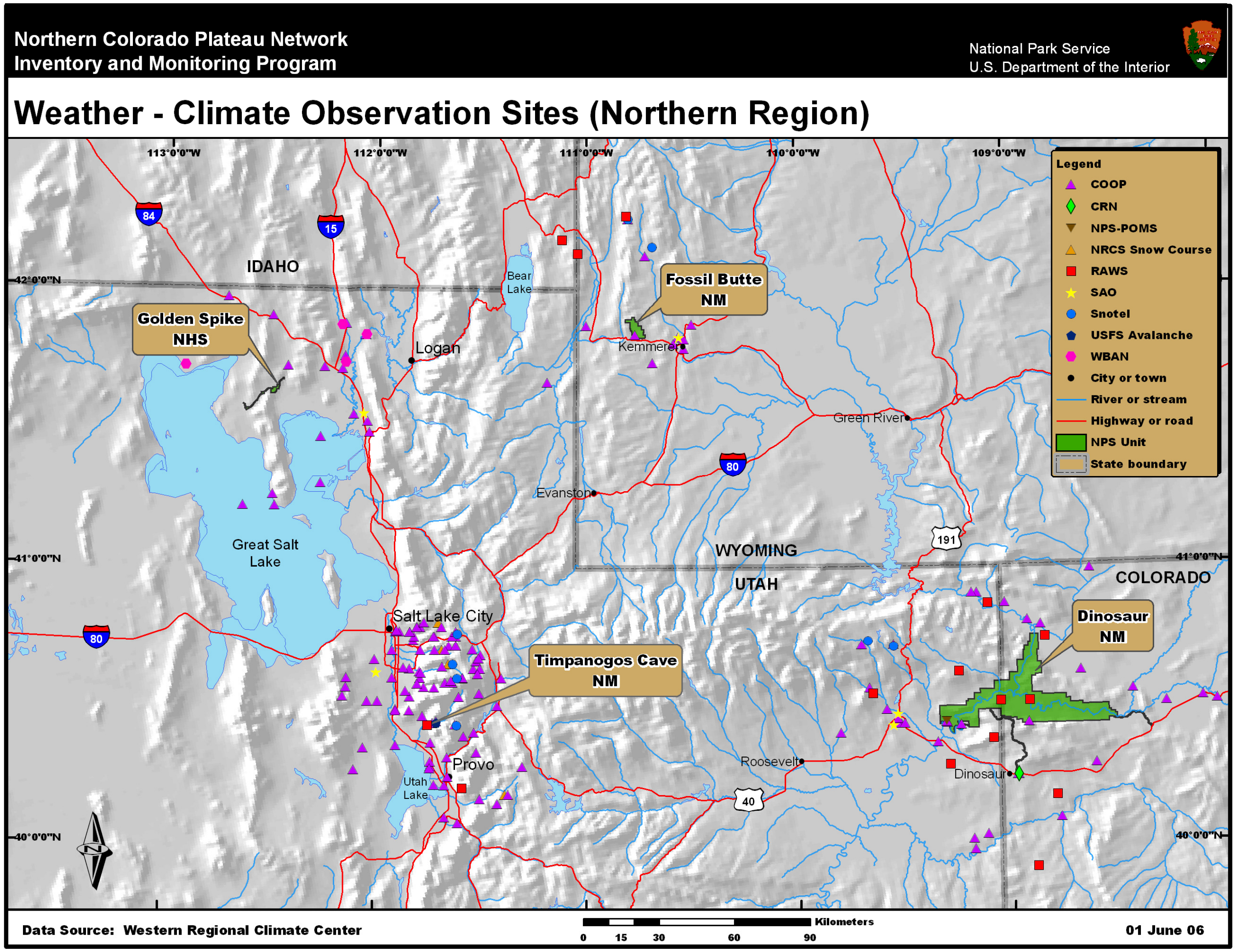


Figure 4.1. Station locations for the northern park units in NCPN, including DINO, FOBU, GOSP, and TICA.

4.3.2. Eastern Park Units

The three stations that are inside the boundaries of CURE are manual COOP stations (Figure 4.2). Of these, only two are currently operating, Blue Mesa Dam and Blue Mesa Lake. The COOP site at Blue Mesa Dam has the longest digital data record, which started in 1962.

The closest automated stations to the CURE park boundary are the SAO sites near Gunnison, Colorado, near the east boundary of CURE. The SAO site at the Gunnison County Airport has data records extending back to 1946 (Table 4.2). There are also nearby automated sites in BLCA.

There are five weather and climate stations within BLCA park boundaries (Table 4.2). Three of the stations within BLCA (the COOP and CRN stations named “Montrose 11 ENE”, along with the “Black Canyon” RAWS site are near park headquarters and are all within a mile of each other, along the canyon’s south rim.

All of the stations inside BLCA have relatively short data records (Table 4.2). The longest record is the “Black Canyon” RAWS site, which has a complete digital data record that starts in 1997. The other stations, including the COOP stations start in 2003 or later. Nearby SAO and COOP sites outside BLCA do provide longer periods of record. These include the SAO at the Montrose Regional Airport, whose record extends back to 1947, and the COOP station “Montrose No 2”, which has operated since 1895.

There is only one station inside COLM. This station is a COOP site (“Colorado Natl Monument”) that has a data record starting in 1940 (Table 4.2). The only automated site we have identified near COLM is the SAO station at Walker Field in Grand Junction, Colorado, about 15 km east of COLM. This station’s record starts in 1946.

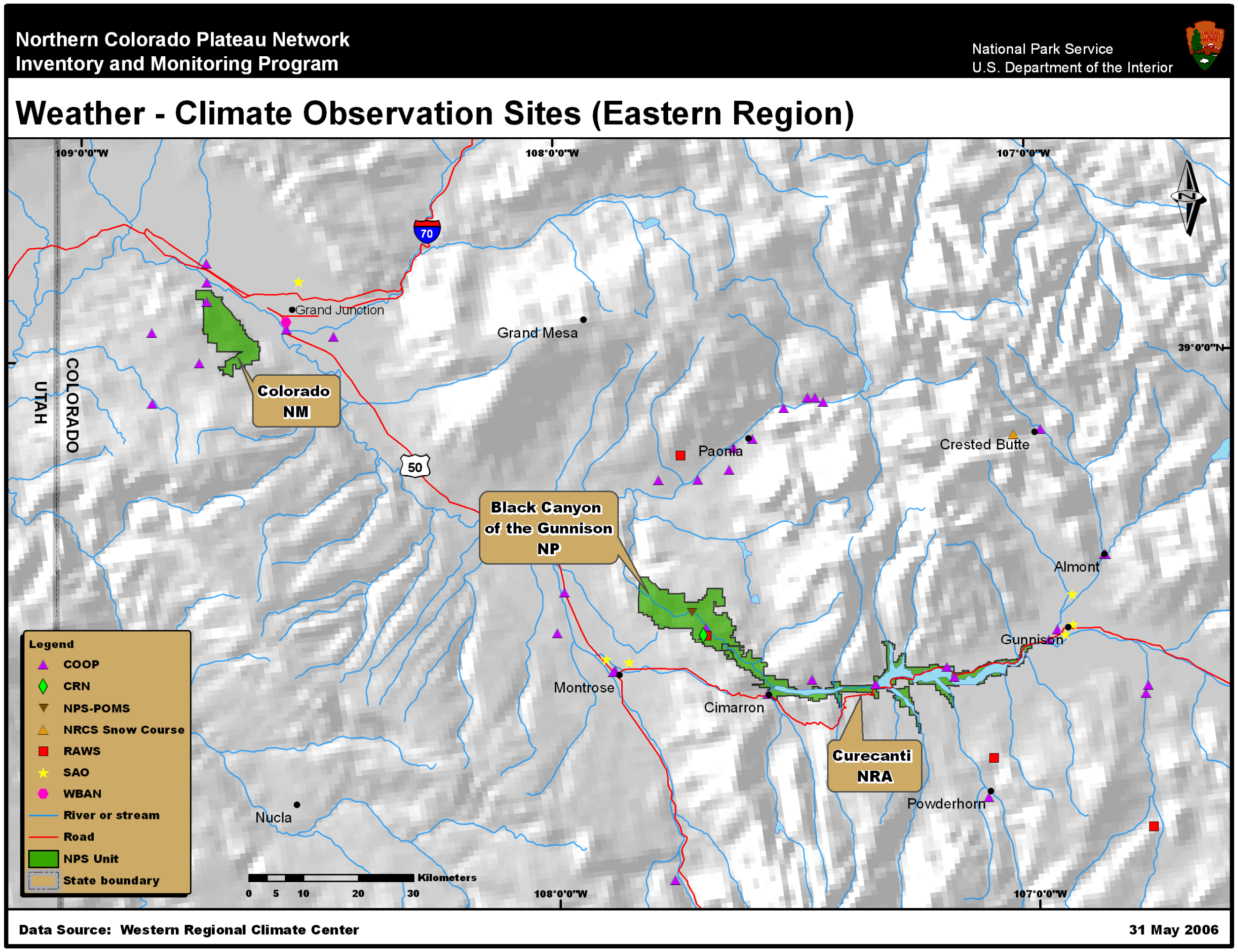


Figure 4.2. Station locations for the eastern park units in NCPN, including BLCA, COLM, and CURE.

4.3.3. Southern Park Units

The NCPN park units in southern Utah and northwestern Arizona show a noticeable decrease in weather and climate station coverage from west to east (Figure 4.3). In particular, the BRCA, CEBR, and ZION park units have relatively dense station coverage.

We found four stations within the park boundaries of ZION (Figure 4.3; Table 4.2). These include three COOP sites and one RAWS site. The longest period of record is available for the COOP site at ZION park headquarters ("Zion National Park"), with a data record extending back to 1904. The next longest period of record is from the COOP station "Lava Point", which has a data record starting in 1953. Besides the RAWS site inside ZION, there are at least two other RAWS sites within 30 km of the park, including "Lava Point" (not to be confused with the identically-named COOP site) and "White Reef – Hurricane 5W". SAO sites in the vicinity of ZION include "Cedar City A", whose data records go back to 1937, and the recently-installed SAO site at Colorado City Municipal Airport. Other automated sites include four SNOTEL sites in the mountains north of ZION, some of which are quite close to CEBR.

We have identified no weather/climate stations that are currently operating in CEBR. There have been at least two COOP sites that have operated in CEBR in the past, most recently in the 1970s. However, there are some COOP sites currently operating in the vicinity of CEBR, including the "Blowhard Mtn Radar" COOP site, which has a period of record starting in 1964. There are also some nearby automated stations such as SNOTEL sites operating in the vicinity of ZION (Figure 4.3). The longest period of record for stations around CEBR is found at the "Cedar City A" SAO site, mentioned previously.

One of the best-sampled park units in the NCPN is BRCA. In addition to having at least a dozen past and present manual or automated sites within 40 km of the park, BRCA has at least six weather/climate stations inside park boundaries (Figure 4.3; Table 4.2). Five of these are currently in operation. These include one COOP site ("Bryce Canyon NP Hqrs"), two RAWS sites ("Aqua Canyon – Bryce Canyon NP." and "Bryce Canyon"), a SNOTEL station ("Agua Canyon"), and a snow course ("Bryce Canyon"). The station with longest period of record is the COOP site at BRCA park headquarters; this data record extends back to 1959 and has very few data gaps. In addition to the RAWS and SNOTEL sites in BRCA, there are near-real-time observations available at the Bryce Canyon Airport SAO site ("Bryce Canyon AP"), whose data record extends back to 1945.

Unlike the BRCA, CEBR, and ZION park units, PISP has sparse weather and climate station coverage (Figure 4.3). One currently-operating COOP station is located near, but not in, the park ("Pipe Springs Natl Mon"). This site's period of record starts in 1963 and is mostly complete except for a few gaps, including the first half of 2002. The nearest automated stations to PISP are the previously-mentioned SAO site at Colorado City Municipal Airport (see Figure 4.3) and the "Gunsight" RAWS site southeast of PISP. Stations with longer periods of record are found at the "Fredonia" and "Kanab" COOP sites, which have data records starting in 1904 and 1899, respectively. The data record at Kanab is much more reliable than that of Fredonia, as the Fredonia site had no reliable observations between the mid-1970s and 2005.

Next, we move to park units in southeastern Utah and extreme southwestern Colorado, where station coverage is not as dense as in the park units in southwestern Utah (Figure 4.3). The smallest park units are HOVE and NABR and these will be discussed first.

We found one station within the boundaries of HOVE. This is a COOP site ("Hovenweep NM") that has a period of record starting in 1955. The data record from this site is largely complete but has occasional one-month data gaps starting in the 1980s. The nearest real-time measurements come from a SAO site in Cortez, Colorado ("Cortez Montezuma Co Ap"), which has operated since 1949. Other stations near HOVE include eight COOP stations, five of which are currently operating. Of these currently-operational COOP stations, the stations with the longest periods of record are "Cedar Point" and "Cortez", which started in 1946 and 1911, respectively. The data record at Cedar Point is mostly complete. The data record at Cortez is also largely complete, with the exception of a year-long data gap around 1975 and occasional one-month data gaps starting in the 1980s.

Like HOVE, NABR has one station within its boundaries. This is a COOP site ("Natural Bridges N M") that has a period of record starting in 1965 (Table 4.2). This is the longest period of record of any of the sites near NABR. This site's data record has very few small data gaps but is otherwise complete. There are also three COOP sites indicated about 10 km east of NABR (Bears Ears Lower, Bears Ears Upper, Elk Ridge Kigalia). These are all historical sites and are not currently operating. The closest automated station is a RAWS station which is 15 km southeast of NABR ("Kane Gulch – Blanding 23WSW") and has operated since 1991.

The remaining park units to be discussed in southeastern Utah are the larger units: ARCH, CANY, and CARE. The only weather/climate station inside ARCH is a COOP station at park headquarters, on the southern edge of ARCH (Figure 4.3). This station's period of record extends back to 1980 and is largely complete. There are no automated stations inside ARCH; however, there currently is a SAO site ("Moab Canyonland Ap"), located 10 km west of ARCH, which provides real-time data to the region. This SAO station has operated since 1964. The SAO station 10 km southeast of Moab was operated during the 1950s and 1960s. The remaining sites around ARCH are COOPs and are located primarily to the east of ARCH. Only two of these COOPs are still operating (Cisco 11 S; Castle Valley). The longest period of record among the currently-operating weather/climate stations around ARCH is the "Moab Canyonland Ap" SAO station. There are two historical COOP sites (no longer operating) which also have longer periods of record. These two sites are "Thompson" (1911-1995) and "Dewey" (1967-2004).

There are three stations within CANY. Two of these are manual COOP stations, while the remaining station is a CASTNet station (Figure 4.3). The visitor center area at the north end of the park has a COOP station ("Canyonlands The Neck") and a CASTNet station ("Island in the Sky"). The COOP station has operated since 1965 (Table 4.2) and has a largely-complete data record. A similar period of record is also available at the second COOP station inside CANY, "Canyonlands The Needle", which is located at the end of the eastern access road to CANY. Four RAWS stations are within 40 km of the park boundaries, with the most reliable RAWS station ("North Long Point"; operational since 1997) being located on the south side of CANY.

Inside CARE, there are only two weather/climate stations, a COOP station and a CRN station. The COOP station ("Capital Reef NP") has a largely-complete data record extending back to 1938 (Table 4.2). Despite the low station coverage inside CARE, there are a number of COOP stations, along with several automated stations, outside of CARE, which sample the larger region. The lowest station coverage, in the region surrounding CARE, is found in the areas north and east of CARE (Figure 4.3). Besides one SAO site in Hanksville, with a data record going back to 1946, we found no weather and climate stations in this area. COOP and SAO sites near Lake Powell provide the closest weather and climate data for the southern portions of CARE.

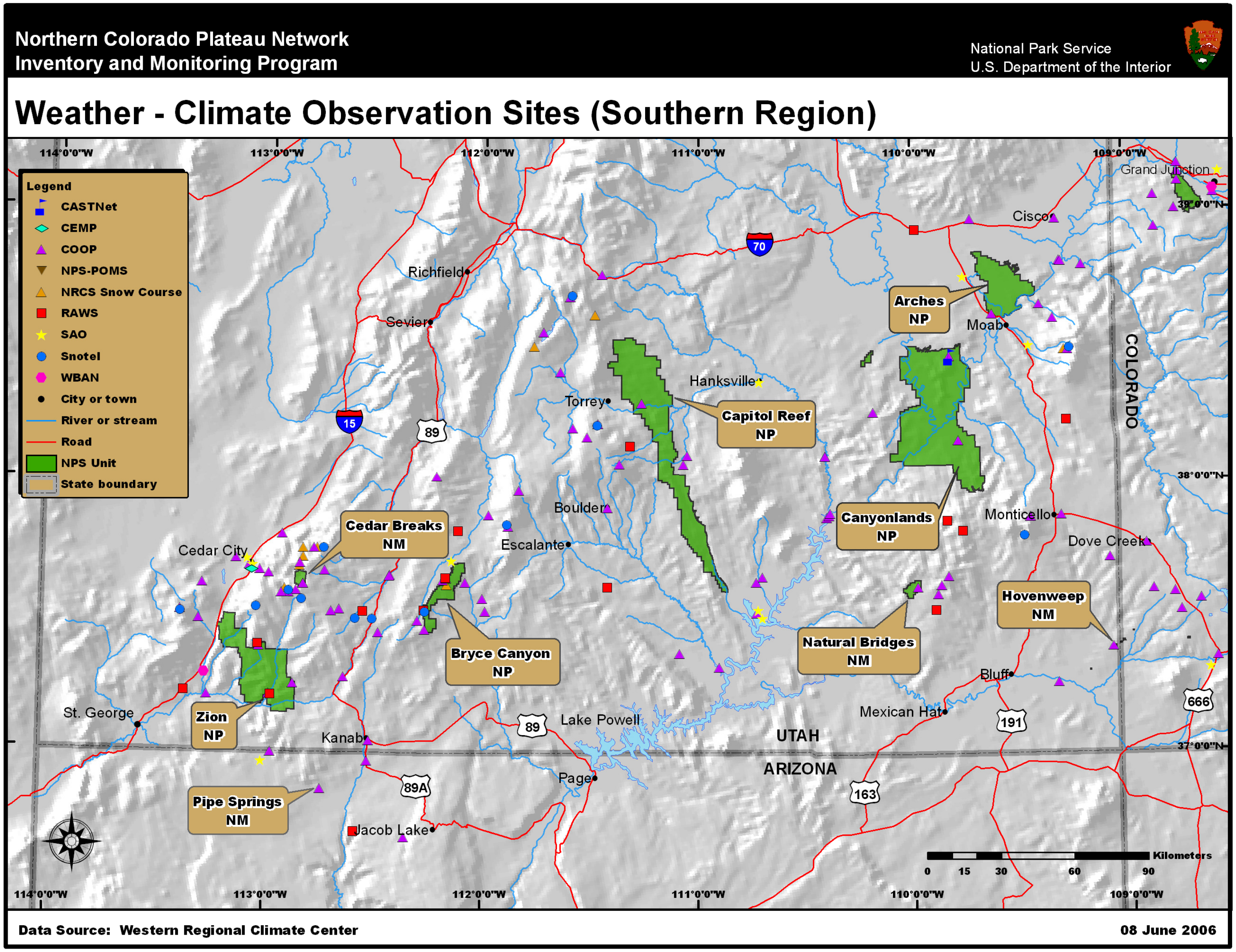


Figure 4.3. Station locations for the southern park units in NCPN.

5.0. Conclusions and Recommendations

We have based our findings on an examination of the available records and the topography and climate within NCPN units, discussions with NPS staff and other collaborators, and prior knowledge of the area. Here, we offer an evaluation and general comments pertaining to the status, prospects, and needs for climate-monitoring capabilities in NCPN. Garman et al. (2004) did much preliminary work to identify weather and climate stations in NCPN. They compiled much useful information on network specifications and protocols for each of the weather and climate networks in NCPN. This report builds upon these previous station inventories and suggestions for investigative climate protocols.

5.1. Northern Colorado Plateau Inventory and Monitoring Network

5.1.1. Northern Park Units

No known near-real-time automated weather stations were identified in the FOBU and GOSP park units. The nearest automated stations are at least 20 km outside the park boundaries of FOBU and GOSP. Despite the small size and relative remoteness of these two park units, it could be useful to consider deploying an inexpensive automated station at each park unit. In the case of FOBU, it may be useful to install an automated station near the existing COOP site, augmenting its manual observations with near-real-time data. Since there are very few weather or climate stations at either FOBU or GOSP, great effort must be made to encourage the continuation of those stations having the longest climate records in the FOBU and GOSP areas.

Despite its relatively small size, TICA has a relative abundance of weather and climate data, both inside the park unit and in its greater surroundings. As long as currently-operating stations are properly maintained, they will continue to provide valuable data describing the climate of the mountainous areas at and surrounding TICA. The weather and climate characteristics within DINO are also well-sampled. Like TICA, DINO will benefit by continuing to maintain its existing weather and climate station network.

5.1.2. Eastern Park Units

The park units in west-central Colorado are adequately sampled by manual observations, with one-two stations being present in each park unit. It is important to retain these sites for long-term climate monitoring efforts within the region. With the exception of BLCA, there are no automated, real-time weather data being recorded inside the boundaries of these park units. In the case of COLM, the only real-time observations are from the SAO Walker Field in Grand Junction, which is in a valley setting below COLM and thus may not be representative of COLM. An interesting finding is the lack of RAWS stations in the entire area surrounding COLM. It could therefore be beneficial for NPS to partner with the BLM to have a RAWS station installed inside COLM, for example, near the existing COOP site. By doing so, this park unit could obtain a useful automated station for real-time management decisions within the park, while at the same time providing a much-needed RAWS station for fire-monitoring efforts in the wider region around COLM.

Similarly, CURE may benefit by augmenting the existing COOP site at Blue Mesa Dam. While it is important that the existing manual COOP site be retained for the purpose of long-term climate monitoring within CURE, this site could be enhanced by adding an automated RAWS station. Access to near-real-time weather conditions would be beneficial both for managing recreational activities and for monitoring ecosystem characteristics at Blue Mesa Reservoir.

5.1.3. Southern Park Units

The park units in southwestern Utah and northwestern Arizona appear to be well-sampled by both manual and automated weather and climate stations. The only exception to this is PISP. However, even in the case of PISP, long-term climate records and at least two automated sites (one SAO site, one RAWS site) are available within 30 km of the park unit. Taking great care to maintain the abundant stations in these areas will ensure the continued availability of reliable, high-quality climate records for these park units.

In comparison with this, the park units in southeastern Utah and extreme southwestern Colorado have sparser weather and climate station coverage. Fortunately, for the three biggest park units in this region, there are one-two manual COOP sites with longer climate records inside each park. Also, there are usually one-two automated weather stations that are either inside, (in the case of CANY and CARE) or very near (in the case of ARCH), the park units. If resources would allow, an excellent place to install an automated site would be in CANY, alongside the existing COOP site at the Needles visitor center, to provide real-time conditions for the south half of CANY.

The current weather and climate monitoring efforts at NABR are likely adequate. NABR has one reliable COOP site within park boundaries and a few additional COOP and RAWS sites within 15 km.

Besides the COOP station at park headquarters, weather and climate monitoring is sparse in HOVE and its surrounding regions. Although there is an automated station within 40 km of the park unit (the SAO station at the Cortez Municipal Airport), HOVE could likely benefit by having a closer automated site. Since RAWS stations are non-existent in this region, it may be prudent to partner with BLM to install a RAWS station at HOVE park headquarters, complementing the existing COOP site.

5.2. Spatial Variations in Mean Climate

Topography is a major controlling factor on the park units within NCPN, leading to systematic spatial variations in mean surface climate. With local variations over short horizontal and vertical distances, topography introduces considerable fine-scale structure to mean climate (temperature and precipitation). Issues encountered in mapping mean climate are discussed in Appendix E and in Redmond et al. (2005).

If only a few stations will be emplaced, the primary goal should be overall characterization of the main climate elements (temperature and precipitation and their joint relative, snow). This level of characterization generally requires that (a) stations should not be located in deep valley bottoms (cold air drainage pockets) or near excessively steep slopes and (b) stations should be distributed spatially in the major biomes of each park. If such stations already are present in the vicinity, then additional stations would be best used for two important and somewhat competing purposes: (a) add redundancy as backup for loss of data from current stations (or loss of the physical stations) or (b) provide added information on spatial heterogeneity in climate arising from topographic diversity.

5.3. Climate Change Detection

The Colorado Plateau is one of the most rapidly warming areas in the U.S. Along with these warming trends, this region is also receiving less precipitation over time. Thus, the need for credible, accurate, complete, and long-term climate records for NCPN—from any location—cannot be overemphasized. This consideration always should have a high priority. However, because of spatial diversity in climate, monitoring that fills knowledge gaps and provides information on long-term temporal variability in short-distance relationships also will be valuable. We cannot be sure that climate variability and climate change will affect all parts of a given park unit equally. In fact, it is appropriate to speculate that this is not the case, and spatial variations in temporal variability extend to small spatial scales (a few kilometers or less in some cases), a consequence of extreme topographic diversity within NCPN.

5.4. Aesthetics

This issue arises frequently enough to deserve comment. Standards for quality climate measurements require open exposures away from heat sources, buildings, pavement, close vegetation and tall trees, and human intrusion (thus away from property lines). By their nature, sites that meet these standards are usually quite visible. These sites also are quite rare, making them precisely the same places that managers wish to protect from aesthetic intrusion. The most suitable and scientifically defensible sites frequently are rejected as candidate locations for weather/climate stations. Most weather/climate stations, therefore, tend to be “hidden” but many of these hidden locations have inferior exposures. Some measure of compromise is nearly always called for in siting weather and climate stations.

The public has vast interest in weather and climate, and within the NPS I&M networks, such measurements consistently rate near or at the top of desired public information. There seem to be many possible opportunities for exploiting and embracing this widespread interest within the interpretive mission of the NPS. One way to do this would be to highlight rather than hide these stations and educate the public about the need for adequate siting. A number of weather displays we have encountered during visits have proven inadvertently to serve as counterexamples for how measurements should not be made.

5.5. Information Access

Access to information promotes its use, which in turn promotes attention to station care and maintenance, better data, and more use. An end-to-end view that extends from sensing to decision support is far preferable to isolated and disconnected activities and aids the support infrastructure that is ultimately so necessary for successful, long-term climate monitoring.

Decisions about improvements in monitoring capacity are facilitated greatly by the ability to examine available climate information. Various methods are being created at WRCC to improve access to that information. Web pages providing historic and ongoing climate data, and information from NCPN park units can be accessed at http://www.wrcc.dri.edu/nps. In the event that this URL changes, there still will be links from the main WRCC Web page entitled "Projects" under NPS.

The WRCC has been steadily developing software to summarize data from hourly sites. This has been occurring under the aegis of the RAWS program and a growing array of product generators ranging from daily and monthly data lists to wind roses and hourly frequency distributions. All park data are available to park personnel via an access code (needed only for data listings) that can be acquired by request. The WRCC RAWS Web page is located at http://www.wrcc.dri.edu/wraws or http://www.raws.dri.edu.

Web pages have been developed to provide access not only to historic and ongoing climate data and information from NCPN park units but also to climate-monitoring efforts for NCPN. These pages can be found through http://www.wrcc.dri.edu/nps.

Additional access to more standard climate information is accessible though the previously mentioned pages, as well as through http://www.wrcc.dri.edu/summary. These summaries are generally for COOP stations.

5.6. Summarized Conclusions and Recommendations

- Much work already has been done by the NCPN office to locate weather/climate stations (e.g., Garman et al. 2004).
- Climate within NCPN is highly variable spatially due to regional topography and the spatially-varying influence of the southwestern monsoon.
- Recent climate variations in NCPN (e.g. drought) will likely lead to significant ecological responses.
- FOBU and BLCA are two park units that lack long-term climate records within park boundaries. If long-term climate studies are conducted in these park units, nearby sites with longer data records must be used.
- Many of the NCPN park units have excellent coverage of weather and climate stations. These include TICA, DINO, and the park units that are in southwestern Utah and northwestern Arizona.
- Some park units are not close to automated weather/climate stations (e.g., GOSP, HOVE). NPS will benefit by partnering with BLM to install RAWS stations in these NCPN park units. We recommend that these park units retain existing COOP sites for long-term climate records.

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Appendix A. Climate-monitoring principles.

Since the late 1990s, frequent references have been made to a set of climate-monitoring principles enunciated in 1996 by Tom Karl, director of the NOAA NCDC in Asheville, North Carolina. These monitoring principles also have been referred to informally as the "Ten Commandments of Climate Monitoring." Both versions are given here. In addition, these principles have been adopted by the Global Climate Observing System (GCOS 2004).

(Compiled by Kelly Redmond, Western Regional Climate Center, Desert Research Institute, August 2000.)

A.1. Full Version (Karl et al. 1996)

A. Effects on climate records of instrument changes, observing practices, observation locations, sampling rates, etc., must be known before such changes are implemented. This can be ascertained through a period where overlapping measurements from old and new observing systems are collected or sometimes by comparing the old and new observing systems with a reference standard. Site stability for in situ measurements, both in terms of physical location and changes in the nearby environment, also should be a key criterion in site selection. Thus, many synoptic network stations, which are primarily used in weather forecasting but also provide valuable climate data, and dedicated climate stations intended to be operational for extended periods must be subject to this policy.

B. Processing algorithms and changes in these algorithms must be well documented. Documentation should be carried with the data throughout the data-archiving process.

C. Knowledge of instrument, station, and/or platform history is essential for interpreting and using the data. Changes in instrument sampling time, local environmental conditions for in situ measurements, and other factors pertinent to interpreting the observations and measurements should be recorded as a mandatory part in the observing routine and be archived with the original data.

D. In situ and other observations with a long, uninterrupted record should be maintained. Every effort should be applied to protect the data sets that have provided long-term, homogeneous observations. "Long-term" for space-based measurements is measured in decades, but for more conventional measurements, "long-term" may be a century or more. Each element in the observational system should develop a list of prioritized sites or observations based on their contribution to long-term climate monitoring.

E. Calibration, validation, and maintenance facilities are critical requirements for long-term climatic data sets. Homogeneity in the climate record must be assessed routinely, and corrective action must become part of the archived record.

F. Where feasible, some level of "low-technology" backup to "high-technology" observing systems should be developed to safeguard against unexpected operational failures.

G. Regions having insufficient data, variables and regions sensitive to change, and key measurements lacking adequate spatial and temporal resolution should be given the highest priority in designing and implementing new climate-observing systems.

H. Network designers and instrument engineers must receive long-term climate requirements at the outset of the network design process. This is particularly important because most observing systems have been designed for purposes other than long-term climate monitoring. Instruments must possess adequate accuracy with biases small enough to document climate variations and changes.

I. Much of the development of new observational capabilities and the evidence supporting the value of these observations stem from research-oriented needs or programs. A lack of stable, long-term commitment to these observations and lack of a clear transition plan from research to operations are two frequent limitations in the development of adequate, long-term monitoring capabilities. Difficulties in securing a long-term commitment must be overcome in order to improve the climate-observing system in a timely manner with minimal interruptions.

J. Data management systems that facilitate access, use, and interpretation are essential. Freedom of access, low cost, mechanisms that facilitate use (directories, catalogs, browse capabilities, availability of metadata on station histories, algorithm accessibility and documentation, etc.) and quality control should guide data management. International cooperation is critical for successful management of data used to monitor long-term climate change and variability.

A.2. Abbreviated version, “Ten Commandments of Climate Monitoring”

A. Assess the impact of new climate-observing systems or changes to existing systems before they are implemented.

   “Thou shalt properly manage network change.” (assess effects of proposed changes)

B. Require a suitable period where measurement from new and old climate-observing systems will overlap.

   “Thou shalt conduct parallel testing.” (compare old and replacement systems)

C. Treat calibration, validation, algorithm-change, and data-homogeneity assessments with the same care as the data.

   "Thou shalt collect metadata." (fully document system and operating procedures)

D. Verify capability for routinely assessing the quality and homogeneity of the data including high-resolution data for extreme events.

"Thou shalt assure data quality and continuity." (assess as part of routine operating procedures)

E. Integrate assessments like those conducted by the International Panel on Climate Change into global climate-observing priorities.

   "Thou shalt anticipate the use of data." (integrated environmental assessment; component in operational plan for system)

F. Maintain long-term weather and climate stations.

   "Thou shalt worship historic significance." (maintain homogeneous data sets from long–term, climate-observing systems)

G. Place high priority on increasing observations in regions lacking sufficient data and in regions sensitive to change and variability.

   "Thou shalt acquire complementary data." (new sites to fill observational gaps)

H. Provide network operators, designers, and instrument engineers with long-term requirements at the outset of the design and implementation phases for new systems.

   "Thou shalt specify requirements for climate observation systems." (application and usage of observational data)

I. Carefully consider the transition from research-observing system to long-term operation.

   "Thou shalt have continuity of purpose." (stable long-term commitments)

J. Focus on data-management systems that facilitate access, use, and interpretation of weather data and metadata.

   "Thou shalt provide access to data and metadata." (readily-available weather and climate information)

A.3. Literature Cited

Karl, T. R., V. E. Derr, D. R. Easterling, C. K. Folland, D. J. Hoffman, S. Levitus, N. Nicholls, D. E. Parker, and G. W. Withee. 1996. Critical issues for long-term climate monitoring. Pages 55-92 *in* T. R. Karl, editor. Long Term Climate Monitoring by the Global Climate Observing System, Kluwer Publishing.

Global Climate Observing System. 2004. Implementation plan for the global observing system for climate in support of the UNFCCC. GCOS-92, WMO/TD No. 1219, World Meteorological Organization, Geneva, Switzerland.

Appendix B. Glossary.

Climate—Complete and entire ensemble of statistical descriptors of temporal and spatial properties comprising the behavior of the atmosphere. These descriptors include means, variances, frequency distributions, autocorrelations, spatial correlations and other patterns of association, temporal lags, and element-to-element relationships. The descriptors have a physical basis in flows and reservoirs of energy and mass. Climate and weather phenomena shade gradually into each other and are ultimately inseparable.

Climate Element—(same as Weather Element) Attribute or property of the state of the atmosphere that is measured, estimated, or derived. Examples of climate elements include temperature, wind speed, wind direction, precipitation amount, precipitation type, relative humidity, dewpoint, solar radiation, snow depth, soil temperature at a given depth, etc. A derived element is a function of other elements (like degree days or number of days with rain) and is not measured directly with a sensor. The terms "parameter" or "variable" are not used to describe elements.

Climate Network—Group of climate stations having a common purpose; the group is often owned and maintained by a single organization.

Climate Station—Station where data are collected to track atmospheric conditions over the long-term. Often, this station operates to additional standards to verify long-term consistency. For these stations, the detailed circumstances surrounding a set of measurements (siting and exposure, instrument changes, etc.) are important.

Data—Measurements specifying the state of the physical environment. Does not include metadata.

Data Inventory—Information about overall data properties for each station within a weather or climate network. A data inventory may include start/stop dates, percentages of available data, breakdowns by climate element, counts of actual data values, counts or fractions of data types, etc. These properties must be determined by actually reading the data and thus require the data to be available, accessible, and in a readable format.

NPS I&M Network—A set of NPS park units grouped by a common theme, typically by natural resource and/or geographic region.

Metadata—Information necessary to interpret environmental data properly, organized as a history or series of snapshots—data about data. Examples include details of measurement processes, station circumstances and exposures, assumptions about the site, network purpose and background, types of observations and sensors, pre-treatment of data, access information, maintenance history and protocols, observational methods, archive locations, owner, and station start/end period.

Quality Assurance—Planned and systematic set of activities to provide adequate confidence that products and services are resulting in credible and correct information. Includes quality control.

Quality Control—Evaluation, assessment, and improvement of imperfect data by utilizing other imperfect data.

Station Inventory—Information about a set of stations obtained from metadata that accompany the network or networks. A station inventory can be compiled from direct and indirect reports prepared by others.

Weather—Instantaneous state of the atmosphere at any given time, mainly with respect to its effects on biological activities. As distinguished from climate, weather consists of the short-term (minutes to days) variations in the atmosphere. Popularly, weather is thought of in terms of temperature, precipitation, humidity, wind, sky condition, visibility, and cloud conditions.

Weather Element (same as Climate Element)—Attribute or property of the state of the atmosphere that is measured, estimated, or derived. Examples of weather elements include temperature, wind speed, wind direction, precipitation amount, precipitation type, relative humidity, dewpoint, solar radiation, snow depth, soil temperature at a given depth, etc. A derived weather element is a function of other elements (like degree days or number of days with rain) and is not measured directly. The terms "parameter" and "variable" are not used to describe weather elements.

Weather Network—Group of weather stations usually owned and maintained by a particular organization and usually for a specific purpose.

Weather Station—Station where collected data are intended for near-real-time use with less need for reference to long-term conditions. In many cases, the detailed circumstances of a set of measurements (siting and exposure, instrument changes, etc.) from weather stations are not as important as for climate stations.

Appendix C. Factors in operating a climate network.

C.1. Climate versus Weather

- Climate measurements require *consistency through time.*

C.2. Network Purpose

- Anticipated or desired lifetime.
- Breadth of network mission (commitment by needed constituency).
- Dedicated constituency—no network survives without a dedicated constituency.

C.3. Site Identification and Selection

- Spanning gradients in climate or biomes with transects.
- Issues regarding representative spatial scale—site uniformity versus site clustering.
- Alignment with and contribution to network mission.
- Exposure—ability to measure representative quantities.
- Logistics—ability to service station (Always or only in favorable weather?).
- Site redundancy (positive for quality control, negative for extra resources).
- Power—is AC needed?
- Site security—is protection from vandalism needed?
- Permitting often a major impediment and usually underestimated.

C.4. Station Hardware

- Survival—weather is the main cause of lost weather/climate data.
- Robustness of sensors—ability to measure and record in any condition.
- Quality—distrusted records are worthless and a waste of time and money.
  - High quality—will cost up front but pays off later.
  - Low quality—may provide a lower start-up cost but will cost more later (low cost can be expensive).
- Redundancy—backup if sensors malfunction.
- Ice and snow—measurements are much more difficult than rain measurements.
- Severe environments (expense is about two–three times greater than for stations in more benign settings).

C.5. Communications

- Reliability—live data have a much larger constituency.
- One-way or two-way.
  - Retrieval of missed transmissions.
  - Ability to reprogram data logger remotely.
  - Remote troubleshooting abilities.
  - Continuing versus one-time costs.
- Back-up procedures to prevent data loss during communication outages.
- Live communications increase problems but also increase value.

C.6. Maintenance

- Main reason why networks fail (and most networks do eventually fail!).

- Key issue with nearly every network.
- Who will perform maintenance?
- Degree of commitment and motivation to contribute.
- Periodic? On-demand as needed? Preventive?
- Equipment change-out schedules and upgrades for sensors and software.
- Automated stations require skilled and experienced labor.
- Calibration—sensors often drift (climate).
- Site maintenance essential (constant vegetation, surface conditions, nearby influences).
- Typical automated station will cost about $2K per year to maintain.
- Documentation—photos, notes, visits, changes, essential for posterity.
- Planning for equipment life cycle and technological advances.

C.7. Maintaining Programmatic Continuity and Corporate Knowledge

- Long-term vision and commitment needed.
- Institutionalizing versus personalizing—developing appropriate dependencies.

C.8. Data Flow

- Centralized ingest?
- Centralized access to data and data products?
- Local version available?
- Contract out work or do it yourself?
- Quality control of data.
- Archival.
- Metadata—historic information, not a snapshot. Every station should collect metadata.
- Post-collection processing, multiple data-ingestion paths.

C.9. Products

- Most basic product consists of the data values.
- Summaries.
- Write own applications or leverage existing mechanisms?

C.10. Funding

- Prototype approaches as proof of concept.
- Linking and leveraging essential.
- Constituencies—every network needs a constituency.
- Bridging to practical and operational communities? Live data needed.
- Bridging to counterpart research efforts and initiatives—funding source.
- Creativity, resourcefulness, and persistence usually are essential to success.

C.11. Final Comments

- Deployment is by far the easiest part in operating a network.
- Maintenance is the main issue.
- Best analogy: Operating a network is like raising a child; it requires constant attention.

Source: Western Regional Climate Center (WRCC)

Appendix D. Master metadata field list.

Field Name	Field Type	Field Description
begin_date	date	Effective beginning date for a record.
begin_date_flag	char(2)	Flag describing the known accuracy of the begin date for a station.
best_elevation	float(4)	Best known elevation for a station (in feet).
clim_div_code	char(2)	Foreign key defining climate division code (primary in table: clim_div).
clim_div_key	int2	Foreign key defining climate division for a station (primary in table: clim_div.
clim_div_name	varchar(30)	English name for a climate division.
controller_info	varchar(50)	Person or organization who maintains the identifier system for a given weather or climate network.
country_key	int2	Foreign key defining country where a station resides (primary in table: none).
county_key	int2	Foreign key defining county where a station resides (primary in table: county).
county_name	varchar(31)	English name for a county.
Description	text	Any description pertaining to the particular table.
end_date	date	Last effective date for a record.
end_date_flag	char(2)	Flag describing the known accuracy of station end date.
fips_country_code	char(2)	FIPS (federal information processing standards) country code.
fips_state_abbr	char(2)	FIPS state abbreviation for a station.
fips_state_code	char(2)	FIPS state code for a station.
history_flag	char(2)	Describes temporal significance of an individual record among others from the same station.
id_type_key	int2	Foreign key defining the id_type for a station (usually defined in code).
last_updated	date	Date of last update for a record.
Latitude	float(8)	Latitude value.
Longitude	float(8)	Longitude value.
name_type_key	int2	"3": COOP station name, "2": best station name.
Name	varchar(30)	Station name as known at date of last update entry.
ncdc_state_code	char(2)	NCDC, two-character code identifying U.S. state.
network_code	char(8)	Eight-character abbreviation code identifying a network.
network_key	int2	Foreign key defining the network for a station (primary in table: network).
network_station_id	int4	Identifier for a station in the associated network, which is defined by id_type_key.
Remark	varchar(254)	Additional information for a record.
src_quality_code	char(2)	Code describing the data quality for the data source.
state_key	int2	Foreign key defining the U.S. state where a station resides (primary in table: state).
state_name	varchar(30)	English name for a state.
station_alt_name	varchar(30)	Other English names for a station.
station_best_name	varchar(30)	Best, most well-known English name for a station.
time_zone	float4	Time zone where a station resides.
ucan_station_id	int4	Unique station identifier for every station in ACIS.
unit_key	int2	Integer value representing a unit of measure.

Field Name	Field Type	Field Description
updated_by	char(8)	Person who last updated a record.
var_major_id	int2	Defines major climate variable.
var_minor_id	int2	Defines data source within a var_major_id.
Zipcode	char(5)	Zipcode where a latitude/longitude point resides.
nps_netcode	char(4)	Network four-character identifier.
nps_netname	varchar(128)	Displayed English name for a network.
Parkcode	char(4)	Park four-character identifier.
Parkname	varchar(128)	Displayed English name for a park/
im_network	char(4)	NPS I&M network where park belongs (a net code)/
station_id	varchar(16)	Station identifier.
station_id_type	varchar(16)	Type of station identifier.
network.subnetwork.id	varchar(16)	Identifier of a sub-network in associated network.
subnetwork_key	int2	Foreign key defining sub-network for a station.
subnetwork_name	varchar(30)	English name for a sub-network.
Slope	integer	Terrain slope at the location.
Aspect	integer	Terrain aspect at the station.
Gps	char(1)	Indicator of latitude/longitude recorded via GPS (global positioning system).
site_description	text(0)	Physical description of site.
route_directions	text(0)	Driving route or site access directions.
station_photo_id	integer	Unique identifier associating a group of photos to a station. Group of photos all taken on same date.
photo_id	char(30)	Unique identifier for a photo.
photo_date	datetime	Date photograph taken.
Photographer	varchar(64)	Name of photographer.
maintenance_date	datetime	Date of station maintenance visit.
contact_key	Integer	Unique identifier associating contact information to a station.
full_name	varchar(64)	Full name of contact person.
Organization	varchar(64)	Organization of contact person.
contact_type	varchar(32)	Type of contact person (operator, administrator, etc.)
position_title	varchar(32)	Title of contact person.
Address	varchar(32)	Address for contact person.
City	varchar(32)	City for contact person.
State	varchar(2)	State for contact person.
zip_code	char(10)	Zipcode for contact person.
Country	varchar(32)	Country for contact person.
Email	varchar(64)	E-mail for contact person.
work_phone	varchar(16)	Work phone for contact person.
contact_notes	text(254)	Other details regarding contact person.
equipment_type	char(30)	Sensor measurement type; i.e., wind speed, air temperature, etc.
eq_manufacturer	char(30)	Manufacturer of equipment.
eq_model	char(20)	Model number of equipment.
serial_num	char(20)	Serial number of equipment.
eq_description	varchar(254)	Description of equipment.
install_date	datetime	Installation date of equipment.
remove_date	datetime	Removal date of equipment.
ref_height	integer	Sensor displacement height from surface.
sampling_interval	varchar(10)	Frequency of sensor measurement.

Appendix E. General design considerations for weather/ climate-monitoring programs.

The process for designing a climate-monitoring program benefits from anticipating design and protocol issues discussed here. Much of this material is been excerpted from a report addressing the Channel Islands National Park (Redmond and McCurdy 2005), where an example is found illustrating how these factors can be applied to a specific setting. Many national park units possess some climate or meteorology feature that sets them apart from more familiar or "standard" settings.

E.1. Introduction

There are several criteria that must be used in deciding to deploy new stations and where these new stations should be sited.

- Where are existing stations located?
- Where have data been gathered in the past (discontinued locations)?
- Where would a new station fill a knowledge gap about basic, long-term climatic averages for an area of interest?
- Where would a new station fill a knowledge gap about how climate behaves over time?
- As a special case for behavior over time, what locations might be expected to show a more sensitive response to climate change?
- How do answers to the preceding questions depend on the climate element? Are answers the same for precipitation, temperature, wind, snowfall, humidity, etc.?
- What role should manual measurements play? How should manual measurements interface with automated measurements?
- Are there special technical or management issues, either present or anticipated in the next 5–15 years, requiring added climate information?
- What unique information is provided in addition to information from existing sites? "Redundancy is bad."
- What nearby information is available to estimate missing observations because observing systems always experience gaps and lose data? "Redundancy is good."
- How would logistics and maintenance affect these decisions?

In relation to the preceding questions, there are several topics that should be considered. The following topics are not listed in a particular order.

E.1.1. Network Purpose

Humans seem to have an almost reflexive need to measure temperature and precipitation, along with other climate elements. These reasons span a broad range from utilitarian to curiosity-driven. Although there are well-known recurrent patterns of need and data use, new uses are always appearing. The number of uses ranges in the thousands. Attempts have been made to categorize such uses (see NRC 1998; NRC 2001). Because climate measurements are accumulated over a long time, they should be treated as multi-purpose and should be undertaken in a manner that serves the widest possible applications. Some applications remain constant, while others rise and fall in importance. An insistent issue today may subside, while the next pressing issue of tomorrow barely may be anticipated. The notion that humans might affect the climate of the entire Earth was nearly unimaginable when the national USDA (later NOAA) cooperative weather network began in the late 1800s. Abundant experience has shown, however, that there always will be a demand for a history record of climate measurements and their properties. Experience also shows that there is an expectation that climate measurements will be taken and made available to the general public.

An exhaustive list of uses for data would fill many pages and still be incomplete. In broad terms, however, there are needs to document environmental conditions that disrupt or otherwise affect park operations (e.g., storms and droughts). Design and construction standards are determined by climatological event frequencies that exceed certain thresholds. Climate is a determinant that sometimes attracts and sometimes discourages visitors. Climate may play a large part in the park experience (e.g., Death Valley and heat are nearly synonymous). Some park units are large enough to encompass spatial or elevation diversity in climate, and the sequence of events can vary considerably inside or close to park boundaries. That is, temporal trends and statistics may not be the same everywhere, and this spatial structure should be sampled. The granularity of this structure depends on the presence of topography or large climate gradients or both, such as that found along the U.S. West Coast in summer with the rapid transition from the marine layer to the hot interior.

Plant and animal communities and entire ecosystems react to every nuance in the physical environment. No aspect of weather and climate goes undetected in the natural world. Wilson (1998) proposed “an informal rule of biological evolution” that applies here: “If an organic sensor can be imagined that is capable of detecting any particular environmental signal, a species exists somewhere that possesses this sensor.” Every weather and climate event, whether dull or extraordinary to humans, matters to some organism. Dramatic events and creeping incremental change both have consequences to living systems. Extreme events or disturbances can “reset the clock” or “shake up the system” and lead to reverberations that last for years to centuries or longer. Slow change can carry complex nonlinear systems (e.g., any living assemblage) into states where chaotic transitions and new behavior occur. These changes are seldom predictable, typically are observed after the fact, and understood only in retrospect. Climate changes may not be exciting, but as a well-known atmospheric scientist, Mike Wallace, from the University of Washington once noted, “subtle does not mean unimportant”.

Thus, individuals who observe the climate should be able to record observations accurately and depict both rapid and slow changes. In particular, an array of artificial influences easily can confound detection of slow changes. The record as provided can contain both real climate variability (that took place in the atmosphere) and fake climate variability (that arose directly from the way atmospheric changes were observed and recorded). As an example, trees growing near a climate station with an excellent anemometer will make it appear that the wind gradually slowed down over many years. Great care must be taken to protect against sources of fake climate variability on the longer-time scales of years to decades. Processes leading to the observed climate are not stationary; rather these processes draw from probability distributions that vary with time. For this reason, climatic time series do not exhibit statistical stationarity. The implications are manifold. There are no true climatic “normals” to which climate inevitably must return. Rather, there are broad ranges of climatic conditions. Climate does not demonstrate exact repetition but instead continual fluctuation and sometimes approximate repetition. In addition, there is always new behavior waiting to occur. Consequently, the business of climate monitoring is never finished, and there is no point where we can state confidently that "enough" is known.

E.1.2. Robustness

The most frequent cause for loss of weather data is the weather itself, the very thing we wish to record. The design of climate and weather observing programs should consider the meteorological equivalent of "peaking power" employed by utilities. Because environmental disturbances have significant effects on ecologic systems, sensors, data loggers, and communications networks should be able to function during the most severe conditions that realistically can be anticipated over the next 50–100 years. Systems designed in this manner are less likely to fail under more ordinary conditions, as well as more likely to transmit continuous, quality data for both tranquil and active periods.

E.1.3. Weather versus Climate

For "weather" measurements, pertaining to what is approximately happening here and now, small moves and changes in exposure are not as critical. For "climate" measurements, where values from different points in time are compared, siting and exposure are critical factors, and it is vitally important that the observing circumstances remain essentially unchanged over the duration of the station record.

Station moves can affect different elements to differing degrees. Even small moves of several meters, especially vertically, can affect temperature records. Hills and knolls act differently from the bottoms of small swales, pockets, or drainage channels (Whiteman 2000; Geiger et al. 2003). Precipitation is probably less subject to change with moves of 50–100 m than other elements (that is, precipitation has less intrinsic variation in small spaces) except if wind flow over the gauge is affected.

E.1.4. Physical Setting

Siting and exposure, and their continuity and consistency through time, significantly influence the climate records produced by a station. These two terms have overlapping connotations. We use the term "siting" in a more general sense, reserving the term "exposure" generally for the particular circumstances affecting the ability of an instrument to record measurements that are representative of the desired spatial or temporal scale.

E.1.5. Measurement Intervals

Climatic processes occur continuously in time, but our measurement systems usually record in discrete chunks of time: for example, seconds, hours, or days. These measurements often are referred to as "systematic" measurements. Interval averages may hide active or interesting periods of highly intense activity. Alternatively, some systems record "events" when a certain threshold of activity is exceeded (examples: another millimeter of precipitation has fallen, another kilometer of wind has moved past, the temperature has changed by a degree, a gust higher than 9.9 m/s has been measured). When this occurs, measurements from all sensors are reported. These measurements are known as “breakpoint” data. In relatively unchanging conditions (long calm periods or rainless weeks, for example), event recorders should send a signal that they are still “alive and well.” If systematic recorders are programmed to note and periodically report the highest, lowest, and mean value within each time interval, the likelihood is reduced that interesting behavior will be glossed over or lost. With the capacity of modern data loggers, it is recommended to record and report extremes within the basic time increment (e.g., hourly or 10 minutes). This approach also assists quality-control procedures.

There is usually a trade-off between data volume and time increment, and most automated systems now are set to record approximately hourly. A number of field stations maintained by WRCC are programmed to record in 5- or 10-minute increments, which readily serve to construct an hourly value. However, this approach produces 6–12 times as much data as hourly data. These systems typically do not record details of events at sub-interval time scales, but they easily can record peak values, or counts of threshold exceedance, within the time intervals.

Thus, for each time interval at an automated station, we recommend that several kinds of information—mean or sum, extreme maximum and minimum, and sometimes standard deviation—be recorded. These measurements are useful for quality control and other purposes. Modern data loggers and office computers have quite high capacity. Diagnostic information indicating the state of solar chargers or battery voltages and their extremes is of great value. This topic will be discussed in greater detail in a succeeding section.

Automation also has made possible adaptive or intelligent monitoring techniques where systems vary the recording rate based on detection of the behavior of interest by the software. Sub-interval behavior of interest can be masked on occasion (e.g., a 5-minute extreme downpour with high-erosive capability hidden by an innocuous hourly total). Most users prefer measurements that are systematic in time because they are much easier to summarize and manipulate.

For breakpoint data produced by event reporters, there also is a need to send periodically a signal that the station is still functioning, even though there is nothing more to report. “No report” does not necessarily mean “no data,” and it is important to distinguish between the actual observation that was recorded and the content of that observation (e.g., an observation of “0.00” is not the same as “no observation”).

E.1.6. Mixed Time Scales

There are times when we may wish to combine information from radically different scales. For example, over the past 100 years we may want to know how the frequency of 5-minute precipitation peaks has varied or how the frequency of peak 1-second wind gusts have varied. We may also want to know over this time if nearby vegetation gradually has grown up to increasingly block the wind or to slowly improve precipitation catch. Answers to these questions require knowledge over a wide range of time scales.

E.1.7. Elements

For manual measurements, the typical elements recorded included temperature extremes, precipitation, and snowfall/snow depth. Automated measurements typically include temperature, precipitation, humidity, wind speed and direction, and solar radiation. An exception to this exists in very windy locations where precipitation is difficult to measure accurately. Automated measurements of snow are improving, but manual measurements are still preferable, as long as shielding is present. Automated measurement of frozen precipitation presents numerous challenges that have not been resolved fully, and the best gauges are quite expensive ($3–8K). Soil temperatures also are included sometimes. Soil moisture is extremely useful, but measurements are not made at many sites. In addition, care must be taken in the installation and maintenance of instruments used in measuring soil moisture. Soil properties vary tremendously in short distances as well, and it is often very difficult ("impossible") to accurately document these variations (without digging up all the soil!). In cooler climates, ultrasonic sensors that detect snow depth are becoming commonplace.

E.1.8. Wind Standards

Wind varies the most in the shortest distance, since it always decreases to zero near the ground and increases rapidly (approximately logarithmically) with height near the ground. Changes in anemometer height obviously will affect distribution of wind speed as will changes in vegetation, obstructions such as buildings, etc. A site that has a 3-m (10-ft) mast clearly will be less windy than a site that has a 6-m (20-ft) or 10-m (33-ft) mast. Historically, many U.S. airports (FAA and NWS) and most current RAWS sites have used a standard 6-m (20-ft) mast for wind measurements. Some NPS RAWS sites utilize shorter masts. Over the last decade, as Automated Surface Observing Systems (ASOSs, mostly NWS) and Automated Weather Observing Systems (AWOSs, mostly FAA) have been deployed at most airports, wind masts have been raised to 8 or 10 m (26 or 33 ft), depending on airplane clearance. The World Meteorological Organization recommends 10 m as the height for wind measurements (WMO 1983; 2005), and more groups are migrating slowly to this standard. The American Association of State Climatologists (AASC 1985) have recommended that wind be measured at 3 m, a standard geared more for agricultural applications than for general purpose uses where higher levels usually are preferred. Different anemometers have different starting thresholds; therefore, areas that frequently experience very light winds may not produce wind measurements thus affecting long-term mean estimates of wind speed. For both sustained winds (averages over a short interval of 2–60 minutes) and especially for gusts, the duration of the sampling interval makes considerable difference. For the same wind history, 1–second gusts are higher than gusts averaging 3 seconds, which in turn are greater than 5-second averages, so that the same sequence would be described with different numbers (all three systems and more are in use). Changes in the averaging procedure, or in height or exposure, can lead to "false" or "fake" climate change with no change in actual climate. Changes in any of these should be noted in the metadata.

E.1.9. Wind Nomenclature

Wind is a vector quantity having a direction and a speed. Directions can be two- or three-dimensional; they will be three-dimensional if the vertical component is important. In all common uses, winds always are denoted by the direction they blow *from* (north wind or southerly breeze). This convention exists because wind often brings weather, and thus our attention is focused upstream. However, this approach contrasts with the way ocean currents are viewed. Ocean currents usually are denoted by the direction they are moving *towards* (e.g. eastward current moves from west to east). In specialized applications (such as in atmospheric modeling), wind velocity vectors point in the direction that the wind is blowing. Thus, a southwesterly wind (from the southwest) has both northward and eastward (to the north and to the east) components. Except near mountains, wind cannot blow up or down near the ground, so the vertical component of wind often is approximated as zero, and the horizontal component is emphasized.

E.1.10. Frozen Precipitation

Frozen precipitation is more difficult to measure than liquid precipitation, especially with automated techniques. Goodison et al. (1998), Sevruk and Harmon (1984), and Yang et al. (1998; 2001) provide many of the reasons to explain this. The importance of frozen precipitation varies greatly from one setting to another. This subject was discussed in greater detail in a related inventory and monitoring report for the Alaska park units (Redmond et al. 2005).

In climates that receive frozen precipitation, a decision must be made whether or not to try to record such events accurately. This usually means that the precipitation must be turned into liquid either by falling into an antifreeze fluid solution that is then weighed or by heating the precipitation enough to melt and fall through a measuring mechanism such as a nearly-balanced tipping bucket. Accurate measurements from the first approach require expensive gauges; tipping buckets can achieve this resolution readily but are more apt to lose some or all precipitation. Improvements have been made to the heating mechanism on the NWS tipping-bucket gauge used for the ASOS to correct its numerous deficiencies making it less problematic; however, this gauge is not inexpensive. A heat supply needed to melt frozen precipitation usually requires more energy than renewable energy (solar panels or wind recharging) can provide thus AC power is needed. The availability of AC power is severely limited in many cold or remote U.S. settings. Furthermore, periods of frozen precipitation or rime often provide less-than-optimal recharging conditions with heavy clouds, short days, low-solar-elevation angles and more horizon blocking, and cold temperatures causing additional drain on the battery.

E.1.11. Save or Lose

A second consideration with precipitation is determining if the measurement should be saved (as in weighing systems) or lost (as in tipping-bucket systems). With tipping buckets, after the water has passed through the tipping mechanism, it usually just drops to the ground. Thus, there is no checksum to ensure that the sum of all the tips adds up to what has been saved in a reservoir at some location. By contrast, the weighing gauges continually accumulate until the reservoir is emptied, the reported value is the total reservoir content (for example, the height of the liquid column in a tube), and the incremental precipitation is the difference in depth between two known times. These weighing gauges do not always have the same fine resolution. Some gauges only record to the nearest centimeter, which is usually acceptable for hydrology but not necessarily for other needs. (For reference, a millimeter of precipitation can get a person in street clothes quite wet.) This is how the NRCS/USDA SNOTEL system works in climates that measure up to 3000 cm of snow in a winter. (See http://www.wcc.nrcs.usda.gov/publications for publications or http://www.wcc.nrcs.usda.gov/factpub/aib536.html for a specific description.) No precipitation is lost this way. A thin layer of oil is used to suppress evaporation, and anti-freeze ensures that frozen precipitation melts. When initially recharged, the sum of the oil and starting antifreeze solution is treated as the zero point. The anti-freeze usually is not sufficiently environmentally friendly to discharge to the ground and thus must be hauled into the area and then back out. Other weighing gauges are capable of measuring to the 0.25-mm (0.01-in.) resolution but do not have as much capacity and must be emptied more often. Day/night and storm-related thermal expansion and contraction and sometimes wind shaking can cause fluid pressure from accumulated totals to go up and down in SNOTEL gauges by small increments (commonly 0.3-3 cm, or 0.01–0.10 ft) leading to “negative precipitation” followed by similarly non-real light precipitation when, in fact, no change took place in the amount of accumulated precipitation.

E.1.12. Time

Time should always be in local standard time (LST), and daylight savings time (DST) should never be used under any circumstances with automated equipment and timers. Using DST leads to one duplicate hour, one missing hour, and a season of displaced values, as well as needless confusion and a data-management nightmare. Absolute time, such as Greenwich Mean Time (GMT) or Coordinated Universal Time (UTC), also can be used because these formats are unambiguously translatable. Since measurements only provide information about what already *has* occurred or *is* occurring and not what *will* occur, they should always be assigned to the *ending time* of the associated interval with hour 24 marking the end of the last hour of the day. In this system, midnight always represents the end of the day, not the start. To demonstrate the importance of this differentiation, we have encountered situations where police officers seeking corroborating weather data could not recall whether the time on their crime report from a year ago was the starting midnight or the ending midnight! Station positions should be known to within a few meters, easily accomplished with GPS, so that time zones and solar angles can be determined accurately.

E.1.13. Automated versus Manual

Most of this report has addressed automated measurements. Historically, most measurements are manual and typically collected once a day. In many cases, manual measurements continue because of habit, usefulness, and desire for continuity over time. Manual measurements are extremely useful and when possible should be encouraged. However, automated measurements are becoming more common. For either, it is important to record time in a logically consistent manner.

It should not be automatically assumed that newer data and measurements are "better" than older data or that manual data are "worse" than automated data. Older or simpler manual measurements are often of very high quality even if they sometimes are not in the most convenient digital format.

There is widespread desire to use automated systems to reduce human involvement. This is admirable and understandable, but every automated weather/climate station or network requires significant human attention and maintenance. A telling example concerns the Oklahoma Mesonet (see Brock et al. 1995, and bibliography at http://www.mesonet.ou.edu), a network of about 115 high–quality, automated meteorological stations spread over Oklahoma, where about 80 percent of the annual ($2–3M) budget is nonetheless allocated to humans with only about 20 percent allocated to equipment.

E.1.14. Manual Conventions

Manual measurements typically are made once a day. Elements usually consist of maximum and minimum temperature, temperature at observation time, precipitation, snowfall, snow depth, and sometimes evaporation, wind, or other information. Since it is not actually known when extremes occurred, the only logical approach, and the nationwide convention, is to ascribe the entire measurement to the time-interval date and to enter it on the form in that way. For morning observers (for example, 8 am to 8 am), this means that the maximum temperature written for today often is from yesterday afternoon and sometimes the minimum temperature for the 24-hr period actually occurred yesterday morning. However, this is understood and expected. It is often a surprise to observers to see how many maximum temperatures do not occur in the afternoon and how many minimum temperatures do not occur in the predawn hours. This is especially true in environments that are colder, higher, northerly, cloudy, mountainous, or coastal. As long as this convention is strictly followed every day, it has been shown that truly excellent climate records can result (Redmond 1992). Manual observers should reset equipment only one time per day at the official observing time. Making more than one measurement a day is discouraged strongly; this practice results in a hybrid record that is too difficult to interpret. The only exception is for total daily snowfall. New snowfall can be measured up to four times per day with no observations closer than six hours. It is well known that more frequent measurement of snow increases the annual total because compaction is a continuous process.

Two main purposes for climate observations are to establish the long-term averages for given locations and to track variations in climate. Broadly speaking, these purposes address topics of absolute and relative climate behavior. Once absolute behavior has been "established" (a task that is never finished because long-term averages continue to vary in time)—temporal variability quickly becomes the item of most interest.

E.2. Representativeness

Having discussed important factors to consider when new sites are installed, we now turn our attention to site "representativeness." In popular usage, we often encounter the notion that a site is "representative" of another site if it receives the same annual precipitation or records the same annual temperature or if some other element-specific, long-term average has a similar value. This notion of representativeness has a certain limited validity, but there are other aspects of this idea that need to be considered.

A climate monitoring site also can be said to be representative if climate records from that site show sufficiently strong temporal correlations with a large number of locations over a sufficiently large area. If station A receives 20 cm a year and station B receives 200 cm a year, these climates obviously receive quite differing amounts of precipitation. However, if their monthly, seasonal, or annual correlations are high (for example, 0.80 or higher for a particular time scale), one site can be used as a surrogate for estimating values at the other if measurements for a particular month, season, or year are missing. That is, a wet or dry month at one station is also a wet or dry month (relative to its own mean) at the comparison station. Note that high correlations on one time scale do not imply automatically that high correlations will occur on other time scales.

Likewise, two stations having similar mean climates (for example, similar annual precipitation) might not co-vary in close synchrony (for example, coastal versus interior). This may be considered a matter of climate "affiliation" for a particular location.

Thus, the representativeness of a site can refer either to the basic climatic averages for a given duration (or time window within the annual cycle) or to the extent that the site co-varies in time with respect to all surrounding locations. One site can be representative of another in the first sense but not the second, or vice versa, or neither, or both—all combinations are possible.

If two sites are perfectly correlated then, in a sense, they are "redundant." However, redundancy has value because all sites will experience missing data especially with automated equipment in rugged environments and harsh climates where outages and other problems nearly can be guaranteed. In many cases, those outages are caused by the weather, particularly by unusual weather and the very conditions we most wish to know about. Methods for filling in those values will require proxy information from this or other nearby networks. Thus, redundancy is a virtue rather than a vice.

In general, the cooperative stations managed by the NWS have produced much longer records than automated stations like RAWS or SNOTEL stations. The RAWS stations often have problems with precipitation, especially in winter, or with missing data, so that low correlations may be data problems rather than climatic dissimilarity. The RAWS records also are relatively short, so correlations should be interpreted with care. In performing and interpreting such analyses, however, we must remember that there are physical climate reasons and observational reasons why stations within a short distance (even a few tens or hundreds of meters) may not correlate well.

E.2.1. Temporal Behavior

It is possible that high correlations will occur between station pairs during certain portions of the year (i.e., January) but low correlations may occur during other portions of the year (e.g., September or October). The relative contributions of these seasons to the annual total (for precipitation) or average (for temperature) and the correlations for each month are both factors in the correlation of an aggregated time window of longer duration that encompasses those seasons (e.g., one of the year definitions such as calendar year or water year). A complete and careful evaluation ideally would include such a correlation analysis but requires more resources and data. Note that it also is possible and frequently is observed that temperatures are highly correlated while precipitation is not or vice versa, and these relations can change according to the time of year. If two stations are well correlated for all climate elements for all portions of the year, then they can be considered redundant.

With scarce resources, the initial strategy should be to try to identify locations that do not correlate particularly well, so that each new site measures something new that cannot be guessed easily from the behavior of surrounding sites. (An important caveat here is that lack of such correlation could be a result of physical climate behavior and not a result of faults with the actual measuring process; i.e., by unrepresentative or simply poor-quality data. Unfortunately, we seldom have perfect climate data.) As additional sites are added, we usually wish for some combination of unique and redundant sites to meet what amounts to essentially orthogonal constraints: new information and more reliably-furnished information.

A common consideration is whether to observe on a ridge or in a valley, given the resources to place a single station within a particular area of a few square kilometers. Ridge and valley stations will correlate very well for temperatures when lapse conditions prevail, particularly summer daytime temperatures. In summer at night or winter at daylight, the picture will be more mixed and correlations will be lower. In winter at night when inversions are common and even the rule, correlations may be zero or even negative and perhaps even more divergent as the two sites are on opposite sides of the inversion. If we had the luxury of locating stations everywhere, we would find that ridge tops generally correlate very well with other ridge tops and similarly valleys with other valleys, but ridge tops correlate well with valleys only under certain circumstances. Beyond this, valleys and ridges having similar orientations usually will correlate better with each other than those with perpendicular orientations, depending on their orientation with respect to large-scale wind flow and solar angles.

Unfortunately, we do not have stations everywhere, so we are forced to use the few comparisons that we have and include a large dose of intelligent reasoning, using what we have observed elsewhere. In performing and interpreting such analyses, we must remember that there are physical climatic reasons and observational reasons why stations within a short distance (even a few tens or hundreds of meters) may not correlate well.

Examples of correlation analyses include those for the Channel Islands and for southwest Alaska, which can be found in Redmond and McCurdy (2005) and Redmond et al. (2005). These examples illustrate what can be learned from correlation analyses. Spatial correlations generally vary by time of year. Thus, results should be displayed in the form of annual correlation cycles—for monthly mean temperature and monthly total precipitation and perhaps other climate elements like wind or humidity—between station pairs selected for climatic setting and data availability and quality.

In general, the COOP stations managed by the NWS have produced much longer records than have automated stations like RAWS or SNOTEL stations. The RAWS stations also often have problems with precipitation, especially in winter or with missing data, so that low correlations may be data problems rather than climate dissimilarity. The RAWS records are much shorter, so correlations should be interpreted with care, but these stations are more likely to be in places of interest for remote or under-sampled regions.

E.2.2. Spatial Behavior

A number of techniques exist to interpolate from isolated point values to a spatial domain. For example, a common technique is simple inverse distance weighting. Critical to the success of the simplest of such techniques is that some other property of the spatial domain, one that is influential for the mapped element, does not vary significantly. Topography greatly influences precipitation, temperature, wind, humidity, and most other meteorological elements. Thus, this criterion clearly is not met in any region having extreme topographic diversity. In such circumstances, simple Cartesian distance may have little to do with how rapidly correlation deteriorates from one site to the next, and in fact, the correlations can decrease readily from a mountain to a valley and then increase again on the next mountain. Such structure in the fields of spatial correlation is not seen in the relatively (statistically) well-behaved flat areas like those in the eastern United States.

To account for dominating effects such as topography and inland–coastal differences that exist in certain regions, some kind of additional knowledge must be brought to bear to produce meaningful, physically plausible, and observationally based interpolations. Historically, this has proven to be an extremely difficult problem, especially to perform objective and repeatable analyses. An analysis performed for southwest Alaska (Redmond et al. 2005) concluded that the PRISM (Parameter Regression on Independent Slopes Model) maps (Daly et al. 1994; 2002; Gibson et al. 2002; Doggett et al. 2004) were probably the best available. An analysis by Simpson et al. (2005) further discussed many issues in the mapping of Alaska's climate and resulted in the same conclusion about PRISM.

E.2.3. Climate-Change Detection

Although general purpose climate stations should be situated to address all aspects of climate variability, it is desirable that they also be in locations that are more sensitive to climate change from natural or anthropogenic influences should it begin to occur. The question here is how well we know such sensitivities. The polar regions and especially the North Pole are generally regarded as being more sensitive to changes in radiative forcing of climate because of positive feedbacks. The climate-change issue is quite complex because it encompasses more than just greenhouse gases.

Sites that are in locations or climates particularly vulnerable to climate change should be favored. How this vulnerability is determined is a considerably challenging research issue. Candidate locations or situations are those that lie on the border between two major biomes or just inside the edge of one or the other. In these cases, a slight movement of the boundary in anticipated direction (toward "warmer," for example) would be much easier to detect as the boundary moves past the site and a different set of biota begin to be established. Such a vegetative or ecologic response would be more visible and would take less time to establish as a real change than would a smaller change in the center of the distribution range of a marker or key species.

E.2.4. Element-Specific Differences

The various climate elements (temperature, precipitation, cloudiness, snowfall, humidity, wind speed and direction, solar radiation) do not vary through time in the same sequence or manner nor should they necessarily be expected to vary in this manner. The spatial patterns of variability should not be expected to be the same for all elements. These patterns also should not be expected to be similar for all months or seasons. The suitability of individual sites for measurement also varies from one element to another. A site that has a favorable exposure for temperature or wind may not have a favorable exposure for precipitation or snowfall. A site that experiences proper air movement may be situated in a topographic channel, such as a river valley or a pass, which restricts the range of wind directions and affects the distribution of speed-direction categories.

E.2.5. Logistics and Practical Factors

Even with the most advanced scientific rationale, sites in some remote or climatically challenging settings may not be suitable because of the difficulty in servicing and maintaining equipment. Contributing to these challenges are scheduling difficulties, animal behavior, snow burial, icing, snow behavior, access and logistical problems, and the weather itself. Remote and elevated sites usually require far more attention and expense than a rain-dominated, easily accessible valley location.

For climate purposes, station exposure and the local environment should be maintained in their original state (vegetation especially), so that changes seen are the result of regional climate variations and not of trees growing up, bushes crowding a site, surface albedo changing, fire clearing, etc. Repeat photography has shown many examples of slow environmental change in the vicinity of a station in rather short time frames (5–20 years), and this technique should be employed routinely and frequently at all locations. In the end, logistics, maintenance, and other practical factors almost always determine the success of weather- and climate-monitoring activities.

E.2.6. Personnel Factors

Many past experiences (almost exclusively negative) strongly support the necessity to place primary responsibility for station deployment and maintenance in the hands of seasoned, highly qualified, trained, and meticulously careful personnel, the more experienced the better. Over time, even in “benign” climates but especially where harsher conditions prevail, every conceivable problem will occur and both the usual and unusual should be anticipated: weather, animals, plants, salt, sensor and communication failure, windblown debris, corrosion, power failures, vibrations, avalanches, snow loading and creep, corruption of the data logger program, etc. An ability to anticipate and forestall such problems, a knack for innovation and improvisation, knowledge of electronics, practical and organizational skills, and presence of mind to bring the various small but vital parts, spares, tools, and diagnostic troubleshooting equipment are highly valued qualities. Especially when logistics are so expensive, a premium should be placed on using experienced personnel, since the slightest and seemingly most minor mistake can render a station useless or, even worse, uncertain. Exclusive reliance on individuals without this background can be costly and almost always will result eventually in unnecessary loss of data. Skilled labor and an apprenticeship system to develop new skilled labor will greatly reduce (but not eliminate) the types of problems that can occur in operating a climate network.

E.3. Site Selection

In addition to considerations identified previously in this appendix, various factors need to be considered in selecting sites for new or augmented instrumentation.

E.3.1. Equipment and Exposure Factors

E.3.1.1. Measurement Suite: All sites should measure temperature, humidity, wind, solar radiation, and snow depth. Precipitation measurements are more difficult but probably should be attempted with the understanding that winter measurements may be of limited or no value unless an all-weather gauge has been installed. Even if an all-weather gauge has been installed, it is desirable to have a second gauge present that operates on a different principle–for example, a fluid-based system like those used in the SNOTEL stations in tandem with a higher–resolution, tipping bucket gauge for summertime. Without heating, a tipping bucket gauge usually is of use only when temperatures are above freezing and when temperatures have not been below freezing for some time, so that accumulated ice and snow is not melting and being recorded as present precipitation. Gauge undercatch is a significant issue in snowy climates, so shielding should be considered for all gauges designed to work over the winter months. It is very important to note the presence or absence of shielding, the type of shielding, and the dates of installation or removal of the shielding.

E.3.1.2. Overall Exposure: The ideal, general all-purpose site has gentle slopes, is open to the sun and the wind, has a natural vegetative cover, avoids strong local (less than 200 m) influences, and represents a reasonable compromise among all climate elements. The best temperature sites are not the best precipitation sites, and the same is true for other elements. Steep topography in the immediate vicinity should be avoided unless settings where precipitation is affected by steep topography are being deliberately sought or a mountaintop or ridgeline is the desired location. The potential for disturbance should be considered: fire and flood risk, earth movement, wind-borne debris, volcanic deposits or lahars, vandalism, animal tampering, and general human encroachment are all factors.

E.3.1.3. Elevation: Mountain climates do not vary in time in exactly the same manner as adjoining valley climates. This concept is emphasized when temperature inversions are present to a greater degree and during precipitation when winds rise up the slopes at the same angle. There is considerable concern that mountain climates will be (or already are) changing and perhaps changing differently than lowland climates, which has direct and indirect consequences for plant and animal life in the more extreme zones. Elevations of special significance are those that are near the mean rain/snow line for winter, near the tree line, and near the mean annual freezing level (all of these may not be quite the same). Because the lapse rates in wet climates often are nearly moist-adiabatic during the main precipitation seasons, measurements at one elevation may be extrapolated to nearby elevations. In drier climates and in the winter, temperature and to a lesser extent wind will show various elevation profiles.

E.3.1.4. Transects: The concept of observing transects that span climatic gradients is sound. This is not always straightforward in topographically uneven terrain, but these transects could still be arranged by setting up station(s) along the coast; in or near passes atop the main coastal interior drainage divide; and inland at one, two, or three distances into the interior lowlands. Transects need not—and by dint of topographic constraints probably cannot—be straight lines, but the closer that a line can be approximated the better. The main point is to systematically sample the key points of a behavioral transition without deviating too radically from linearity.

E.3.1.5. Other Topographic Considerations: There are various considerations with respect to local topography. Local topography can influence wind (channeling, upslope/downslope, etc.), precipitation (orographic enhancement, downslope evaporation, catch efficiency, etc.), and temperature (frost pockets, hilltops, aspect, mixing or decoupling from the overlying atmosphere, bowls, radiative effects, etc.), to different degrees at differing scales. In general, for measurements to be areally representative, it is better to avoid these local effects to the extent that they can be identified before station deployment (once deployed, it is desirable not to move a station). The primary purpose of a climate-monitoring network should be to serve as an infrastructure in the form of a set of benchmark stations for comparing other stations. Sometimes, however, it is exactly these local phenomena that we want to capture. Living organisms, especially plants, are affected by their immediate environment, whether it is representative of a larger setting or not. Specific measurements of limited scope and duration made for these purposes then can be tied to the main benchmarks. This experience is useful also in determining the complexity needed in the benchmark monitoring process in order to capture particular phenomena at particular space and time scales.

Sites that drain (cold air) well generally are better than sites that allow cold air to pool. Slightly sloped areas (1 degree is fine) or small benches from tens to hundreds of meters above streams are often favorable locations. Furthermore, these sites often tend to be out of the path of hazards (like floods) and to have rocky outcroppings where controlling vegetation will not be a major concern. Benches or wide spots on the rise between two forks of a river system are often the only flat areas and sometimes jut out to give greater exposure to winds from more directions.

E.3.1.6. Prior History: The starting point in designing a program is to determine what kinds of observations have been collected over time, by whom, in what manner, and if these observation are continuing to the present time. It also may be of value to “re-occupy” the former site of a station that is now inactive to provide some measure of continuity or a reference point from the past. This can be of value even if continuous observations were not made during the entire intervening period.

E.3.2. Element-Specific Factors

E.3.2.1. Temperature: An open exposure with uninhibited air movement is the preferred setting. The most common measurement is made at approximately eye level, 1.5–2.0 m. In snowy locations sensors should be at least one meter higher than the deepest snowpack expected in the next 50 years or perhaps 2–3 times the depth of the average maximum annual depth. Sensors should be shielded above and below from solar radiation (bouncing off snow), from sunrise/sunset horizontal input, and from vertical rock faces. Sensors should be clamped tightly, so that they do not 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 it is best avoid these areas. Side slopes of perhaps a degree or two of angle facilitate air movement and drainage and, in effect, sample a large area during nighttime hours. The very bottom of a valley should be avoided. Temperature can change substantially from moves of only a few meters. Situations have been observed where flat and seemingly uniform conditions (like airport runways) appear to demonstrate different climate behaviors over short distances of a few tens or hundreds of meters (differences of 5–10°C). When snow is on the ground, these microclimatic differences can be stronger, and differences of 2–5°C can occur in the short distance between the thermometer and the snow surface on calm evenings.

E.3.2.2. Precipitation (liquid): Calm locations with vegetative or artificial shielding are preferred. Wind will adversely impact readings; therefore, the less the better. Wind effects on precipitation are far less for rain than for snow. Devices that "save" precipitation present advantages, but most gauges are built to dump precipitation as it falls or to empty periodically. Automated gauges give both the amount and the timing. Simple backups that record only the total precipitation since the last visit have a certain advantage (for example, storage gauges or lengths of PVC pipe perhaps with bladders on the bottom). The following question should be asked: Does the total precipitation from an automated gauge add up to the measured total in a simple bucket (evaporation is prevented with an appropriate substance such as mineral oil)? Drip from overhanging foliage and trees can augment precipitation totals.

E.3.2.3. Precipitation (frozen): Calm locations or shielding are a must. Undercatch for rain is only about 5 percent, but with winds of only 2–4 m/s, gauges may catch only 30–70 percent of the actual snow falling depending on density of the flakes. To catch 100 percent of the snow, the standard configuration for shielding is employed by the CRN (Climate Reference Network): the DFIR (Double-Fence Intercomparison Reference) shield with 2.4-m (8-ft.) vertical, wooden slatted fences in two concentric octagons with diameters of 8 m and 4 m (26 ft and 13 ft, respectively) and an inner Alter shield (flapping vanes). Numerous tests have shown this is the only way to achieve complete catch of snowfall (e.g., Yang et al. 1998; 2001). The DFIR shield is large and bulky; it is recommended that all precipitation gauges have at least Alter shields on them.

Near the ocean, much snow is heavy and falls more vertically. In colder locations or storms, light flakes frequently will fly in and then out of the gauge. Clearings in forests are usually excellent sites. Snow blowing from trees that are too close can augment actual precipitation totals. Artificial shielding (vanes, etc.) placed around gauges in snowy locales always should be used if accurate totals are desired. Moving parts tend to freeze up. Capping of gauges during heavy snowfall events is a common occurrence. When the cap becomes pointed, snow falls off to 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 during an extended period of freezing temperature or above or when sunlight finally occurs. Liquid-based measurements (e.g., SNOTEL "rocket" gauges) do not have the resolution (usually 0.3 cm [0.1 in.] rather than 0.03 cm [0.01 in.]) that tipping bucket and other gauges have but are known to be reasonably accurate in very snowy climates. Light snowfall events might not be recorded until enough of them add up to the next reporting increment. More expensive gauges like Geonors can be considered and could do quite well in snowy settings; however, they need to be emptied every 40 cm (15 in.) or so (capacity of 51 cm [20 in.]) until the new 91-cm (36-in.) capacity gauge is offered for sale. Recently, the NWS has been trying out the new (and very expensive) Ott all-weather gauge. Riming can be an issue in windy foggy environments below freezing. Rime, dew, and other forms of atmospheric condensation are not real precipitation, since they are caused by the gauge.

E.3.2.4. Snow Depth: Windswept areas tend to be blown clear of snow. Conversely, certain types of vegetation can act as a snow fence and cause artificial drifts. However, some amount of vegetation in the vicinity generally can help slow down the wind. The two most common types of snow-depth gauges are the Judd Snow Depth Sensor, produced by Judd Communications, and the snow depth gauge produced by Campbell Scientific, Inc. Opinions vary on which one is better. These gauges use ultrasound and look downward in a cone about 22 degrees in diameter. The ground should be relatively clear of vegetation and maintained in a manner so that the zero point on the calibration scale does not change.

E.3.2.5. Snow Water Equivalent: This is determined by the weight of snow on fluid-filled pads about the size of a desktop set up sometimes in groups of four or in larger hexagons several meters in diameter. These pads require flat ground some distance from nearby sources of windblown snow and shielding that is "just right": not too close to the shielding to act as a kind of snow fence and not too far from the shielding so that blowing and drifting become a factor. Generally, these pads require fluids that possess antifreeze-like properties, as well as handling and replacement protocols.

E.3.2.6. Wind: Open exposures are needed for wind measurements. Small prominences or benches without blockage from certain sectors are preferred. A typical rule for trees is to site stations 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 topographic steering should be avoided to the extent possible. Avoiding major mountain chains or single isolated mountains or ridges is usually a favorable approach, if there is a choice. Sustained wind speed and the 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 with all 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 m) 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 made by Taylor, are worth considering. These anemometers are expensive but durable and can withstand substantial abuse. In exposed locations, personnel should plan for winds to be at least 50 m/s and be able to measure these wind speeds. At a minimum, anemometers should be rated to 75 m/s.

E.3.2.7. Humidity: Humidity is a relatively straightforward climate element. Close proximity to lakes or other water features can affect readings. Humidity readings typically are less accurate near 100 percent and at low humidities in cold weather.

E.3.2.8. Solar Radiation: A site with an unobstructed horizon obviously is the most desirable. This generally implies a flat plateau or summit. However, in most locations trees or mountains will obstruct the sun for part of the day.

E.3.2.9. Soil Temperature: It is desirable to measure soil temperature at locations where soil is present. If soil temperature is recorded at only a single depth, the most preferred depth is 10 cm. Other common depths include 25 cm, 50 cm, 2 cm, and 100 cm. Biological activity in the soil will be proportional to temperature with important threshold effects occurring near freezing.

E.3.2.10. Soil Moisture: Soil-moisture gauges are somewhat temperamental and require care to install. The soil should be characterized by a soil expert during installation of the gauge. The readings may require a certain level of experience to interpret correctly. If accurate, readings of soil moisture are especially useful.

E.3.2.11. Distributed Observations: It can be seen readily that compromises must be struck among the considerations described in the preceding paragraphs because some are mutually exclusive.

How large can a "site" be? Generally, the equipment footprint should be kept as small as practical with all components placed next to each other (within less than 10–20 m or so). Readings from one instrument frequently are used to aid in interpreting readings from the remaining instruments.

What is a tolerable degree of separation? Some consideration may be given to locating a precipitation gauge or snow pillow among protective vegetation, while the associated temperature, wind, and humidity readings would be collected more effectively in an open and exposed location within 20–50 m. Ideally, it is advantageous to know the wind measurement precisely at the precipitation gauge, but a compromise involving a short split, and in effect a "distributed observation," could be considered. There are no definitive rules governing this decision, but it is suggested that the site footprint be kept within approximately 50 m. There also are constraints imposed by engineering and electrical factors that affect cable lengths, signal strength, and line noise; therefore, the shorter the cable the better. Practical issues include the need to trench a channel to outlying instruments or to allow lines to lie atop the ground and associated problems with animals, humans, weathering, etc. Separating a precipitation gauge up to 100 m or so from an instrument mast may be an acceptable compromise if other factors are not limiting.

E.3.2.12. Instrument Replacement Schedules: Instruments slowly degrade, and a plan for replacing them with new, refurbished, or recalibrated instruments should be in place. After approximately five years, a systematic change-out procedure should result in replacing most sensors in a network. Certain parts, such as solar radiation sensors, are candidates for annual calibration or change-out. Anemometers tend to degrade as bearings erode or electrical contacts become uneven. Noisy bearings are an indication, and a stethoscope might aid in hearing such noises. Increased internal friction affects the threshold starting speed; once spinning, they tend to function properly. Increases in starting threshold speeds can lead to more zero-wind measurements and thus reduce the reported mean wind speed with no real change in wind properties. A field calibration kit should be developed and taken on all site visits, routine or otherwise. Rain gauges can be tested with drip testers during field visits. Protective conduit and tight water seals can prevent abrasion and moisture problems with the equipment, although seals can keep moisture in as well as out. Bulletproof casings sometimes are 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 to allow replacement of worn or nonfunctional instruments during field visits. In addition, this approach allows instruments to be calibrated in the relative convenience of the operational home—the larger the network, the greater the need for a parts depot.

E.3.3. Long-Term Comparability and Consistency

E.3.3.1. Consistency: The emphasis here is to hold biases constant. Every site has biases, problems, and idiosyncrasies of one sort or another. The best rule to follow is simply to try to keep biases constant through time. Since the goal is to track climate through time, keeping sensors, methodologies, and exposure constant will ensure that only true climate change is being measured. This means leaving the site in its original state 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 meters or to allow significant changes to occur within 100 m for the next several decades.

Sites in or near rock outcroppings likely will experience less vegetative disturbance or growth through the years and will not usually retain moisture, a factor that could speed corrosion. Sites that will remain locally similar for some time are usually preferable. However, in some cases the intent of a station might be to record the local climate effects of changes within a small-scale system (for example, glacier, recently burned area, or scene of some other disturbance) that is subject to a regional climate influence. In this example, the local changes might be much larger than the regional changes.

E.3.3.2. Metadata: Since the climate of every site is affected by features in the immediate vicinity, it is vital to record this information over time and to update the record repeatedly at 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 one–two years.

Photographic documentation should be taken at each site in a standard manner and repeated every two–three years. Guidelines for methodology were developed by Redmond (2004) as a result of experience with the NOAA CRN and can be found on the WRCC NPS Web pages at http://www.wrcc.dri.edu/nps and at ftp://ftp.wrcc.dri.edu/nps/photodocumentation.pdf.

The main purpose for climate stations is to *track climatic conditions through time*. Anything that affects the interpretation of records through time must to be noted and recorded for posterity. The important factors should be clear to a person who has never visited the site, no matter how long ago the site was installed.

In regions with significant, climatic transition zones, transects are an efficient way to span several climates and make use of available resources. Discussions on this topic at greater detail can be found in Redmond and Simeral (2004) and in Redmond et al. (2005).

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Appendix F. Descriptions of weather/climate-monitoring networks.

F.1. USDA/USFS Avalanche Network (Avalanche)

- Purpose of network: provide weather data for monitoring of avalanche conditions in mountainous areas of the U.S.
- Data website: http://www.met.utah.edu/jhorel/html/mesonet.
- Measured weather/climate elements:
  - Air temperature.
  - Relative humidity and dewpoint temperature.
  - Precipitation.
  - Wind speed and direction.
- Sampling frequency: hourly.
- Reporting frequency: hourly.
- Estimated station cost: unknown.
- Network strengths:
  - Data are in near-real-time.
  - Sites are located in areas that traditionally have sparse weather and climate station coverage.
- Network weaknesses:
  - Station operation can be seasonal (e.g. winter).
  - Data are sometimes of questionable quality.

The USFS administers a collection of weather stations run by various state- and local-level avalanche centers throughout the western U.S. and around the Mt. Washington area in New Hampshire.

F.2. Clean Air Status and Trends Network (CASTNet)

- Purpose of network: provide information for evaluating the effectiveness of national emission-control strategies.
- Primary management agency: EPA.
- Data website: http://epa.gov/castnet/.
- Measured weather/climate elements:
  - Air temperature.
  - Precipitation.
  - Relative humidity.
  - Wind speed.
  - Wind direction.
  - Wind gust.
  - Gust direction.
  - Solar radiation.
  - Soil moisture and temperature.
- Sampling frequency: hourly.
- Reporting frequency: hourly.

- Estimated station cost: $13K.
- Network strengths:
  - High-quality data.
  - Sites are well-maintained.
- Network weaknesses:
  - Density of station coverage is low.
  - Shorter periods of record for western United States.

CASTNet primarily is an air-quality-monitoring network managed by the EPA. The elements shown here are intended to support interpretation of measured air-quality parameters such as ozone, nitrates, sulfides, etc., which also are measured at CASTNet sites.

F.3. Community Environmental Monitoring Program (CEMP)

- Purpose of network: monitor airborne levels of manmade radioactivity from activities at the Nevada Test Site.
- Primary management agencies: WRCC and Desert Research Institute.
- Data website: http://www.wrcc.dri.edu.
- Measured weather/climate elements:
  - Air temperature.
  - Precipitation.
  - Relative humidity and dewpoint temperature.
  - Wind speed and direction.
  - Barometric Pressure.
  - Solar radiation.
- Sampling frequency: hourly.
- Reporting frequency: hourly.
- Estimated station cost: $50K for installation ($20K in equipment; $30K in construction of station). Maintenance costs are site-dependent and vary widely.
- Network strengths:
  - High-quality data and metadata.
  - Sites are well-maintained.
- Network weaknesses:
  - Density of station coverage is low.
  - Network has relatively small geographical extent (Nevada and its immediate surroundings).
  - Sites are expensive to operate.

The CEMP network has 26 monitoring stations in areas surrounding the Nevada Test Site. CEMP is a joint effort of the Nevada Operations office of the Department of Energy and the Desert Research Institute.

F.4. NWS Cooperative Observer Program (COOP)

- Purpose of network:
  - Provide observational, meteorological data required to define U.S. climate and help measure long-term climate changes.

  - Provide observational, meteorological data in near real-time to support forecasting and warning mechanisms and other public service programs of the NWS.
- Primary management agency: NOAA (NWS).
- Data website: data are available from the NCDC (http://www.ncdc.noaa.gov), RCCs (e.g., WRCC, http://www.wrcc.dri.edu), and state climate offices.
- Measured weather/climate elements
  - Maximum, minimum, and observation-time temperature.
  - Precipitation, snowfall, snow depth.
  - Pan evaporation (some stations).
- Sampling frequency: daily.
- Reporting frequency: daily or monthly (station-dependent).
- Estimated station cost: $2K with maintenance costs of $500–900/year.
- Network strengths:
  - Decade–century records at most sites.
  - Widespread national coverage (thousands of stations).
  - Excellent data quality when well-maintained.
  - Relatively inexpensive; highly cost effective.
  - Manual measurements; not automated.
- Network weaknesses:
  - Uneven exposures; many are not well-maintained.
  - Dependence on schedules for volunteer observers.
  - Slow entry of data from many stations into national archives.
  - Data subject to observational methodology; not always documented.
  - Manual measurements; not automated and not hourly.

The COOP network has long served as the main climate observation network in the United States. Readings are usually made by volunteers using equipment supplied, installed, and maintained by the federal government. The observer in effect acts as a host for the data-gathering activities and supplies the labor; this is truly a "cooperative" effort. The SAO sites often are considered to be part of the cooperative network as well if they collect the previously mentioned types of weather/climate observations. Typical observation days are morning to morning, evening to evening, or midnight to midnight. By convention, observations are ascribed to the date the instrument was reset at the end of the observational period. For this reason, midnight observations represent the end of a day. The Historical Climate Network is a subset of the cooperative network but contains longer and more complete records.

F.5. NOAA Climate Reference Network (CRN)

- Purpose of network: provide long-term homogeneous measurements of temperature and precipitation that can be coupled with long-term historic observations to monitor present and future climate change.
- Primary management agency: NOAA.
- Data website: http://www.ncdc.noaa.gov/crn/.
- Measured weather/climate elements:
  - Air temperature (triply redundant, aspirated).
  - Precipitation (three-wire Geonor gauge).

- Wind speed.
- Solar radiation.
- Ground surface temperature.

- Sampling frequency: precipitation can be sampled either 5 or 15 minutes. Temperature sampled every 5 minutes. All other elements sampled every 15 minutes.
- Reporting frequency: hourly or every three hours.
- Estimated station cost: $30K with maintenance costs around $2K/year.
- Network strengths:
  - Station siting is excellent (appropriate for long-term climate monitoring).
  - Data quality is excellent.
  - Site maintenance is excellent.
- Network weaknesses:
  - CRN network is still developing.
  - Period of record is short compared to other automated networks. Earliest sites date from 2004.
  - Station coverage is limited.
  - Not intended for snowy climates.

Data from the CRN are used in operational climate-monitoring activities and are used to place current climate patterns into a historic perspective. The CRN is intended as a reference network for the United States that meets the requirements of the Global Climate Observing System. Up to 115 CRN sites are planned for installation, but the actual number of installed sites will depend on available funding.

F.6. Portable Ozone Monitoring System (POMS)

- Purpose of network: provide seasonal, short-term (1-5 years) monitoring of near-surface atmospheric ozone levels in remote locations.
- Primary management agency: NPS.
- Data website: http://www2.nature.nps.gov/air/studies/portO3.htm.
- Measured weather/climate elements:
  - Air temperature.
  - Precipitation.
  - Relative Humidity
  - Wind speed and direction.
  - Solar radiation.
- Sampling frequency: hourly.
- Reporting frequency: hourly.
- Estimated station cost: $20K with operation and maintenance costs of up to $10K/year.
- Network strengths:
  - High-quality data.
  - Site maintenance is excellent.
- Network weaknesses:
  - No long-term sites, so not as useful for climate monitoring.
  - Sites are somewhat expensive to operate.

The POMS network of stations is owned and operated by the NPS Air Resources Division. Since the primarily role of the network is ozone monitoring, weather observations are a secondary objective.

F.7. Remote Automated Weather Station (RAWS)

- Purpose of network: provide near-real-time (hourly or near hourly) measurements of meteorological variables for use in fire weather forecasts and climatology. Data from RAWS also are used for natural resource management, flood forecasting, natural hazard management, and air-quality monitoring.
- Primary management agency: WRCC, National Interagency Fire Center.
- Data website: http://www.raws.dri.edu/index.html.
- Measured weather/climate elements:
  - Air temperature.
  - Precipitation.
  - Relative humidity.
  - Wind speed.
  - Wind direction.
  - Wind gust.
  - Gust direction.
  - Solar radiation.
  - Soil moisture and temperature.
- Sampling frequency: 1 or 10 minutes, element-dependent.
- Reporting frequency: generally hourly. Some stations report every 15 or 30 minutes.
- Estimated station cost: $12K with satellite telemetry ($8K without satellite telemetry); maintenance costs are around $2K/year.
- Network strengths:
  - Metadata records are usually complete.
  - Sites are located in remote areas.
  - Sites are generally well-maintained.
  - Entire period of record available on-line.
- Network weaknesses:
  - RAWS network is focused largely on fire management needs (formerly focused only on fire needs).
  - Frozen precipitation is not measured reliably.
  - Station operation is not always continuous.
  - Data transmission is completed via one-way telemetry. Data are therefore recoverable either in real-time or not at all.

The RAWS network is used by many land-management agencies, such as the BLM, NPS, Fish and Wildlife Service, Bureau of Indian Affairs, Forest Service, and other agencies. The RAWS network was one of the first automated weather station networks to be installed in the United States. Most gauges do not have heaters, so hydrologic measurements are of little value when temperatures dip below freezing or reach freezing after frozen precipitation events. There are approximately 1,100 real-time sites in this network and about 1,800 historic sites (some are decommissioned or moved). The sites can transmit data all winter but may be in deep snow in some locations. The WRCC is the archive for this network and receives station data and metadata through a special connection to the National Interagency Fire Center in Boise, Idaho.

F.8. NWS Surface Airways Observation Program (SAO)

- Purpose of network: provide near-real-time (hourly or near hourly) measurements of meteorological variables and are used both for airport operations and weather forecasting.
- Primary management agency: NOAA, FAA.
- Data website: data are available from state climate offices, RCCs (e.g., WRCC, http://www.wrcc.dri.edu), and NCDC (http://www.ncdc.noaa.gov).
- Measured weather/climate elements:
  - Air temperature.
  - Dewpoint and/or relative humidity.
  - Wind speed.
  - Wind direction.
  - Wind gust.
  - Gust direction.
  - Barometric pressure.
  - Precipitation (not at many FAA sites).
  - Sky cover.
  - Ceiling (cloud height).
  - Visibility.
- Sampling frequency: element-dependent.
- Reporting frequency: element-dependent.
- Estimated station cost: $100–$200K with maintenance costs approximately $10K/year.
- Network strengths:
  - Records generally extend over several decades.
  - Consistent maintenance and station operations.
  - Data record is reasonably complete and usually high quality.
  - Hourly or sub-hourly data.
- Network weaknesses:
  - Nearly all sites are located at airports.
  - Data quality can be related to size of airport—smaller airports tend to have poorer datasets.
  - Influences from urbanization and other land-use changes.

These stations are managed by NOAA, U. S. Navy, U. S. Air Force, and FAA. These stations are located generally at major airports and military bases. The FAA stations often do not record precipitation, or they may provide precipitation records of reduced quality. Automated stations are typically ASOSs for the NWS or AWOSs for the FAA. Some sites only report episodically with observers paid per observation.

F.9. USDA/NRCS Snowfall Telemetry (SNOTEL) network

- Purpose of network: collect snowpack and related climate data to assist in forecasting water supply in the western United States.
- Primary management agency: NRCS.

- Data website: http://www.wcc.nrcs.usda.gov/snow/.
- Measured weather/climate elements:
  - Air temperature.
  - Precipitation.
  - Snow water content.
  - Snow depth.
  - Relative humidity (enhanced sites only).
  - Wind speed (enhanced sites only).
  - Wind direction (enhanced sites only).
  - Solar radiation (enhanced sites only).
  - Soil moisture and temperature (enhanced sites only).
- Sampling frequency: 1-minute temperature; 1-hour precipitation, snow water content, and snow depth. Less than one minute for relative humidity, wind speed and direction, solar radiation, and soil moisture and temperature (all at enhanced site configurations only).
- Reporting frequency: reporting intervals are user-selectable. Commonly used intervals are every one, two, three, or six hours.
- Estimated station cost: $20K with maintenance costs approximately $2K/year.
- Network strengths:
  - Sites are located in high-altitude areas that typically do not have other weather or climate stations.
  - Data are of high quality and are largely complete.
  - Very reliable automated system.
- Network weaknesses:
  - Historically limited number of elements.
  - Remote so data gaps can be long.
  - Metadata sparse and not high quality; site histories are lacking.
  - Measurement and reporting frequencies vary.
  - Many hundreds of mountain ranges still not sampled.
  - Earliest stations were installed in the late 1970s; temperatures have only been recorded since the 1980s.

USDA/NRCS maintains a set of automated snow-monitoring stations known as the SNOTEL (snowfall telemetry) network. These stations are designed specifically for cold and snowy locations. Precipitation and snow water content measurements are intended for hydrologic applications and water-supply forecasting, so these measurements are measured generally to within 2.5 mm (0.1 in.). Snow depth is tracked to the nearest 25 mm, or one inch. These stations function year around.

F.10. USDA/NRCS Snowcourse Network (NRCS-SC)

- Purpose of network: collect snowpack and related climate data to assist in forecasting water supply in the western United States.
- Primary management agency: NRCS.
- Data website: http://www.wcc.nrcs.usda.gov/snowcourse/.
- Measured weather/climate elements:
  - Snow depth.
  - Snow water equivalent.

- Measurement, reporting frequency: monthly or seasonally.
- Estimated station cost: cost of man-hours needed to set up snowcourse and make measurements.
- Network strengths
  - Periods of record are generally long.
  - Large number of high-altitude sites.
- Network weaknesses
  - Measurement and reporting only occurs on monthly to seasonal basis.
  - Few weather/climate elements are measured.

USDA/NRCS maintains another network of snow-monitoring stations in addition to SNOTEL. These sites are known as snowcourses. Many of these sites have been in operation since the early part of the twentieth century. These are all manual sites where only snow depth and snow water content are measured.

Appendix G. Electronic supplements.

G.1. ACIS metadata file for weather and climate stations associated with the NCPN: http://www.wrcc.dri.edu/nps/pub/ncpn/metadata/NCPN_from_ACIS.tar.gz.

G.2. NCPN metadata files for weather and climate stations associated with the NCPN: http://www.wrcc.dri.edu/nps/pub/ncpn/metadata/NCPN.mdb.

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