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Weather and Climate Inventory
National Park Service
Sonoran Desert Network

Natural Resource Technical Report NPS/SODN/NRTR—2007/044

ON THE COVER
Weather station at Chiricahua National Monument
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Natural Resource Technical Report NPS/SODN/NRTR—2007/044
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Acronyms

AASC	American Association of State Climatologists
ACIS	Applied Climate Information System
ASOS	Automated Surface Observing System
AWOS	Automated Weather Observing System
ALERT	Automated Local Evaluation in Real Time
AZ ALERT	The Arizona ALERT network
AZMET	The Arizona Meteorological Network
BLM	Bureau of Land Management
CAGR	Casa Grande Ruins National Monument
CASTNet	Clean Air Status and Trends Network
CHIR	Chiricahua National Monument
COOP	Cooperative Observer Program
CORO	Coronado National Memorial
CRBFC	Colorado River Basin Forecast Center
CRN	Climate Reference Network
CWOP	Citizen Weather Observer Program
DFIR	Double-Fence Intercomparison Reference
DST	daylight savings time
ENSO	El Niño Southern Oscillation
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FIPS	Federal Information Processing Standards
FOBO	Fort Bowie National Historic Site
GICL	Gila Cliff Dwellings National Monument
GMT	Greenwich Mean Time
GOES	Geostationary Operational Environmental Satellite
GPMP	NPS Gaseous Pollutant Monitoring Program
GPS	Global Positioning System
GPS-MET	NOAA ground-based GPS meteorology
I&M	NPS Inventory and Monitoring Program
LEO	Low Earth Orbit
LST	local standard time
MDN	Mercury Deposition Network
MEXICO	Mexico weather/climate stations
MOCA	Montezuma Castle National Monument
NADP	National Atmospheric Deposition Program
NAMS	North American Monsoon System
NASA	National Aeronautics and Space Administration
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	NRCS snowcourse network

NWS	National Weather Service
ORPI	Organ Pipe Cactus National Monument
PDO	Pacific Decadal Oscillation
PRISM	Parameter Regression on Independent Slopes Model
RAWS	Remote Automated Weather Station network
RCC	regional climate center
SAGU	Saguaro National Park
SAO	Surface Airways Observation network
SOD	Summary Of the Day
SODN	Sonoran Desert Inventory and Monitoring Network
Surfrad	Surface Radiation Budget network
SNOTEL	Snowfall Telemetry network
TONT	Tonto National Monument
TUMA	Tumacacori National Historical Park
TUZI	Tuzigoot National Monument
UCC	Utah Climate Center
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
WX4U	Weather For You network

Executive Summary

Climate is a dominant factor driving the physical and ecologic processes affecting the Sonoran Desert Inventory and Monitoring Network (SODN). The climate of the SODN is characterized by little precipitation along with temperature extremes. Winter temperatures are generally mild and summers are quite hot across the SODN. The SODN exhibits a unique bimodal precipitation regime and steep topographic gradients, which in turn supports a high level of biological diversity. Precipitation typically increases dramatically with elevation in the SODN, due to the orographic effects of the Sonoran Desert "sky islands." Both El Niño Southern Oscillation (ENSO) variations and passages of tropical storm remnants influence interannual climate variations in the SODN, particularly regarding precipitation. The potential impacts of climate change in the SODN to sensitive ecosystems, endemic species, and threatened or endangered species are of particular concern. Because of its influence on the ecology of SODN park units and the surrounding areas, climate was identified as a high-priority vital sign for SODN and is one of the 12 basic inventories to be completed for all National Park Service (NPS) Inventory and Monitoring Program (I&M) networks.

This project was initiated to inventory past and present climate monitoring efforts in the SODN. In this report, we provide the following information:

- Overview of broad-scale climatic factors and zones important to SODN park units.
- Inventory of weather and climate station locations in and near SODN park units relevant to the NPS I&M Program.
- 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.

Mean annual precipitation in the SODN park units ranges from under 300 mm in Organ Pipe Cactus National Monument (ORPI) to almost 750 mm in southeastern Arizona park units like Chiricahua National Monument (CHIR) and Saguaro National Park (SAGU). This precipitation generally falls in the form of rain, with some snow during the winter months at the higher-elevations. Much of the precipitation throughout eastern SODN is associated with the summer monsoon. Mean annual temperatures in the SODN range from around 10°C at Gila Cliff Dwellings National Monument (GICL) to over 20°C in western portions of ORPI. Summer temperatures are quite high, regularly exceeding 40°C at lower elevations. Events in the tropical Pacific and northern Pacific Ocean are linked to variations in temperature and precipitation across the SODN. During El Niño events, the SODN generally receives above-normal precipitation due to the dominant winter storm track being shifted further south than in an average winter. The frequency and intensity of ENSO events could increase dramatically in upcoming years in response to projected climate changes. Precipitation shows no obvious trend over time, but temperatures in the SODN have become warmer, especially in the last few decades. This signal is most noticeable in northern SODN.

Through a search of national databases and inquiries to NPS staff, we identified 39 weather and climate stations within SODN park units. The most stations within park boundaries were found in ORPI (14). Most weather and climate stations identified for SODN park units had metadata and data records that are sufficiently complete and satisfactory in quality.

Much of the desert environment around SODN park units has little or no weather or climate station coverage, particularly for those units that are not near major cities such as Phoenix and Tucson. For example, we only identified six stations within 40 km of the boundaries of ORPI. Fortunately, ORPI has an active network of weather stations within its boundaries, providing valuable weather data across the desert landscape of ORPI.

Many of the SODN park units are quite small and must therefore rely heavily on outside sources of weather and climate data. This is particularly true for near-real-time data. Two park units, Fort Bowie National Historic Site (FOBO) and Tonto National Monument (TONT), have no weather or climate stations within their boundaries. There are no near-real-time stations within 15 km of FOBO. If near-real-time weather data is desired from FOBO, the park unit could consider working with local agencies to install a RAWS (Remote Automated Weather Station) site, as the RAWS network already has a notable presence in the area. Due to the relatively close proximity of CHIR and FOBO to each other, FOBO can also rely on stations identified in and near CHIR for its weather and climate data. Casa Grande Ruins National Monument (CAGR) and SAGU are located near more urban settings (CAGR – southeast Phoenix/Mesa; SAGU – Tucson) and can take advantage of weather and climate data provided by numerous stations in these areas.

Despite the limited station coverage in and around many SODN park units, many of these same park units have at least one reliable long-term climate station located within their boundaries. This situation is very helpful in meeting the SODN climate monitoring objective of documenting long-term trends in temperature and precipitation. Other climate monitoring objectives of the SODN include better documentation of spatial weather and climate variations, particularly at local scales with respect to topographical variations in and around SODN park units. Some park units, such as ORPI and the eastern unit of SAGU, are already actively establishing weather station networks to help meet this objective. However, other larger park units in the SODN, such as the western unit of SAGU, are still lacking sufficient station coverage to begin addressing spatial weather and climate characteristics. We identified no near-real-time stations within the western unit of SAGU. The closest automated data for this unit comes from the CRN (Climate Reference Network) station “Tucson 11 W.” Although observations from this site are probably sufficient at the present time to document overall near-real-time conditions within the western unit of SAGU, additional weather stations would be needed to better understand local-scale characteristics such as the spatial distribution of precipitation during convective storms in the summer monsoon season. Expansion of the NPS-operated networks of weather stations such as those already in place in ORPI and eastern SAGU could help address this issue.

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1.0. Introduction

Weather and climate are key drivers in ecosystem structure and function. Global- and regional-scale climate variations will have a tremendous impact on natural systems (Chapin et al. 1996; Schlesinger 1997; Jacobson et al. 2000; Bonan 2002). Proper understanding of ecosystem dynamics requires an understanding of the roles of climate variability, hydrologic interactions with soils, and adaptive strategies of biota to capitalize on spatially and temporally variable moisture dynamics (Noy-Meir 1973; Bailey 1995; Rodriguez-Iturbe 2000; Reynolds et al. 2004). Long-term patterns in temperature and precipitation provide first-order constraints on potential ecosystem structure and function. Secondary constraints are realized from the intensity and duration of individual weather events and, additionally, from seasonality and inter-annual climate variability. These constraints influence the fundamental properties of ecologic systems, such as soil–water relationships, plant–soil processes, and nutrient cycling, as well as disturbance rates and intensity. These properties, in turn, influence the life-history strategies supported by a climatic regime (Neilson 1987; Mau-Crimmins et al. 2005).

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 climatic conditions.

It is essential that park units within the Sonoran Desert Inventory and Monitoring Network (SODN) have an effective climate-monitoring system in place to track climate changes and to aid in management decisions relating to these changes. The purpose of this report is to determine the current status of weather and climate monitoring within the SODN (Table 1.1; Figure 1.1). In this report, we provide the following informational elements:

- Overview of broad-scale climatic factors and zones important to SODN park units.
- Inventory of locations for all weather stations in and near SODN park units that are relevant to the NPS I&M networks.
- 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.

The primary objectives for climate- and weather-monitoring activities in SODN are as follows (Mau-Crimmins et al. 2005):

A. Determine long-term trends in temperature, precipitation, and synthetic variables (potential evapotranspiration, drought indices, etc) in the Sonoran Desert region.
B. Determine how broad-scale climate is related to other vital signs.

C. Evaluate spatial and temporal trends in temperature, precipitation, wind speed, wind direction, relative humidity, snow depth, and variables appropriate for understanding other vital signs in SODN park units.
D. Determine how local weather conditions influence biotic and abiotic processes (e.g., leaf-out, flowering, invasion by nonnative species, fire threat).
E. Determine how climatic variables vary over complex topography within the scale of a park unit.

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 A for a full definition of these terms.

Table 1.1. Park units in the Sonoran Desert Network.

Acronym	Name
CAGR	Casa Grande Ruins National Monument
CHIR	Chiricahua National Monument
CORO	Coronado National Memorial
FOBO	Fort Bowie National Historic Site
GICL	Gila Cliff Dwellings National Monument
MOCA	Montezuma Castle National Monument
ORPI	Organ Pipe Cactus National Monument
SAGU	Saguaro National Park
TONT	Tonto National Monument
TUMA	Tumacacori National Historical Park
TUZI	Tuzigoot National Monument

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 additional inventory data and station-tracking procedures. Some national weather and 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 (RAWS) network 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 or 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.

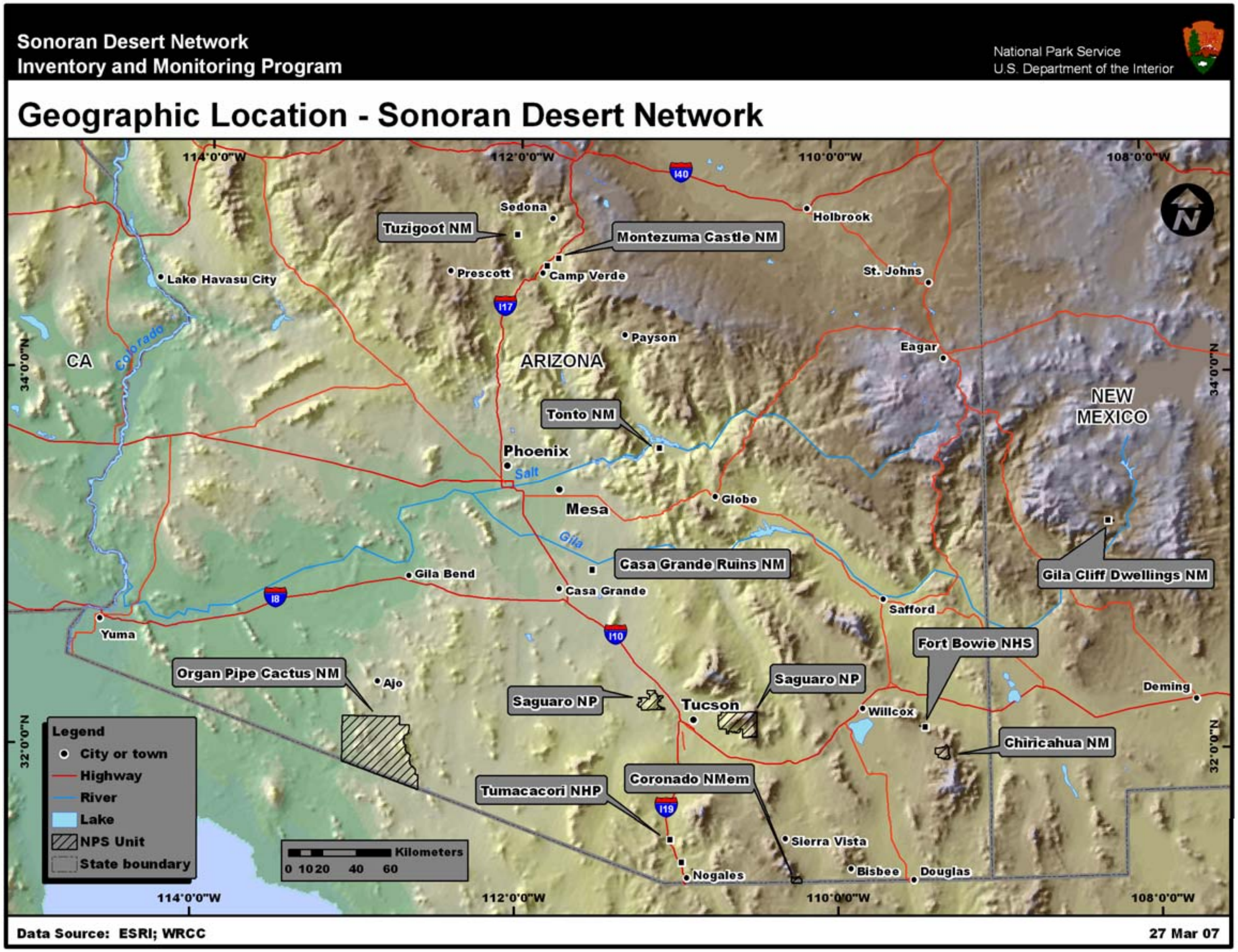


Figure 1.1. Map of the Sonoran Desert Network.

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 station networks, however, are intended for long-term tracking of atmospheric conditions. Siting and exposure are critical factors for climate networks. 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 and 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 A). 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 and 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 and 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 and climate stations suitable for the monitoring program. The context for making these decisions is provided in Chapter 2 where background on the SODN climate is presented. However, this process is only one step in evaluating and designing a climate-monitoring program. The following steps must also be included:

- 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 and 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 B, 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 D.

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 and 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 preventive 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 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 at the major national networks are $1500–2500 per station per year but these costs still can vary greatly depending on the kind of automated site.

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 ($3000–4000) 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, since good data are absolutely crucial for interpreting climate records properly, 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 World Meteorological Organization (WMO 1983; 2005), the American Association of State Climatologists (AASC 1985), the U.S. Environmental Protection Agency (EPA 1987), Finklin and Fischer (1990), the RAWS program (Bureau of Land Management [BLM] 1997), and the National Wildfire Coordinating Group (2004). 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 and 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 and climate measurements collected from nearby stations.

2.0. Climate Background

Climate is a primary factor controlling the structure and function of ecosystems in the SODN. An understanding of both current climate patterns and climate history in the SODN is important to understanding and interpreting change and patterns in ecosystem attributes (Mau-Crimmins et al. 2005). It is essential that the SODN park units have an effective climate monitoring system to track climate changes and to aid in management decisions relating to these changes. In order to do this, it is essential to understand the climate characteristics of the SODN, as discussed in this chapter.

2.1. Climate and the SODN Environment

The climate of the SODN is characterized by little precipitation along with temperature extremes (Mau-Crimmins et al. 2005). Winter temperatures are mild, with valley bottoms typically free of frost, while the surrounding mountains may have dense snow cover at high elevations and on north and east aspects. Summers are quite hot across the SODN, with the exception of the highest elevations. During any season, diurnal swings of 15°C or more are common, as the dry atmosphere and relatively low vegetation cover facilitate overnight re-radiation of daytime heat into the atmosphere.

The SODN exhibits a unique bimodal precipitation regime and steep topographic gradients (Sheppard et al. 2002). This diversity in climatic conditions in turn supports a high level of biological diversity. On a geologic time scale, climate does change and with it the organisms representative of a given biome also change. In contrast, weather is so variable from year to year that detection of significant change is difficult and requires long-term monitoring. Changes in weather events, growing season changes, and other aspects of natural disturbance regimes may alter natural communities and facilitate general change in species/habitat distributions (Neilson 1986, Spellerberg 1991). For instance, recurring Pacific Decadal Oscillation (PDO) or El Niño Southern Oscillation (ENSO) events affect temperature and precipitation patterns and produce significant changes in abiotic and biotic ecosystem components (Swetnam and Betancourt 1990; 1998). These changes are within the natural range of variation, although human activities may be altering the frequency and intensity of these events (NAST 2001). Potential impacts to sensitive ecosystems, endemic species, and threatened or endangered species are of particular concern (Brussard et al. 1998; Mau-Crimmins et al. 2005).

The bimodal precipitation regime is in fact one of the most prominent features of the Sonoran Desert climate (Ingram 2000). Located between the Mojave and Chihuahuan Deserts, the Sonoran Desert receives the more-frequent, low-intensity winter rains (December/January) of the former, as well as the violent summer (July/August) “monsoon” thunderstorms of the latter (see Figure 2.1). These distinct rainy seasons support a broad array of warm- and cool-season flora and fauna and are the primary cause of the amazing species and lifeform diversity of the Sonoran Desert (MacMahon 1985; Nabhan 2000). Winter precipitation occurs in association with the prevailing Pacific storm track which pushes south into the Sonoran Desert region during the winter months (Ingram 2000). In the summer, the North American Monsoon System (NAMS) is a significant source of precipitation for the SODN (Adams and Comrie 1997; Ropelewski et al.

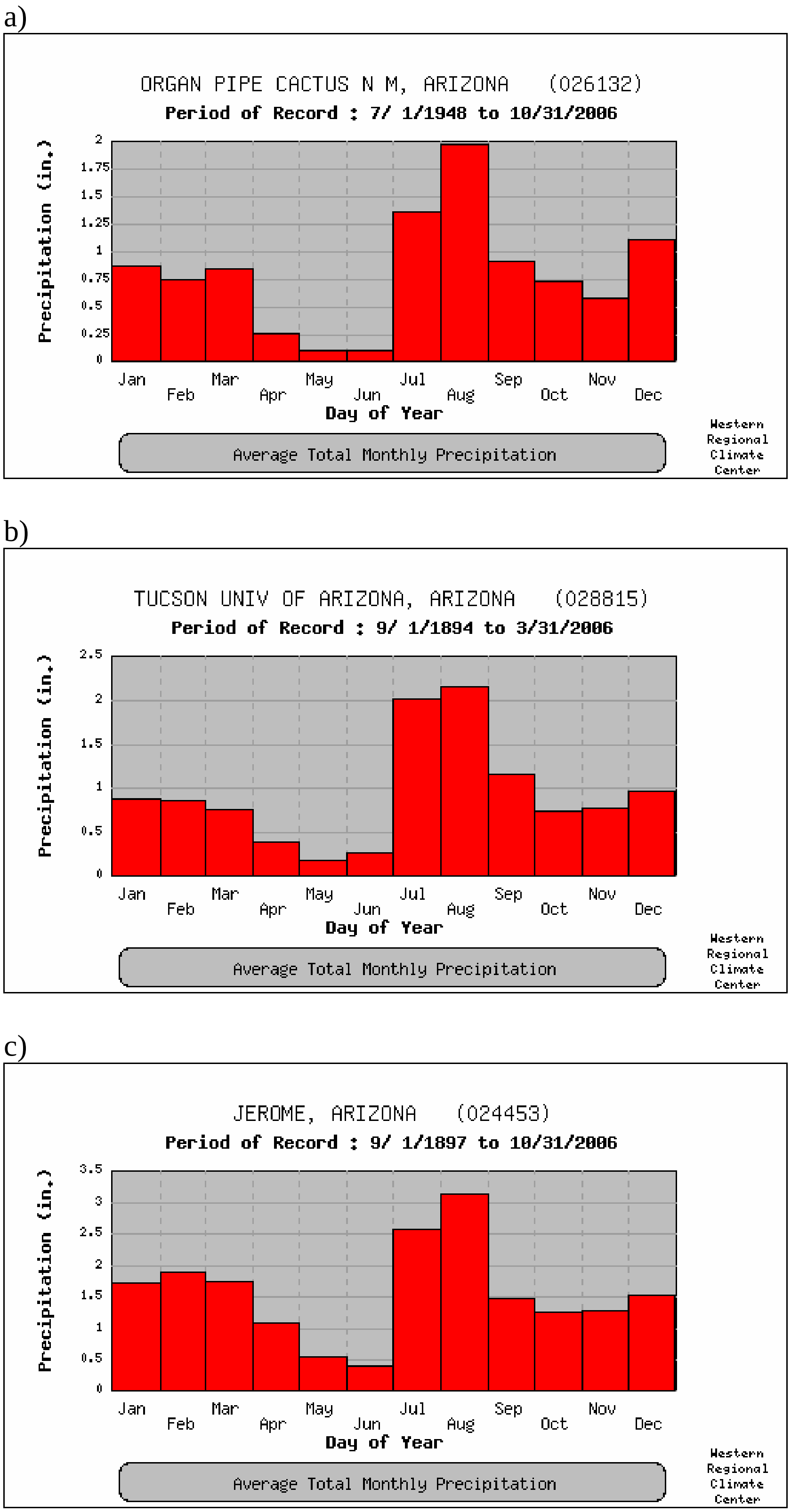


Figure 2.1. Mean monthly precipitation at selected locations in the SODN. Locations include ORPI (a); Tucson Univ. of Arizona, near SAGU (b); and Jerome, Arizona, near CAGR (c).

2005), bringing localized heavy downpours during the months of July and August (Ingram 2000). Though winter and summer precipitation totals are roughly equivalent, there is more effective precipitation available to organisms during the winter, as much of the summer rains evaporate or run off before they can be utilized (Ingram 2000).

Precipitation typically increases dramatically with elevation in the SODN, due to the orographic effects of the “sky islands” (Merriam and Steineger 1890; Marshall 1957; Warshall 2007), where a sizeable proportion of precipitation occurs as snowfall. It is the combination of orographic precipitation with dramatic decreases in temperature that supports the “Canadian Life Zone” flora and fauna at the uppermost elevations of the Sonoran Desert sky islands (Dimmitt 2000).

Tropical storms occasionally move north and east from the tropical Pacific into the SODN, constituting another source of interannual variation in precipitation. These storm events usually occur in early autumn (Mau-Crimmins et al. 2005). While infrequent, the storms have produced many of the largest rainfall events ever recorded in the American Southwest, resulting in widespread flooding and severe erosion throughout the region (Ingram 2000).

2.2. Spatial Variability

Much of the SODN is in a dry, hot desert environment; as a result, annual precipitation totals are generally low, especially at lower elevations. Annual precipitation in the Sonoran Desert itself averages from 76-500 mm depending on location and altitude, with substantial inter-and intra-annual variability in timing and quantity (Sellers et al. 1985, Ingram 2000). This precipitation generally falls in the form of rain, with some snow during the winter months at the higher-elevations. For SODN park units, the driest conditions occur in ORPI, where between 200 and 300 mm of precipitation fall each year on average (Figure 2.2). In contrast, the wettest conditions are found further east, in CHIR, CORO, and portions of the eastern SAGU unit. In these areas, mean annual precipitation can approach 750 mm. Much of the precipitation at these locations and throughout much of eastern SODN is associated with the summer monsoon. For example, mean July precipitation is well over 100 mm for portions of SAGU and can approach 200 mm in CHIR and CORO (Figure 2.3).

Temperatures in the SODN are quite variable, with mean annual temperatures ranging from around 10°C in GICL to over 20°C in western portions of ORPI (Figure 2.4). As the SODN is a hot desert region, it should not be surprising that summer air temperatures are quite high. Mean July maximum temperatures (Figure 2.5) get as high as 40°C in portions of ORPI, with much cooler conditions in park units such as GICL (around 30°C). These summer maximum temperatures routinely exceed 40°C at the lower elevations in the SODN and often reach 48°C (Mau-Crimmins et al. 2005). As stated before, winter temperatures in the SODN are usually mild. Nighttime temperatures generally stay well above freezing in many lower-elevation SODN park units. For example, mean January minimum temperatures (Figure 2.6) often stay above 4°C in ORPI. The coldest conditions occur at GICL, where January minimum temperatures commonly get down to around -10°C.

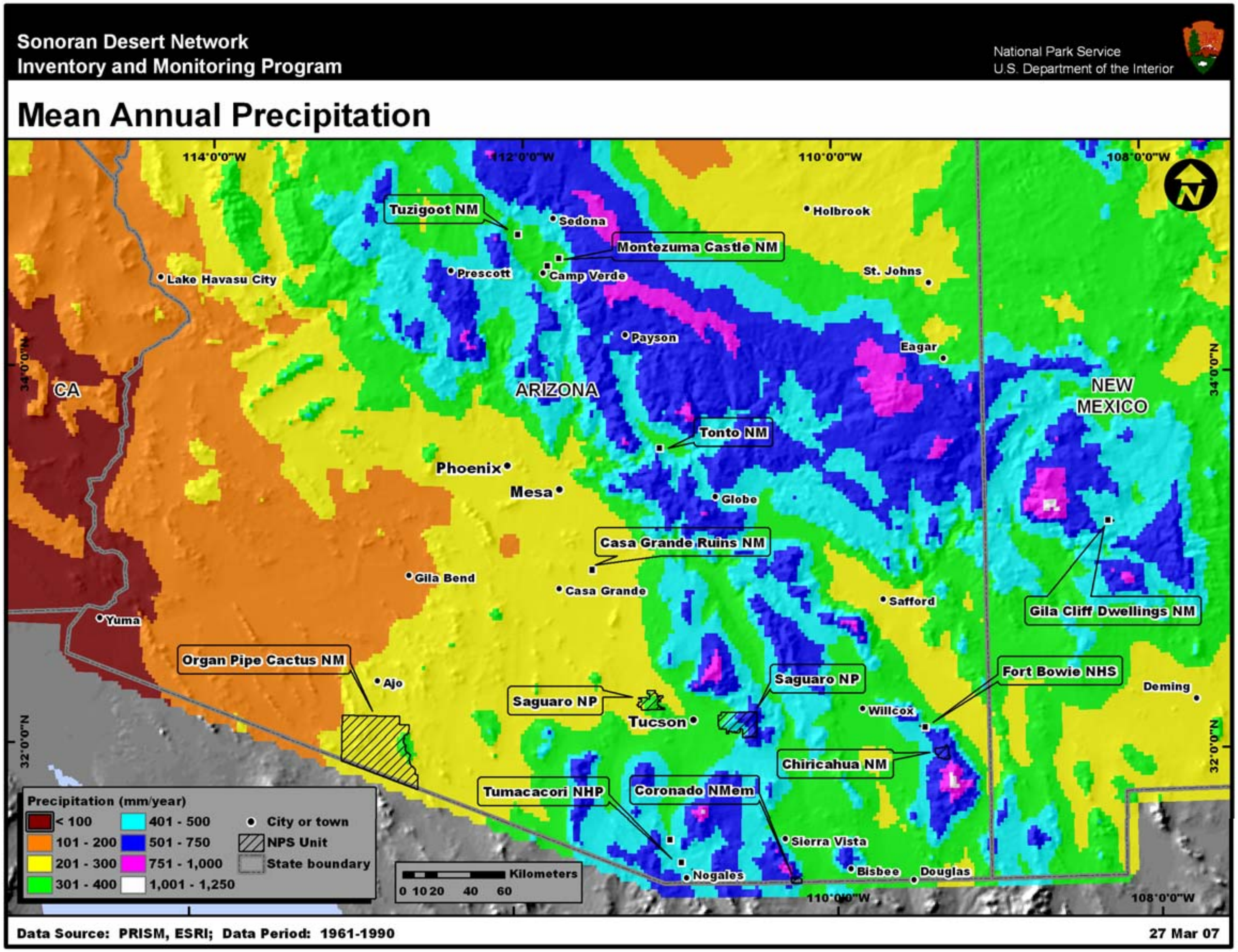


Figure 2.2. Mean annual precipitation, 1961-1990, for the SODN.

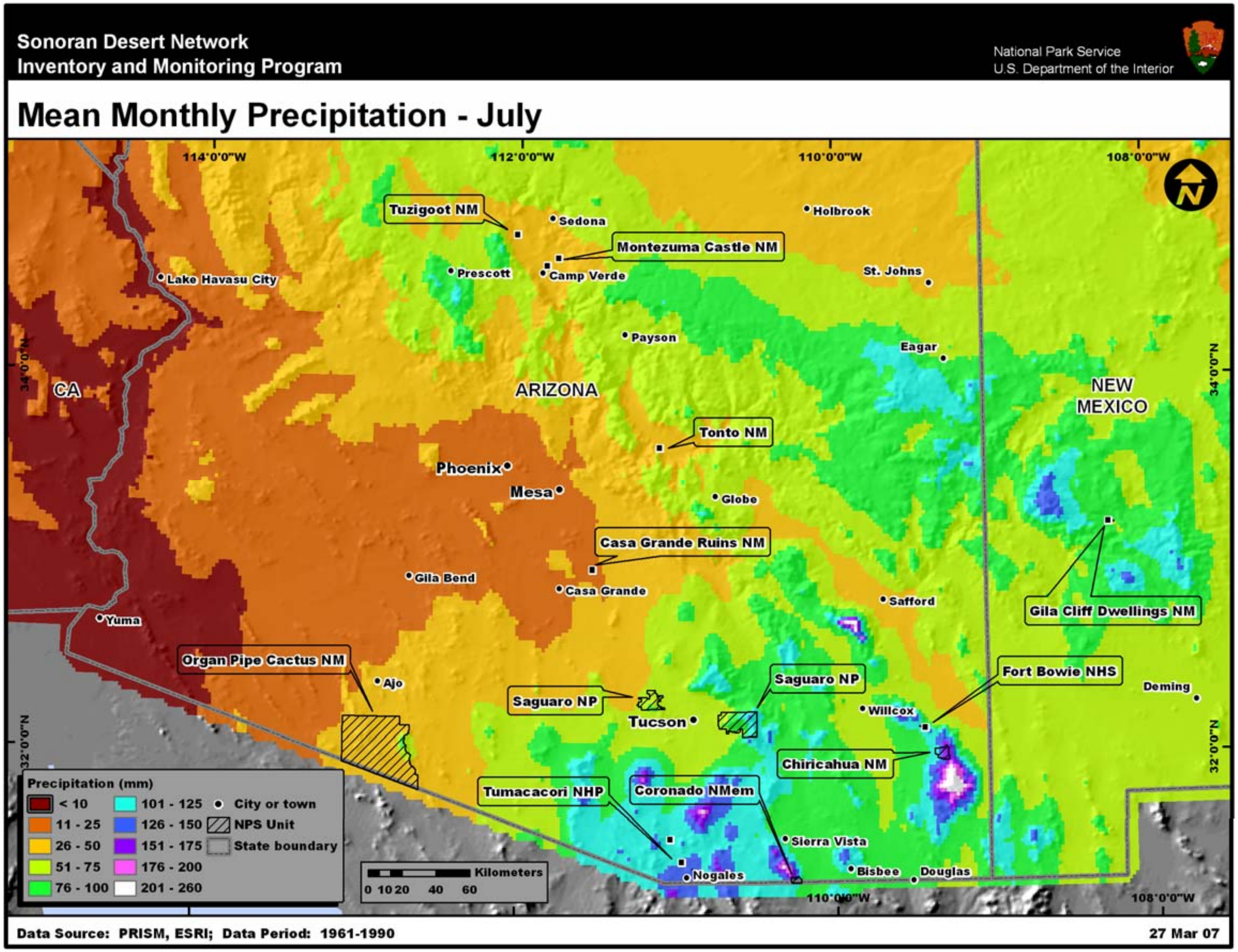


Figure 2.3. Mean July precipitation, 1961-1990, for the SODN.

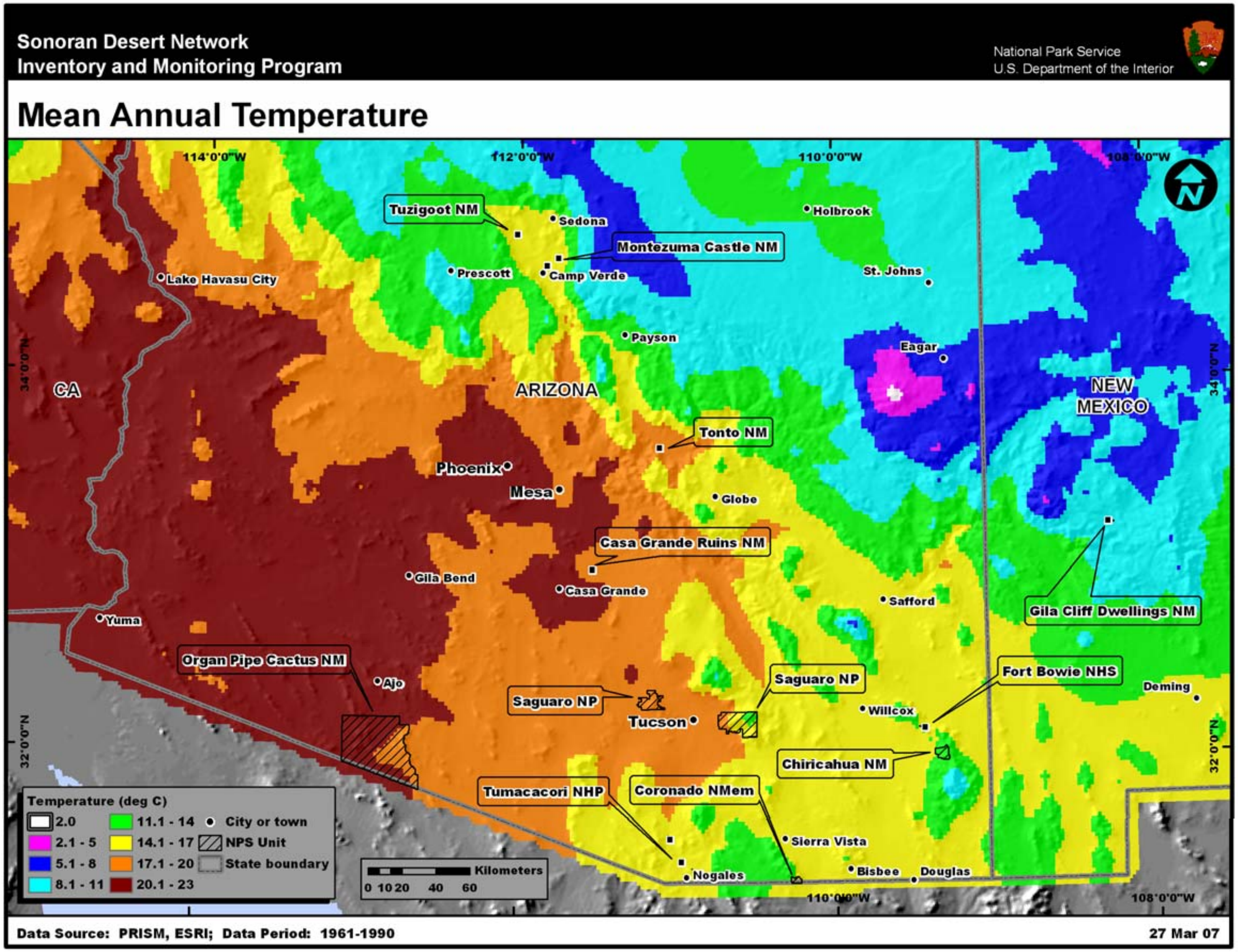


Figure 2.4. Mean annual temperature, 1961-1990, for the SODN.

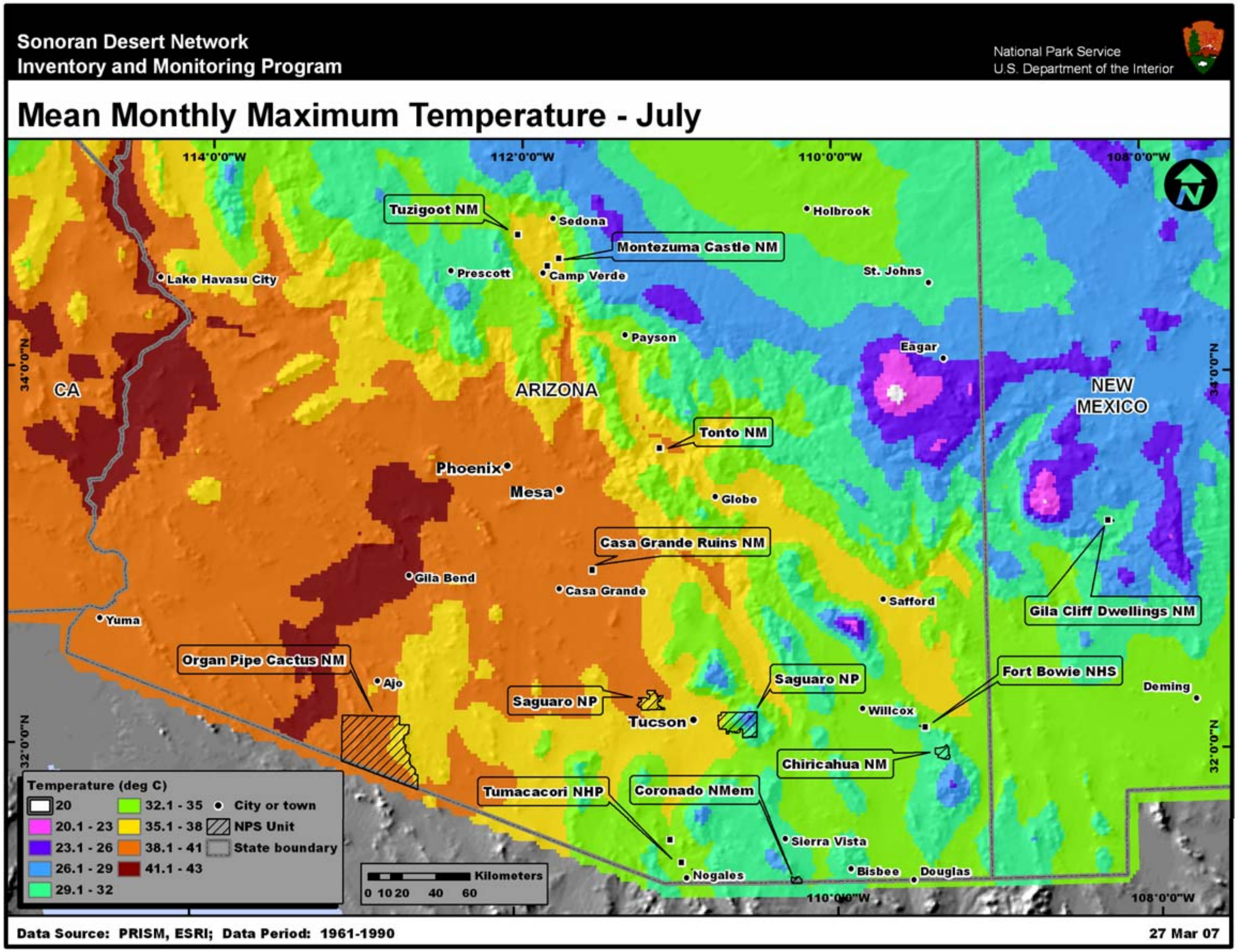


Figure 2.5. Mean July maximum temperature, 1961-1990, for the SODN.

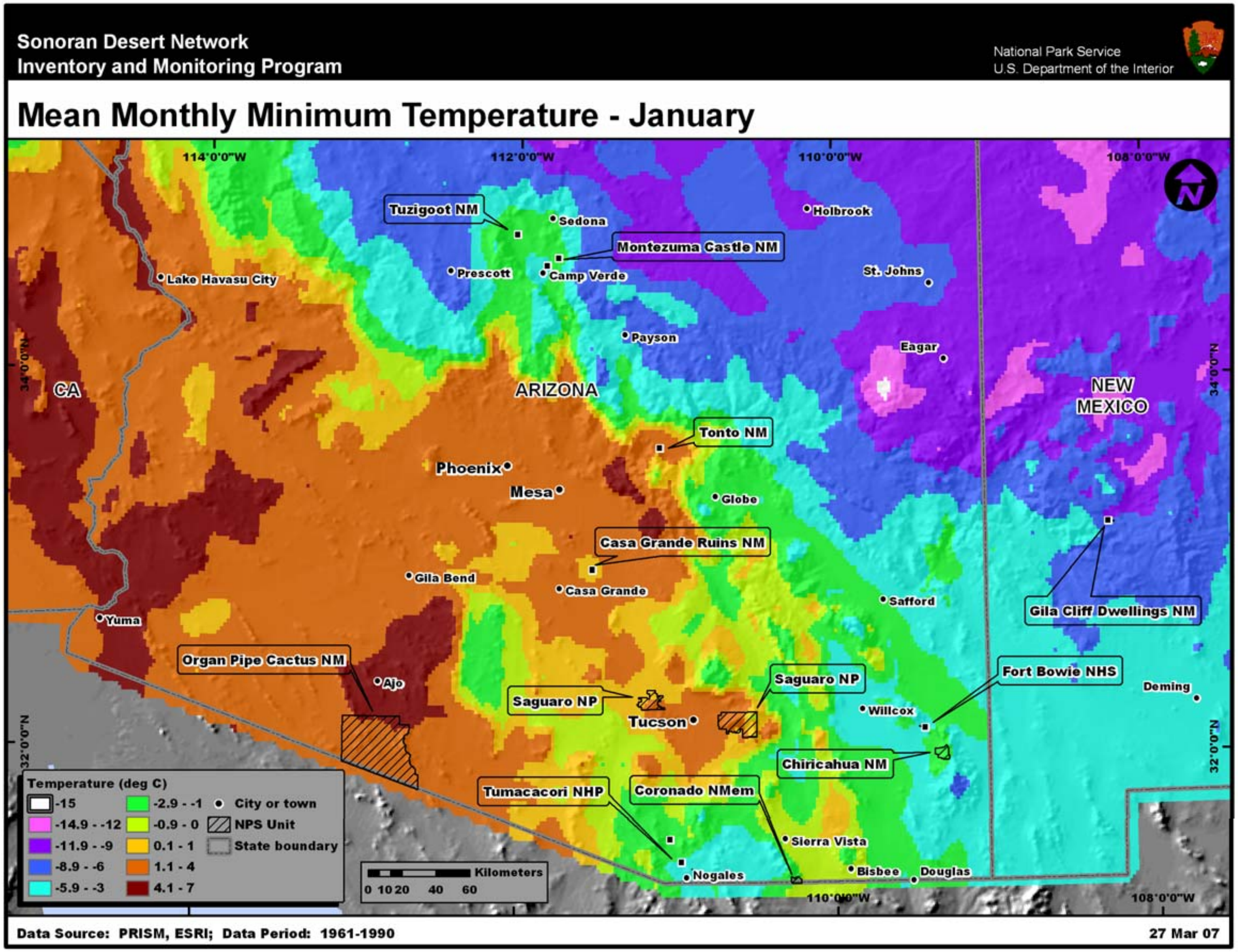


Figure 2.6. Mean January minimum temperature, 1961-1990, for the SODN.

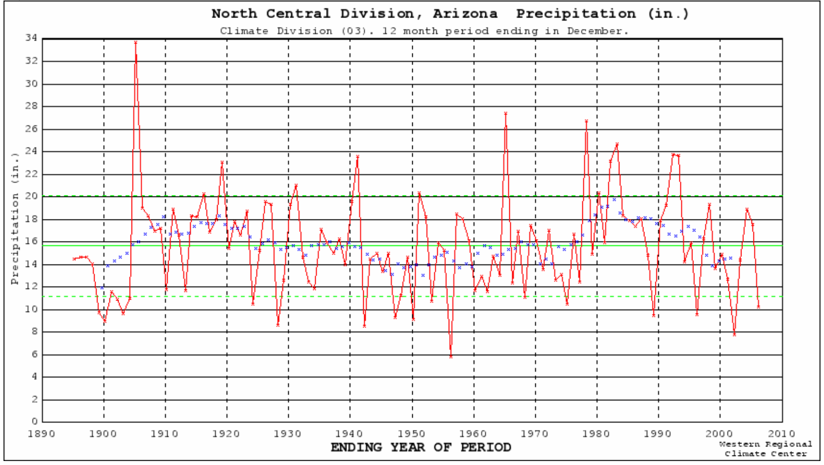
2.3. Temporal Variability

Events in the tropical Pacific and northern Pacific Ocean are linked to variations in temperature and precipitation across the SODN. In particular, interannual climate variations in the SODN are influenced strongly by ENSO cycles (Mau-Crimmins et al. 2005). During El Niño events, the SODN generally receives above-normal precipitation due to the dominant winter storm track being shifted further south than in an average winter (Ingram 2000). On the other hand, La Niña events often bring drought throughout the Sonoran Desert. Climate reconstructions and modeling of potential global change consequences suggest that the frequency and intensity of ENSO events could increase dramatically in upcoming years (e.g., Emmanuel et al. 1985; NAST 2001). Multi-decadal climate variation across the desert region follows a pattern best expressed by the PDO (Mantua 2000; Mantua and Hare 2002). These variations interact in complex ways that affect entire populations, species, and ecosystems at the regional level. Desert plant and animal communities are highly adaptable to the short-term variability in climate but respond on the scale of millennia to large swings in climate variability, which ultimately drives change in desert plant and animal communities. Conservation biologists in the SODN are concerned about the potential impact of global warming on species extinctions and the ability of species to re-colonize in suitable locations under current and potential future climate conditions.

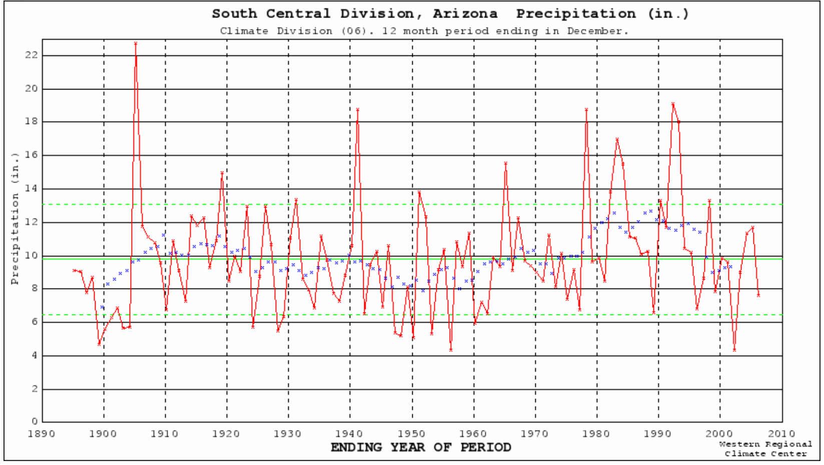
An investigation of daily precipitation amounts around the SODN region over the last century (Figure 2.7) reveals several multi-decadal precipitation regimes (Hereford et al. 2004). The 1890s were dry years, followed by wet years from the early 1900s through the 1920s. The early 1940s and 1950s were drier, followed by wet conditions peaking in the 1980s. Long-term trends in ambient temperature (Figure 2.8) are difficult to detect due to the high variability in daily and annual temperatures. It is generally apparent, however, that temperatures have become warmer over the past century (NAST 2001), especially in the last few decades. However, the signature of this net warming varies quite dramatically across the SODN. Northern portions of the SODN (Figure 2.8a) show a steady warming since the early twentieth century. In contrast, southern portions of the SODN (e.g., Figures 2.8b,c) show little or no warming during the past century. Warmer and colder spells are readily apparent in all regions. The 1910s and the 1970s were both relatively cool in comparison to the warm spells during the beginning of the twentieth century, the 1940s, and in the last two decades (1980s-present). Comparing Figures 2.7 and 2.8, it is apparent that the warm spells coincide roughly with the dry periods in the SODN. In all of these observed patterns, however, it is not clear how much of the signal may be due to discontinuities in observation records at individual stations, caused by artificial changes such as station moves. These patterns highlight the emphasis on measurement consistency that is needed in order to properly detect long-term climatic changes.

2.4. Parameter Regression on Independent Slopes Model (PRISM)

The climate maps presented in this report 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 U.S. (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. This model was developed originally to provide climate information at scales matching available land-cover maps to assist in ecologic modeling. The a)



b)



c)

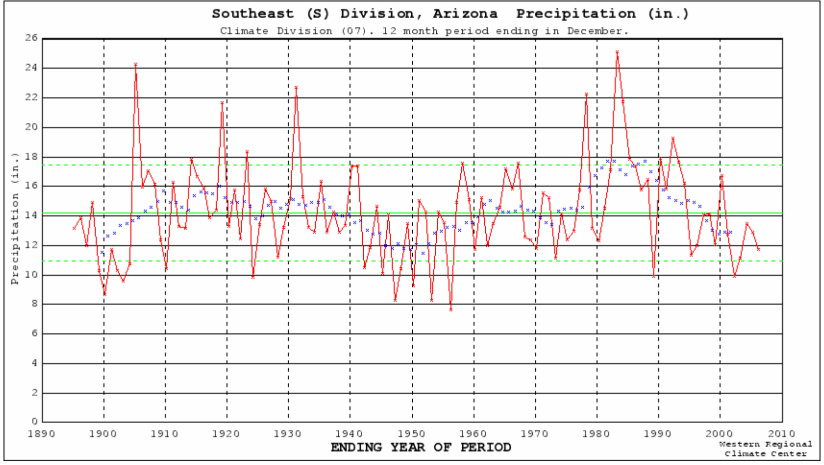
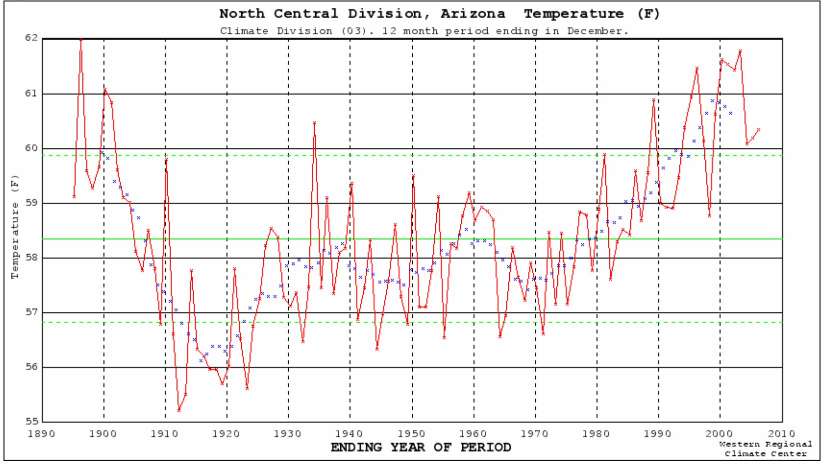
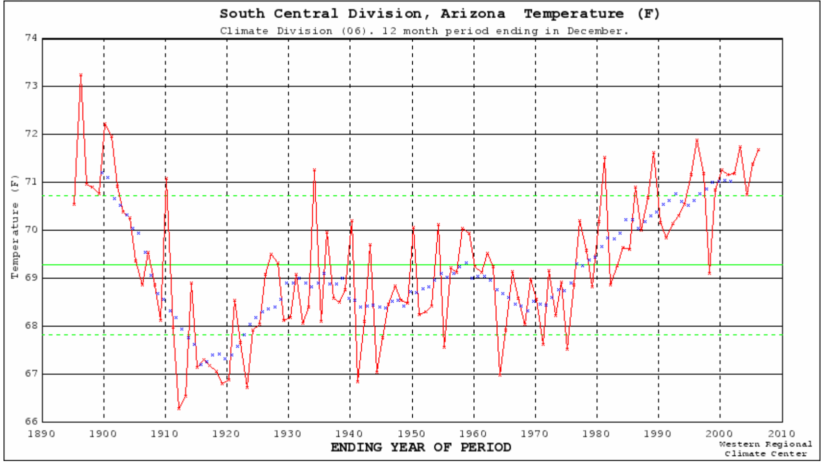


Figure 2.7. Precipitation time series, 1895-2005, for selected regions in the SODN. These include twelve-month precipitation (ending in December) (red), 10-year running mean (blue), mean (green), and plus/minus one standard deviation (green dotted). Locations include north-central Arizona (a), south-central Arizona (b), and southeastern Arizona (c).

a)



b)



c)

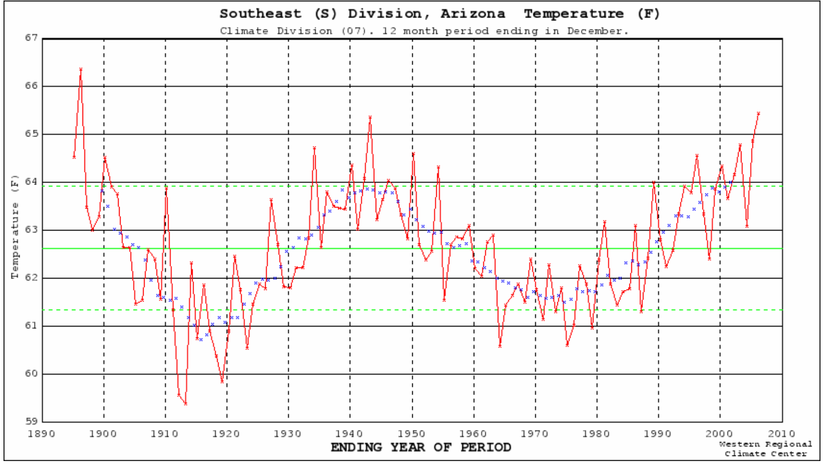


Figure 2.8. Temperature time series, 1895-2005, for selected regions in the SODN. These include twelve-month average temperature (ending in December) (red), 10-year running mean (blue), mean (green), and plus/minus one standard deviation (green dotted). Locations include north-central Arizona (a), south-central Arizona (b), and southeastern Arizona (c).

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 the SODN, we now present the procedures that were used to obtain information for weather and climate stations within the SODN. 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 E. 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.

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. The WRCC conducts live and periodic data collection (ingests) from all major national and western weather and climate networks. These networks include the COOP network, the Surface Airways Observation network (SAO) operated by NWS and the Federal Aviation Administration (FAA), the interagency RAWS 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.

The primary source of metadata at WRCC is the Applied Climate Information System (ACIS), a joint effort among RCCs and other NOAA entities. Metadata for SODN weather and climate stations identified from the ACIS database are available in file “SODN_from_ACIS.tar.gz” (see Appendix F). Historic metadata pertaining to major climate- and weather-observing systems in the U.S. 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. For this project, the available metadata from many smaller networks also have been entered but in most cases the actual data 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.

Table 3.1. Primary metadata fields for SODN weather and climate stations. Explanations are provided as appropriate.

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 (COOP, RAWS, 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.
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.

In addition to obtaining SODN weather and climate station metadata from ACIS, metadata were obtained from NPS staff at the SODN office. The metadata provided from the SODN office are available in file "SODN_NPS.tar.gz." Most of the stations noted by SODN staff are already accounted for in ACIS. We have also relied on information supplied at various times in the past by the BLM, NPS, NCDC, and NWS.

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

- 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 and 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 and 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 weather and climate stations for each park unit in the SODN we selected only those stations located within 40 km of the SODN park units. This buffer distance was selected in an attempt to include at least a few automated stations from major networks such as RAWS and SAO.

The station locator maps presented in Chapter 4 were designed to show clearly the spatial distributions of all major weather and climate station networks in SODN. 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 and climate stations for the SODN region in relation to the boundaries of the NPS park units within the SODN. 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 SODN region are associated with at least one of 16 major weather and climate networks (Table 4.1). Brief descriptions of these networks are provided below (see Appendix G for greater detail).

Table 4.1. Weather and climate networks represented within the SODN.

Acronym	Name
AZ ALERT	Arizona Automated Local Evaluation in Real Time network
AZMET	The Arizona Meteorological Network
CASTNet	Clean Air Status and Trends Network
COOP	NWS Cooperative Observer Program
CRBFC	Colorado River Basin Forecast Center network
CRN	Climate Reference Network
CWOP	Citizen Weather Observer Program
GPMP	NPS Gaseous Pollutant Monitoring Program
GPS-MET	NOAA ground-based GPS meteorology network
MEXICO	Mexico weather/climate stations
NADP	National Atmospheric Deposition Program
NRCS-SC	NRCS snowcourse network
RAWS	Remote Automated Weather Station network
SAO	NWS/FAA Surface Airways Observation network
SNOTEL	NRCS Snowfall Telemetry network
WX4U	Weather For You network

4.1.1. The Arizona Automated Local Evaluation in Real Time Network (AZ ALERT)

The AZ ALERT network provides timely information for Pima County residents on possible flooding events. This network measures precipitation, stormwater runoff, and other weather conditions. This network started in 1983 and has grown to 80 precipitation gauges, 30 stream stage sensors, and four automatic weather stations in eastern Pima County and adjoining counties.

4.1.2. The Arizona Meteorological Network (AZMET)

The Arizona Meteorological Network (AZMET) provides near-real-time weather data that is used primarily for agricultural applications in southern and central Arizona. Meteorological elements measured by AZMET include temperature (air and soil), humidity, solar radiation, wind (speed and direction), and precipitation.

4.1.3. Clean Air Status and Trends Network (CASTNet)

CASTNet 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.

4.1.4. NWS Cooperative Observer Program (COOP)

The COOP network has been a foundation of the U.S. climate program for decades and continues to play an important role. 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. Colorado River Basin Forecast Center (CRBFC) Network

The CRBFC network has over 100 weather stations in the Colorado River Basin. The primary purpose of CRBFC stations is to collect meteorological data in support of efforts by the CRBFC to monitor potential flood conditions in the Colorado River Basin.

4.1.6. Climate Reference Network (CRN)

The CRN is intended as a reference network for the U.S. 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.

4.1.7. Citizen Weather Observer Program (CWOP)

The CWOP network consists primarily of automated weather stations operated by private citizens who have either an Internet connection and/or a wireless Ham radio setup. Data from CWOP stations are specifically intended for use in research, education, and homeland security activities. Although standard meteorological elements such as temperature, precipitation, and wind are measured at all CWOP stations, station characteristics do vary, including sensor types and site exposure.

4.1.8. Gaseous Pollutant Monitoring Program (GPMP)

The GPMP network measures hourly meteorological data in support of pollutant monitoring activities. Measured elements include temperature, precipitation, humidity, wind, solar radiation, and surface wetness. These data are generally of high quality, with records extending up to two decades in length.

4.1.9. NOAA Ground-Based GPS Meteorology (GPS-MET) Network

The GPS-MET network is the first network of its kind dedicated to Global Positioning System (GPS) meteorology (see Duan et al. 1996). GPS meteorology utilizes the radio signals broadcast by GPS satellites for atmospheric remote sensing. GPS meteorology applications have evolved along two paths: ground-based (Bevis et al. 1992) and space-based (Yuan et al. 1993). For more information, please see Appendix G. The stations identified in this inventory are all ground-based. The GPS-MET network was developed in response to the need for improved moisture observations to support weather forecasting, climate monitoring, and other research activities. The primary goals of this network are to measure atmospheric water vapor using ground-based GPS receivers, facilitate the operational use of these data, and encourage usage of GPS meteorology for atmospheric research and other applications. GPS-MET is a collaboration between NOAA and several other governmental and university organizations and institutions. Ancillary meteorological observations at GPS-MET stations include temperature, relative humidity, and barometric pressure.

4.1.10. Mexico Weather/Climate Stations (MEXICO)

These include various automated weather and climate station networks from Mexico. The data measured at these sites generally include temperature, precipitation, humidity, wind, barometric pressure, sky cover, ceiling, visibility, and current weather.

4.1.11. National Atmospheric Deposition Program (NADP)

The purpose of the NADP network is to monitor primarily wet deposition at selected sites around the U.S. and its territories. The network is a collaborative effort among several agencies including the U.S. Geological Survey (USGS) and USDA. Precipitation is the primary climate parameter measured at NADP sites. This network includes sites from the Mercury Deposition Network (MDN).

4.1.12. USDA/NRCS snowcourse Network (NRCS-SC)

The USDA/NRCS maintains another network of snow-monitoring stations in addition to SNOTEL (described below). 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.

4.1.13. Remote Automated Weather Station (RAWS) Network

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.

4.1.14. NWS Surface Airways Observation Network (SAO)

These stations are located usually at major airports and military bases. Almost all SAO sites are automated. The hourly data measured at these sites include temperature, precipitation, humidity, wind, barometric 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.

4.1.15. USDA/NRCS Snowfall Telemetry Network (SNOTEL)

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.

4.1.16. Weather For You Network (WX4U)

The WX4U network is a nationwide collection of weather stations run by local observers. Data quality varies with site. Standard meteorological elements are measured and usually include temperature, precipitation, wind, and humidity.

4.1.17. Weather Bureau Army Navy (WBAN)

Some stations are identified in this report as WBAN stations. This is a station identification system rather than a true weather/climate network. Stations identified with WBAN are largely historical stations that reported meteorological observations on the WBAN weather observation forms that were common during the early and middle parts of the twentieth century. The use of WBAN numbers to identify stations was one of the first attempts in the U.S. to use a coordinated station numbering scheme between several weather station networks, such as the COOP and SAO networks.

4.1.18. Other Networks

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. One weather station we identified is associated with the Utah Climate Center (UCC). Local networks of weather stations are administered by NPS, primarily in ORPI and SAGU. Other networks could be present within SODN but have not been identified in this report. Some of the commonly used networks include the following:

- NOAA upper-air stations
- Federal and state departments of transportation
- U.S. Department of Energy Surface Radiation Budget Network (Surfrad)
- Other research or project networks having many possible owners

4.2. Station Locations

The major weather and climate networks in the SODN (discussed in Section 4.1) have at most a couple stations at or inside each park unit (Table 4.2). Most of these are COOP stations.

Lists of stations have been compiled for the SODN. As was noted previously, 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 also significant questions, whose answers can vary according to application, type of element, period of record, procedural or methodological observation conventions, and the like.

Table 4.2. Number of stations within or nearby SODN park units. Numbers are listed by park unit and by weather/climate network. Figures in parentheses indicate the numbers of stations within park boundaries.

Network	**CAGR**	**CHIR**	**CORO**	**FOBO**	**GICL**	**MOCA**	**ORPI**	**SAGU**	**TONT**	**TUMA**	**TUZI**
AZ ALERT	**2**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**3**(0)	**0**(0)	**0**(0)	**1**(0)	**0**(0)	**4**(0)
AZMET	**3**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**2**(0)	**0**(0)	**0**(0)	**1**(0)
CASTNet	**0**(0)	**1**(1)	**0**(0)	**1**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)
COOP	**10**(1)	**14**(1)	**14**(1)	**13**(0)	**15**(0)	**16**(1)	**6**(1)	**39**(2)	**21**(0)	**18**(1)	**14**(1)
CRBFC	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**3**(0)	**0**(0)	**0**(0)	**2**(0)	**0**(0)	**1**(0)
CRN	**0**(0)	**0**(0)	**1**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**1**(0)	**0**(0)	**0**(0)	**0**(0)
CWOP	**1**(0)	**0**(0)	**2**(0)	**0**(0)	**0**(0)	**2**(0)	**0**(0)	**24**(0)	**1**(0)	**1**(0)	**4**(0)
GPMP	**0**(0)	**1**(1)	**0**(0)	**1**(0)	**0**(0)	**0**(0)	**0**(0)	**1**(1)	**0**(0)	**0**(0)	**0**(0)
GPS-MET	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**2**(0)	**0**(0)	**0**(0)	**0**(0)
MEXICO	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**1**(0)	**0**(0)
NADP	**0**(0)	**1**(1)	**0**(0)	**1**(0)	**1**(0)	**0**(0)	**1**(1)	**0**(0)	**0**(0)	**0**(0)	**0**(0)
NPS	**0**(0)	**1**(1)	**0**(0)	**1**(0)	**0**(0)	**0**(0)	**11**(11)	**9**(9)	**0**(0)	**0**(0)	**0**(0)
NRCS-SC	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**2**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)
RAWS	**0**(0)	**4**(1)	**1**(0)	**3**(0)	**3**(1)	**4**(0)	**0**(0)	**7**(1)	**2**(0)	**2**(0)	**5**(0)
SAO	**3**(0)	**0**(0)	**2**(0)	**0**(0)	**0**(0)	**0**(0)	**1**(1)	**2**(0)	**0**(0)	**1**(0)	**1**(0)
SNOTEL	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**1**(0)	**1**(0)	**0**(0)	**0**(0)	**1**(0)	**0**(0)	**1**(0)
UCC	**0**(0)	**1**(0)	**0**(0)	**1**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)
WX4U	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**1**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**1**(0)
Other	**1**(0)	**0**(0)	**1**(0)	**0**(0)	**0**(0)	**0**(0)	**1**(0)	**1**(0)	**0**(0)	**0**(0)	**0**(0)
Total	**20**(1)	**23**(6)	**21**(1)	**21**(0)	**22**(1)	**30**(1)	**20**(14)	**88**(13)	**28**(0)	**23**(1)	**32**(1)

4.2.1. Northern Park Units

One climate station was identified within MOCA (Table 4.3; Figure 4.1). This is an active COOP station (Montezuma Castle NM) whose data record extends back to 1938 and is very complete. Three active AZ ALERT stations were identified within 40 km of the boundaries of MOCA. The closest AZ ALERT station to MOCA is “Sedona Airport,” which is 21 km north of the park unit.

Table 4.3. Weather and climate stations for the northern SODN park units. Stations inside park units and within 40 km of the park unit boundary are included. Missing entries are indicated by “M”.

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Montezuma Castle National Monument (MOCA)							
Montezuma Castle NM	34.611	-111.838	969	COOP	10/12/1938	Present	Yes
Cottonwood PW Yard	34.732	-112.042	1091	AZ ALERT	M	Present	No
Mingus Mountain	34.701	-112.118	2381	AZ ALERT	M	Present	No
Sedona Airport	34.844	-111.793	1444	AZ ALERT	M	Present	No
Beaver Creek	34.642	-111.783	1074	COOP	11/1/1915	Present	No
Camp Verde R.S.	34.549	-111.981	943	COOP	11/27/1978	Present	No
Childs	34.349	-111.698	808	COOP	9/1/1915	6/16/2005	No
Dugas 2 SE	34.350	-111.950	1232	COOP	7/1/1919	12/6/1972	No
Fossil Springs	34.417	-111.567	1302	COOP	1/1/1951	12/1/1970	No
Happy Jack R.S.	34.743	-111.414	2280	COOP	11/1/1954	Present	No
Irving	34.403	-111.618	1157	COOP	1/1/1951	6/3/2005	No
Jerome	34.752	-112.111	1509	COOP	9/1/1897	Present	No
Mingus Mtn. Lookout	34.700	-112.133	2336	COOP	7/1/1948	7/31/1976	No
Mund's Park	34.936	-111.639	1972	COOP	6/1/1986	Present	No
Oak Creek Canyon	34.964	-111.761	1547	COOP	3/1/1935	Present	No
Rimrock	34.650	-111.733	1098	COOP	6/1/1941	6/30/1962	No
Sedona	34.896	-111.764	1286	COOP	10/20/1943	Present	No
Tuzigoot	34.771	-112.026	1058	COOP	11/1/1911	Present	No
Yeager Canyon	34.683	-112.167	1830	COOP	12/1/1917	7/31/1976	No
Crook Trail NR Pine	34.496	-111.574	1798	CRBFC	M	Present	No
Happy Jack R.S. NR Pine	34.742	-111.408	2286	CRBFC	M	Present	No
Montezuma Castle NR Camp Verde	34.364	-111.501	972	CRBFC	M	Present	No
CW4321 Sedona	34.870	-111.801	1378	CWOP	M	Present	No
CW4534 Camp Verde	34.557	-111.871	991	CWOP	M	Present	No
Beaver Creek	34.667	-111.700	2042	RAWS	1/1/1986	1/31/1989	No
Cherry Arizona	34.596	-112.048	1554	RAWS	2/1/1998	Present	No
Oak Creek	34.942	-111.752	1501	RAWS	12/1/1992	Present	No
Verde	34.554	-111.849	945	RAWS	11/1/1993	Present	No
Sugar Loaf	34.746	-111.412	1865	SNOTEL	10/1/1982	Present	No
Sedona	34.842	-111.786	1396	WX4U	M	Present	No
Tuzigoot National Monument (TUZI)							
Tuzigoot	34.771	-112.026	1058	COOP	11/1/1911	Present	Yes
Cottonwood PW Yard	34.732	-112.042	1091	AZ ALERT	M	Present	No
Mingus Mountain	34.701	-112.118	2381	AZ ALERT	M	Present	No
Prescott Valley PD	34.595	-112.331	1556	AZ ALERT	M	Present	No
Sedona Airport	34.844	-111.793	1444	AZ ALERT	M	Present	No
Prescott	34.592	-112.420	1583	AZMET	M	Present	No
Beaver Creek	34.642	-111.783	1074	COOP	11/1/1915	Present	No
Camp Verde R.S.	34.549	-111.981	943	COOP	11/27/1978	Present	No
Chino Valley	34.757	-112.457	1448	COOP	6/1/1941	Present	No
Drake R.S.	34.967	-112.383	1418	COOP	2/18/1915	4/30/1962	No
Jerome	34.752	-112.111	1509	COOP	9/1/1897	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Mingus Mtn. Lookout	34.700	-112.133	2336	COOP	7/1/1948	7/31/1976	No
Montezuma Castle NM	34.611	-111.838	969	COOP	10/12/1938	Present	No
Oak Creek Canyon	34.964	-111.761	1547	COOP	3/1/1935	Present	No
Perkinsville	34.900	-112.200	1177	COOP	5/1/1962	8/25/1972	No
Prescott Love Field	34.652	-112.421	1537	COOP	3/1/1937	Present	No
Rimrock	34.650	-111.733	1098	COOP	6/1/1941	6/30/1962	No
Sedona	34.896	-111.764	1286	COOP	10/20/1943	Present	No
Yeager Canyon	34.683	-112.167	1830	COOP	12/1/1917	7/31/1976	No
J.D. Cabin NR Williams	35.140	-112.057	2048	CRBFC	M	Present	No
CW1003 Prescott	34.629	-112.441	1579	CWOP	M	Present	No
CW1019 Prescott Valley	34.614	-112.333	1553	CWOP	M	Present	No
CW4321 Sedona	34.870	-111.801	1378	CWOP	M	Present	No
CW4534 Camp Verde	34.557	-111.871	991	CWOP	M	Present	No
Beaver Creek	34.667	-111.700	2042	RAWS	1/1/1986	1/31/1989	No
Cherry Arizona	34.596	-112.048	1554	RAWS	2/1/1998	Present	No
Coconini Micro #2	35.032	-111.904	M	RAWS	6/1/1995	1/31/1996	No
Oak Creek	34.942	-111.752	1501	RAWS	12/1/1992	Present	No
Verde	34.554	-111.849	945	RAWS	11/1/1993	Present	No
Prescott Love Field	34.652	-112.421	1537	SAO	3/1/1937	Present	No
Fry	35.067	-111.850	2195	SNOTEL	10/1/1982	Present	No
Sedona	34.842	-111.786	1396	WX4U	M	Present	No

Three active CRBFC stations were identified within 40 km of the boundaries of MOCA (Table 4.3). The closest CRBFC station to MOCA is “Crook Trail NR Pine,” which is 23 km southeast of the park unit.

Fifteen COOP stations (eight of which are active) were identified within 40 km of MOCA (Table 4.3). The COOP station “Jerome” is located 28 km northwest of the park unit and provides the longest climate record in the vicinity of MOCA (1897-present). The data record at this climate station is largely complete, with scattered, small data gaps. The COOP station “Tuzigoot” (1911-present) is located 24 km northwest of the park unit and its data record has been quite reliable since April 1949. Data are also available from this site from 1920 until 1936. The COOP station “Beaver Creek” has been active since 1915 and is just 1 km northeast of MOCA. For precipitation, this station’s data record is quite complete from February 1957 up until 1990, after which scattered data gaps occur. For temperature, this station’s data record has numerous small gaps throughout the record from February 1957 until present; before 1957, the data record is not reliable. The COOP station “Oak Creek Canyon” (1935-present) is 35 km north of MOCA. This station’s data record is very complete after March 1953; before this date, there were scattered data gaps throughout the record. “Sedona,” 27 km north of MOCA, provides a very reliable data record (1943-present).

Three active RAWS stations were identified within 40 km of MOCA (Table 4.3; Figure 4.1). These stations are a valuable source of near-real-time data for the region. The RAWS station

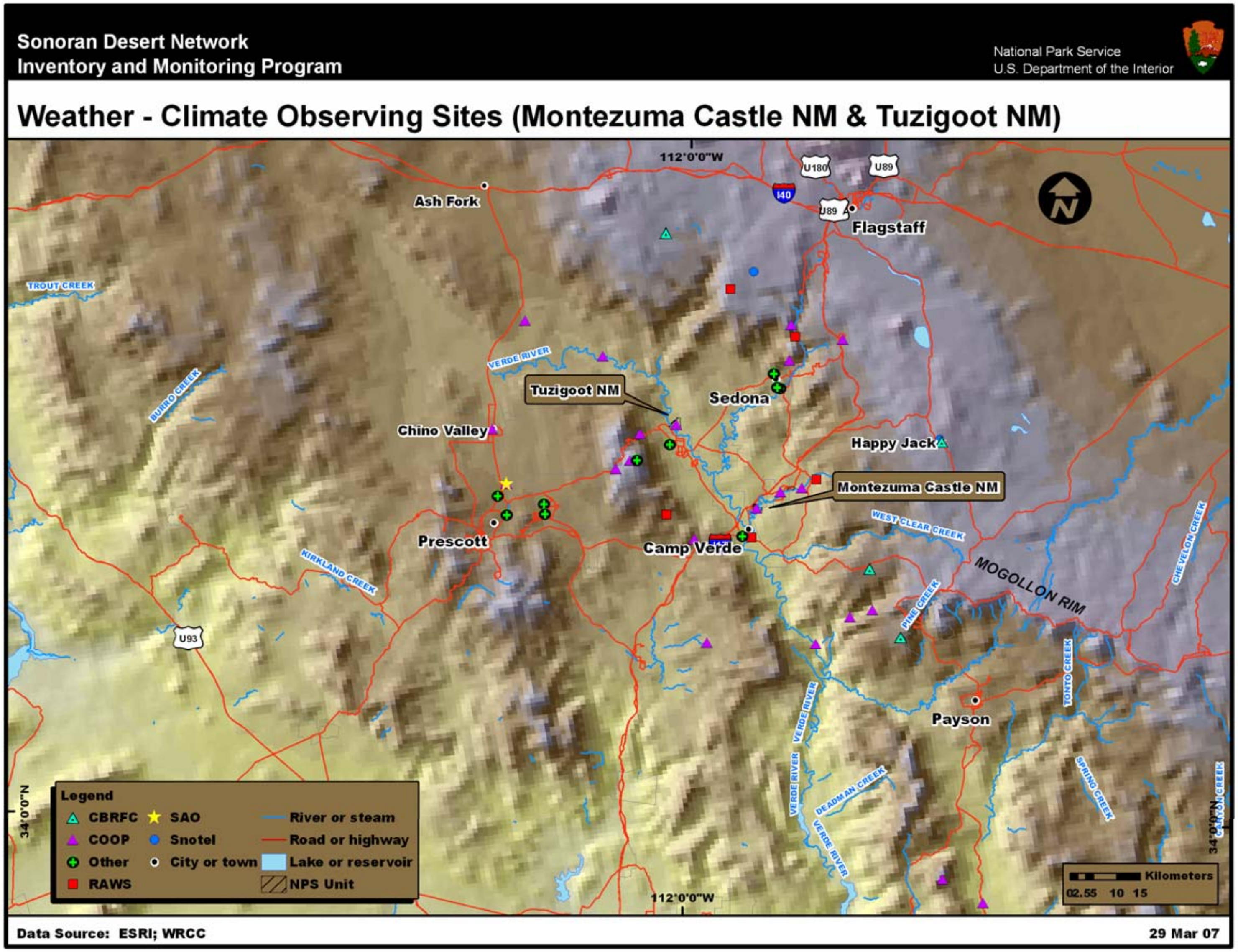


Figure 4.1. Station locations for the northern SODN park units.

“Oak Creek” has the longest data record of these three sites (1992-present) and is located 32 km north of MOCA. The data record from “Oak Creek” has scattered data gaps; the last significant gap occurred between June and August in 2002. The RAWS station “Cherry Arizona” is 18 km southwest of MOCA and has a very complete data record going back to 1998. The RAWS station “Verde” also has a very complete data record (1993-present) and is the closest of the three RAWS sites we identified, being only 6 km south of MOCA.

In addition to these RAWS sites, a few other networks have stations providing near-real-time weather data within 40 km of MOCA. The SNOTEL station “Sugar Loaf” is 22 km northeast of MOCA (Figure 4.1) and has been active since 1982 (Table 4.3). Two CWOP stations have been identified within 40 km of MOCA, one at Sedona and the other at Camp Verde. A WX4U site is also located in Sedona.

One station was identified within TUZI (Table 4.3). This is an active COOP station, “Tuzigoot,” whose data record (1911-present) has been discussed previously.

Four active AZ ALERT stations were identified within 40 km of the boundaries of TUZI (Table 4.3). The closest AZ ALERT station to TUZI is “Cottonwood PW Yard,” which is 4 km southwest of the park unit. The AZMET station “Prescott” is 39 km southwest of TUZI and provides near-real-time data for the region, as does the CRBFC site “J.D. Cabin NR Williams” (40 km north of TUZI).

We identified 13 COOP stations within 40 km of TUZI (Table 4.3). Eight of these stations are currently active. The COOP station “Jerome,” discussed previously, provides the longest data record in the area (1897-present) and is 6 km west of TUZI. The COOP station “Beaver Creek” (1915-present), discussed previously, is 26 km southeast of TUZI. The COOP station “Chino Valley” (1941-present) is 38 km west of TUZI and has a data record which is largely complete, although there are generally no weekend observations at this site after 1980. “Montezuma Castle NM” and “Oak Creek Canyon” have both been discussed previously and are 24 km southeast and 31 km northeast of TUZI, respectively. The COOP station “Prescott Love Field” is 37 km southwest of TUZI and has a data record going back to 1937. A SAO station is also found at this location. A significant gap occurred at this station between January 2001 and September 2003. The COOP station “Sedona,” discussed previously, is 26 km northeast of TUZI.

Three active RAWS stations, all of which have been discussed previously, were identified within 40 km of TUZI (Table 4.3; Figure 4.1). The RAWS station “Oak Creek” is located 30 km northeast of TUZI. The RAWS station “Cherry Arizona” is 19 km south of TUZI. The RAWS station “Verde” is 28 km southeast of TUZI. In addition, a few other networks have stations providing near-real-time weather data within 40 km of TUZI. The SNOTEL station “Fry” is 35 km northeast of MOCA and has been active since 1982. A WX4U site is located in Sedona, northeast of TUZI.

4.2.2. Southern Park Units

One climate station was identified within the boundaries of CAGR (Table 4.4). This is an active COOP station, “Casa Grande NM,” whose data record (1906-present) has been very complete since 1931. A large gap in the record occurred between 1916 and 1931.

Two active AZ ALERT stations were identified within 40 km of the boundaries of CAGR (Table 4.4). The closest AZ ALERT station to CAGR is “Magma FRS,” which is 18 km northeast of the park unit. Three active AZMET stations were identified within 40 km of the boundaries of CAGR (Table 4.4). The closest AZMET station to CAGR is “Coolidge,” which is 6 km southwest of the park unit.

We identified nine COOP stations within 40 km of the boundaries of CAGR (Table 4.4). All but two of these sites are active currently. “Florence,” 35 km east of CAGR, has the longest data record among these COOP sites (1892-present). This site’s data record is quite complete from 1930 until the 1990s. From the 1990s onward, scattered data gaps have occurred, including one significant gap from May 2002 to January 2003. The COOP station “Casa Grande,” 20 km southwest of CAGR,” also has data going back to the 1890s (1898-present). The data record at “Casa Grande” has occasionally large data gaps; the last significant gap occurred between May 1996 and January 1997. The COOP station “Sacaton” (1908-present) is 21 km northwest of CAGR. “Sacaton” had a reliable data record up until the mid-1990s. Data has been sporadic at “Sacaton” for the past 10 years. The COOP station “Chandler Heights” (1941-present), 26 km northwest of CAGR, has a data record that is largely complete, with scattered, small data gaps.

Besides the AZ ALERT and AZMET sites mentioned earlier, a CWOP station in Tempe also provides near-real-time data for CAGR. Other sources of near-real-time weather data include three SAO stations that have been identified within 40 km of CAGR (Table 4.4). “Casa Grande Muni. Arpt.” is 22 km southwest of CAGR (Figure 4.2). “Chandler Muni. Arpt.” is 39 km northwest of CAGR. Finally, “Chandler Williams Arpt.” is 35 km northwest of CAGR.

Six weather and climate stations were identified within the boundaries of CHIR (Table 4.4; Figure 4.2). The CASTNet station, “Chiricahua NM” is located near the main visitor center and has a data record that goes back to 1989. The COOP station “Chiricahua NM” is the primary source of long-term climate data within CHIR. This climate station’s data record, going back to 1909, had a large gap from 1919 to 1948 but has been very complete since 1948. A GPMP station (Chiricahua) operated in CHIR from January to December of 1990. The NADP station “Chiricahua” has been active since 1999. The station “Sugarloaf” is maintained by NPS personnel at CHIR and provides near-real-time weather data. The RAWS station “Chiricahua” has been active since 1995; it has one significant gap in June 2000 but has an otherwise complete data record. The only source of near-real-time data within 40 km of the boundaries of CHIR is the RAWS station “Rucker,” which has been active since 2000 and is 24 km south of CHIR. The data record at “Rucker” has several gaps, including January through March of 2001, December 2001 through February 2002, and February 2004.

Table 4.4. Weather and climate stations for the southern SODN park units. Stations inside park units and within 40 km of the park unit boundary are included. Missing entries are indicated by “M”.

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Casa Grande Ruins National Monument (CAGR)							
Casa Grande NM	32.995	-111.537	433	COOP	3/1/1906	Present	Yes
Crossroads Park	33.320	-111.740	387	AZ ALERT	M	Present	No
Magma FRS	33.120	-111.400	533	AZ ALERT	M	Present	No
Coolidge	32.980	-111.600	422	AZMET	M	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Eloy	32.770	-111.560	461	AZMET	M	Present	No
Queen Creek	33.260	-111.640	430	AZMET	M	Present	No
Arizona City	32.733	-111.664	456	COOP	1/20/2000	Present	No
Ashurst Hayden Dam	33.087	-111.286	472	COOP	1/1/1956	Present	No
Casa Grande	32.888	-111.715	427	COOP	6/1/1898	Present	No
Chandler Hts.	33.206	-111.682	434	COOP	1/1/1941	Present	No
Eloy 4 NE	32.782	-111.519	471	COOP	5/1/1951	Present	No
Florence	33.036	-111.388	427	COOP	12/1/1892	Present	No
Florence Junction	33.283	-111.367	574	COOP	1/1/1968	9/1/1982	No
Picacho Rsvr.	32.867	-111.467	461	COOP	1/1/1956	10/1/1982	No
Sacaton	33.080	-111.742	392	COOP	4/1/1908	Present	No
KD7DR-5 Tempe	33.341	-111.588	450	CWOP	M	Present	No
Casa Grande Muni. Arpt.	32.950	-111.767	446	SAO	6/1/1991	Present	No
Chandler Muni. Arpt.	33.269	-111.813	379	SAO	M	Present	No
Chandler Williams Arpt.	33.300	-111.667	412	SAO	3/1/1942	Present	No
Coolidge AAF	32.933	-111.433	481	WBAN	11/1/1943	10/31/1945	No
Chiricahua National Monument (CHIR)							
Chiricahua NM	32.009	-109.389	1570	CASTNet	4/1/1989	Present	Yes
Chiricahua NM	32.006	-109.357	1615	COOP	1/1/1909	Present	Yes
Chiricahua	32.009	-109.389	1570	GPMP	1/1/1990	12/1/1990	Yes
Chiricahua	32.010	-109.389	1570	NADP	2/23/1999	Present	Yes
Sugarloaf	32.018	-109.321	2088	NPS	M	Present	Yes
Chiricahua	32.000	-109.350	1646	RAWS	1/1/1995	Present	Yes
Apache 6 WNW	31.717	-109.233	1641	COOP	6/4/1938	5/31/1980	No
Bowie	32.324	-109.491	1146	COOP	1/1/1899	Present	No
Dos Cabezas 1 SE	32.167	-109.600	1556	COOP	1/1/1909	4/30/1975	No
Paradise	31.933	-109.217	1656	COOP	1/1/1906	12/31/1937	No
Portal	31.900	-109.167	1525	COOP	1/1/1914	3/31/1955	No
Portal 4 SW	31.883	-109.206	1643	COOP	1/1/1951	Present	No
Rodeo	31.833	-109.033	1254	COOP	7/1/1909	4/30/1978	No
Rodeo CAA Arpt.	31.933	-108.983	1255	COOP	6/1/1932	1/31/1954	No
Rucker Canyon	31.756	-109.413	1637	COOP	1/1/1893	Present	No
Rustlers Park	31.900	-109.283	2562	COOP	7/1/1948	7/31/1976	No
San Simon	32.271	-109.226	1100	COOP	3/1/1898	Present	No
San Simon 5 NW	32.333	-109.267	1101	COOP	5/1/1898	2/28/1949	No
San Simon 9 ESE	32.167	-109.083	1183	COOP	7/1/1962	10/10/1986	No
Dos Cabezas	32.188	-109.569	2164	RAWS	8/1/1994	6/30/1995	No
Howard Canyon	32.195	-109.570	1902	RAWS	2/1/1996	3/31/1996	No
Rucker	31.761	-109.349	1737	RAWS	5/1/2000	Present	No
Wilcox	32.030	-109.230	1336	UCC	M	Present	No
Coronado National Memorial (CORO)							
Coronado NM Hqs.	31.346	-110.254	1598	COOP	2/1/1960	Present	Yes
Bisbee	31.448	-109.929	1695	COOP	1/22/1985	Present	No
Bisbee	31.433	-109.917	1618	COOP	12/1/1892	1/22/1985	No
Bisbee 2	31.427	-109.895	1539	COOP	6/1/1961	10/4/1996	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Canelo 1 NW	31.559	-110.529	1527	COOP	1/1/1910	Present	No
Coronado Natl. Monument	31.367	-110.283	1693	COOP	7/1/1955	2/28/1960	No
Flying H Ranch	31.400	-110.233	1549	COOP	7/1/1948	4/30/1959	No
Ft. Huachuca	31.567	-110.333	1422	COOP	2/1/1900	1/1/1982	No
Hereford	31.450	-110.100	1488	COOP	7/1/1909	6/30/1948	No
Hereford 8 SW	31.400	-110.233	1534	COOP	3/1/1950	12/31/1950	No
Miller Peak	31.383	-110.300	2885	COOP	6/1/1965	8/31/1967	No
San Rafael Ranch S.P.	31.353	-110.613	1452	COOP	12/1/1892	Present	No
Sierra Vista	31.555	-110.285	1402	COOP	2/26/1982	Present	No
Y Lightning Ranch	31.452	-110.227	1399	COOP	1/1/1939	Present	No
Elgin 5 S	31.591	-110.509	1466	CRN	9/14/2002	Present	No
CW3529 Hereford	31.433	-110.236	1477	CWOP	M	Present	No
N7ZGO Sierra Vista	31.546	-110.263	1375	CWOP	M	Present	No
Carr	31.445	-110.280	1646	RAWS	6/1/1999	Present	No
Ft .Huachuca	31.567	-110.333	1422	SAO	2/1/1900	1/1/1982	No
Ft. Huachuca Pioneer Airfield	31.607	-110.428	1453	SAO	5/9/2006	Present	No
Ft. Huachuca	31.533	-110.333	1439	WBAN	1/1/1989	Present	No
Fort Bowie National Historic Site (FOBO)							
Chiricahua NM	32.009	-109.389	1570	CASTNet	4/1/1989	Present	No
Bowie	32.324	-109.491	1146	COOP	1/1/1899	Present	No
Bowie Junction R15	32.433	-109.700	1440	COOP	7/1/1948	3/31/1967	No
Chiricahua NM	32.006	-109.357	1615	COOP	1/1/1909	Present	No
Dos Cabezas 1 SE	32.167	-109.600	1556	COOP	1/1/1909	4/30/1975	No
Paradise	31.933	-109.217	1656	COOP	1/1/1906	12/31/1937	No
Portal	31.900	-109.167	1525	COOP	1/1/1914	3/31/1955	No
Portal 4 SW	31.883	-109.206	1643	COOP	1/1/1951	Present	No
Rustlers Park	31.900	-109.283	2562	COOP	7/1/1948	7/31/1976	No
San Simon	32.271	-109.226	1100	COOP	3/1/1898	Present	No
San Simon 5 NW	32.333	-109.267	1101	COOP	5/1/1898	2/28/1949	No
San Simon 9 ESE	32.167	-109.083	1183	COOP	7/1/1962	10/10/1986	No
San Simon 9 NE	32.367	-109.133	1220	COOP	7/1/1948	8/31/1953	No
Willcox	32.261	-109.850	1273	COOP	6/1/1898	Present	No
Chiricahua	32.009	-109.389	1570	GPMP	1/1/1990	12/1/1990	No
Chiricahua	32.010	-109.389	1570	NADP	2/23/1999	Present	No
Sugarloaf	32.018	-109.321	2088	NPS	M	Present	No
Chiricahua	32.000	-109.350	1646	RAWS	1/1/1995	Present	No
Dos Cabezas	32.188	-109.569	2164	RAWS	8/1/1994	6/30/1995	No
Howard Canyon	32.195	-109.570	1902	RAWS	2/1/1996	3/31/1996	No
Wilcox	32.030	-109.230	1336	UCC	M	Present	No
Gila Cliff Dwellings National Monument (GICL)							
Gila Center	33.223	-108.240	1707	RAWS	8/1/1998	Present	Yes
Bear Creek Ranch	32.950	-108.417	1617	COOP	1/1/1940	12/31/1959	No
Beaverhead R.S.	33.429	-108.100	2033	COOP	5/21/1916	Present	No
Diamond Bar Ranch	33.183	-108.017	2134	COOP	4/24/1914	11/30/1915	No
Fowler Ranch	33.300	-108.133	1873	COOP	6/1/1948	7/31/1959	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
G O S Ranch	33.000	-108.083	1935	COOP	5/1/1912	12/31/1940	No
Gila 6 NNE	33.033	-108.533	1418	COOP	1/1/1897	1/31/1960	No
Gila 7 NE	33.067	-108.533	1421	COOP	8/1/1978	12/1/1992	No
Gila Hot Springs	33.195	-108.208	1707	COOP	5/1/1957	Present	No
Inman Ranch	33.400	-107.900	2379	COOP	1/1/1941	8/31/1954	No
Mc Cauley Ranch	33.350	-107.950	2126	COOP	8/1/1954	12/1/1968	No
Me Own Strip	33.217	-108.017	2288	COOP	5/1/1958	11/30/1976	No
Mimbres R.S.	32.933	-108.014	1901	COOP	5/1/1905	Present	No
O Bar O R.S.	33.567	-108.367	2327	COOP	5/1/1940	9/30/1951	No
Pinos Altos	32.867	-108.217	2135	COOP	7/1/1911	2/7/1973	No
Willow Creek R.S.	33.400	-108.583	2471	COOP	7/1/1939	11/30/1976	No
Gila Cliff Dwellings N M	33.220	-108.235	1772	NADP	7/29/1985	Present	No
Hummingbird	33.333	-108.633	3216	NRCS-SC	1/1/1964	Present	No
Whitewater	33.317	-108.633	3277	NRCS-SC	1/1/1964	Present	No
Beaverhead	33.418	-108.100	2042	RAWS	10/1/1986	Present	No
McKenna	33.233	-108.400	2621	RAWS	9/1/1993	9/30/1998	No
Signal Peak	32.917	-108.133	2548	SNOTEL	10/1/1980	Present	No
Organ Pipe Cactus National Monument (ORPI)							
Organ Pipe Cactus NM	31.956	-112.800	511	COOP	1/1/1944	Present	Yes
Organ Pipe Cactus NM	31.951	-112.800	506	NADP	4/15/1980	Present	Yes
Acuna Habitat	32.036	-112.915	521	NPS	3/1/1988	Present	Yes
Aguajita Wash	31.948	-113.007	349	NPS	10/1/1987	Present	Yes
Alamo Canyon	32.066	-112.714	735	NPS	4/1/1996	Present	Yes
Bull Pasture	32.012	-112.694	960	NPS	M	Present	Yes
East Armenta	32.185	-112.799	518	NPS	M	Present	Yes
Growler Valley	32.161	-113.018	370	NPS	M	Present	Yes
Middle Bajada	32.087	-112.751	637	NPS	M	Present	Yes
Pozo Nuevo	32.007	-113.035	382	NPS	M	Present	Yes
Salsola Site	31.851	-112.713	445	NPS	M	Present	Yes
Senita Basin	31.947	-112.869	497	NPS	M	Present	Yes
Valley Floor	32.195	-112.851	473	NPS	M	Present	Yes
Lukeville	31.883	-112.817	132	SAO	6/19/1978	6/15/1988	Yes
Ajo	32.369	-112.862	549	COOP	5/1/1914	Present	No
Ajo Well	32.450	-112.833	436	COOP	2/1/1940	4/30/1975	No
Papago Farms	31.783	-112.283	555	COOP	2/1/1959	6/30/1960	No
Pisinemo	32.050	-112.317	580	COOP	8/16/1936	2/28/1956	No
Wahak Hotrontk	32.217	-112.367	580	COOP	3/1/1963	1/31/1967	No
Ajo AAF	32.450	-112.850	438	WBAN	1/1/1942	1/31/1946	No
Saguaro National Park (SAGU)							
Saguaro NM	32.180	-110.737	936	COOP	3/1/1975	Present	Yes
Tucson 17 NW	32.254	-111.196	781	COOP	5/1/1982	Present	Yes
Pima County/Saguaro	32.174	-110.736	938	GPMP	6/1/1982	Present	Yes
Grass Shack	32.188	-110.597	1664	NPS	M	Present	Yes
Happy Valley	32.149	-110.522	1564	NPS	M	Present	Yes
Madrona	32.152	-110.608	1042	NPS	M	Present	Yes

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Manzanita	32.194	-110.564	2112	NPS	M	Present	Yes
Mica Meadows	32.213	-110.538	2554	NPS	M	Present	Yes
North Slope	32.221	-110.555	2454	NPS	M	Present	Yes
RAWS Mate	32.207	-110.549	2505	NPS	M	Present	Yes
Rincon Peak	32.118	-110.525	2499	NPS	M	Present	Yes
Shindagger	32.177	-110.609	1417	NPS	M	Present	Yes
Rincon	32.206	-110.548	2512	RAWS	6/1/1994	Present	Yes
Marana	32.460	-111.230	601	AZMET	M	Present	No
Tucson	32.280	-110.950	713	AZMET	M	Present	No
Anvil Ranch	31.979	-111.383	838	COOP	12/1/1942	Present	No
Apache Powder Company	31.900	-110.250	1124	COOP	7/1/1923	4/4/1990	No
Arizona Sonora Dist. M	32.250	-111.167	860	COOP	10/1/1943	7/1/1973	No
Benson	31.967	-110.300	1119	COOP	6/1/1894	8/6/1975	No
Benson 6 SE	31.880	-110.240	1125	COOP	4/4/1990	Present	No
Cascabel	32.322	-110.415	974	COOP	6/1/1965	Present	No
Catalina S.P.	32.418	-110.930	814	COOP	12/1/2006	Present	No
Cortaro 3 SW	32.333	-111.117	692	COOP	3/1/1945	9/30/1976	No
Green Valley	31.893	-110.998	884	COOP	5/1/1988	Present	No
Helmet Peak	31.950	-111.050	982	COOP	10/19/1940	8/31/1954	No
Helmet Peak Ruby Stn.	31.917	-111.083	1110	COOP	7/1/1948	10/17/1983	No
Helvetia Santa Rita	31.867	-110.783	1312	COOP	6/1/1916	5/31/1950	No
Mt. Fagan Ranch	31.933	-110.767	1147	COOP	7/1/1948	3/21/1968	No
Mt. Lemmon	32.417	-110.717	2345	COOP	5/1/1950	8/31/1957	No
Mt. Lemmon	32.450	-110.750	2376	COOP	9/1/1958	8/27/1987	No
Mt. Lemmon Ski Valley	32.449	-110.780	2502	COOP	8/28/1987	Present	No
Mt. Lemmon Summit	32.450	-110.783	2788	COOP	8/1/1957	9/30/1958	No
N Lazy H Ranch	32.117	-110.683	930	COOP	3/1/1941	1/16/1992	No
Palisade R.S.	32.417	-110.717	2425	COOP	12/1/1964	10/1/1981	No
Picacho 8 SE	32.647	-111.401	558	COOP	10/21/1987	Present	No
Red Rock 6 SSW	32.483	-111.333	573	COOP	1/1/1893	4/26/1974	No
Redington	32.390	-110.467	896	COOP	7/1/1941	Present	No
Robles Junction	32.076	-111.318	771	COOP	3/1/1975	Present	No
Sabino Canyon	32.311	-110.819	805	COOP	7/1/1941	Present	No
Sahuarita 2 NW	31.967	-110.967	820	COOP	2/1/1956	8/31/1972	No
Sahuarita 8 W	31.900	-111.067	1085	COOP	10/17/1983	3/31/1988	No
Silver Bell	32.383	-111.500	835	COOP	2/1/1906	Present	No
Tucson C P Ave. Exp. Farm	32.282	-110.944	710	COOP	1/1/1893	Present	No
Tucson Intl. Arpt.	32.131	-110.955	777	COOP	6/1/1946	Present	No
Tucson Magnetic Obsy.	32.250	-110.833	770	COOP	1/1/1912	3/31/1994	No
Tucson Mtn. Park	32.217	-111.133	817	COOP	10/1/1948	11/30/1948	No
Tucson Nursery 4 NW	32.300	-111.050	686	COOP	7/1/1948	1/31/1965	No
Tucson WBO	32.183	-110.917	780	COOP	11/1/1878	10/14/1948	No
Tucson WFO	32.229	-110.954	742	COOP	9/1/1894	Present	No
Tuscon U Of A #1	32.258	-111.005	706	COOP	5/1/1982	Present	No
Vail	32.046	-110.714	985	COOP	9/1/1977	Present	No
Vail	32.126	-110.725	908	COOP	1/16/1992	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Tucson 11 W	32.239	-111.170	833	CRN	9/18/2002	Present	No
CW1287 Tucson	32.263	-110.724	826	CWOP	M	Present	No
CW1508 Tucson	32.282	-110.983	714	CWOP	M	Present	No
CW1919 Tucson	32.276	-111.003	691	CWOP	M	Present	No
CW2115 Benson	31.960	-110.445	1433	CWOP	M	Present	No
CW2274 Tucson	32.248	-111.030	738	CWOP	M	Present	No
CW2380 Marana	32.452	-111.073	841	CWOP	M	Present	No
CW2737 Tucson	32.201	-111.029	777	CWOP	M	Present	No
CW3090 Oro Valley	32.425	-110.993	860	CWOP	M	Present	No
CW4098 Tucson	32.323	-110.844	879	CWOP	M	Present	No
CW4108 Vail	31.950	-110.795	974	CWOP	M	Present	No
CW4335 Tucson	32.157	-110.770	866	CWOP	M	Present	No
CW4744 Tucson	32.288	-110.844	881	CWOP	M	Present	No
CW5024 Catalina	32.533	-110.884	1006	CWOP	M	Present	No
CW5619 Tucson	32.387	-111.041	760	CWOP	M	Present	No
CW5858 Vail	32.054	-110.702	966	CWOP	M	Present	No
K7VIP Tucson	32.109	-110.796	889	CWOP	M	Present	No
KD6VLN-14 Tucson	32.218	-110.768	851	CWOP	M	Present	No
KD7EIR Tucson	32.196	-110.799	831	CWOP	M	Present	No
KD7LUP Corona	31.956	-110.780	1006	CWOP	M	Present	No
KR7RK Tucson	32.239	-110.787	777	CWOP	M	Present	No
LEMMON NE of Tucson	32.442	-110.780	2725	CWOP	M	Present	No
W3EYD Marana	32.442	-111.407	647	CWOP	M	Present	No
W9JIU Tucson	32.365	-110.972	751	CWOP	M	Present	No
WB6RAO Tucson	32.311	-110.858	866	CWOP	M	Present	No
Tucson	32.220	-110.970	762	GPS-MET	M	Present	No
Tucson (UofA)	32.230	-110.950	762	GPS-MET	M	Present	No
Cargodera	32.441	-110.849	1462	RAWS	3/1/1990	11/30/1998	No
Coronado Portable #1	32.200	-110.400	945	RAWS	6/1/1995	3/31/1996	No
Empire	31.781	-110.635	1417	RAWS	12/1/1988	Present	No
Muleshoe Ranch	32.400	-110.271	1273	RAWS	4/1/1988	Present	No
Saguaro	32.317	-110.813	945	RAWS	6/1/1995	Present	No
Sollers	32.403	-110.712	2377	RAWS	4/1/1999	Present	No
Davis Monthan AFB	32.167	-110.883	809	SAO	5/1/1928	Present	No
Tucson Intl. Arpt.	32.131	-110.955	777	SAO	6/1/1946	Present	No
Marana AAF	32.517	-111.317	576	WBAN	10/1/1928	6/30/1955	No
Tonto National Monument (TONT)							
Saguaro Lake	33.580	-111.540	472	AZ ALERT	M	Present	No
Alamo R.S.	33.500	-110.850	927	COOP	11/1/1915	12/31/1946	No
Apache Junction 5 NE	33.463	-111.481	631	COOP	2/12/1987	Present	No
Aztec Peak	33.817	-110.900	2349	COOP	1/1/1952	7/31/1976	No
Four Peaks	33.717	-111.333	1571	COOP	1/1/1952	7/31/1976	No
Grapevine	33.633	-111.050	677	COOP	6/1/1943	2/28/1952	No
Intake	33.617	-110.933	677	COOP	7/1/1906	8/31/1953	No
Miami	33.404	-110.870	1085	COOP	2/1/1914	Present	No
Mormon Flat	33.554	-111.443	520	COOP	8/2/1923	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Mt. Ord Lookout	33.900	-111.400	2184	COOP	12/1/1941	8/31/1976	No
Parker Creek Mntc. Yd.	33.783	-110.967	1522	COOP	7/1/1948	12/9/1975	No
Pinal Ranch	33.350	-110.983	1379	COOP	3/1/1895	11/21/1973	No
Punkin Center	33.856	-111.306	709	COOP	11/9/1915	Present	No
Roosevelt 1 WNW	33.673	-111.151	672	COOP	7/1/1905	Present	No
Sierra Ancha	33.799	-110.971	1554	COOP	11/1/1913	Present	No
Stewart Mtn.	33.558	-111.536	433	COOP	6/1/1939	Present	No
Summit	33.550	-110.950	1113	COOP	10/1/1951	5/31/1977	No
Superior	33.300	-111.097	872	COOP	7/1/1920	Present	No
Superior 2 ENE	33.305	-111.067	1266	COOP	12/1/1973	Present	No
Superior Smelter	33.300	-111.100	851	COOP	7/1/1948	9/30/1958	No
Workman Creek 1	33.817	-110.917	2126	COOP	7/1/1948	12/31/1985	No
Workman Creek 2	33.817	-110.917	2126	COOP	9/1/1941	3/31/1973	No
Fish Creek NR Globe	33.439	-111.269	747	CRBFC	M	Present	No
Sunflower NR Payson	33.515	-111.281	1049	CRBFC	M	Present	No
NU7R Superior	33.297	-111.098	880	CWOP	M	Present	No
Roosevelt	33.655	-111.133	664	RAWS	1/1/1992	Present	No
Tonto P#2 (Cherry Creek)	33.889	-110.901	1495	RAWS	8/1/2001	Present	No
Workman Creek	33.817	-110.917	2103	SNOTEL	10/1/1982	Present	No
Tumacacori National Historical Park (TUMA)							
Tumacacori NM	31.568	-111.050	996	COOP	4/21/1946	Present	Yes
Amado 1 SE	31.717	-111.050	930	COOP	7/1/1941	12/31/1976	No
Arivaca	31.572	-111.335	1103	COOP	10/1/1899	6/28/2005	No
Bear Valley	31.417	-111.183	1229	COOP	9/1/1943	2/28/1958	No
Calabasas	31.450	-110.983	1046	COOP	9/1/1950	4/30/1975	No
Canelo 1 NW	31.559	-110.529	1527	COOP	1/1/1910	Present	No
Green Valley	31.893	-110.998	884	COOP	5/1/1988	Present	No
Helmet Peak Ruby Stn.	31.917	-111.083	1110	COOP	7/1/1948	10/17/1983	No
Helvetia Santa Rita	31.867	-110.783	1312	COOP	6/1/1916	5/31/1950	No
Nogales	31.350	-110.917	1162	COOP	12/1/1892	6/29/1983	No
Nogales 6 N	31.445	-110.965	1085	COOP	10/1/1952	Present	No
Nogales Old Nogales	31.333	-110.950	1190	COOP	12/1/1892	9/30/1945	No
Patagonia	31.548	-110.752	1277	COOP	7/1/1921	Present	No
Ruby	31.467	-111.233	1312	COOP	1/1/1931	12/31/1944	No
Ruby 4 NW	31.500	-111.283	1214	COOP	4/1/1895	12/31/1955	No
Sahuarita 8 W	31.900	-111.067	1085	COOP	10/17/1983	3/31/1988	No
San Rafael Ranch S.P.	31.353	-110.613	1452	COOP	12/1/1892	Present	No
Santa Rita Exp. Range	31.763	-110.846	1311	COOP	5/1/1950	Present	No
CW4232 Patagonia	31.500	-110.773	1250	CWOP	M	Present	No
Nogales	31.230	-110.980	1222	MEXICO	M	Present	No
Hopkins	31.675	-110.880	2170	RAWS	10/1/2001	Present	No
Sasabe	31.691	-111.450	1067	RAWS	3/1/1992	Present	No
Nogales Intl. Arpt.	31.421	-110.846	1198	SAO	8/1/1950	Present	No

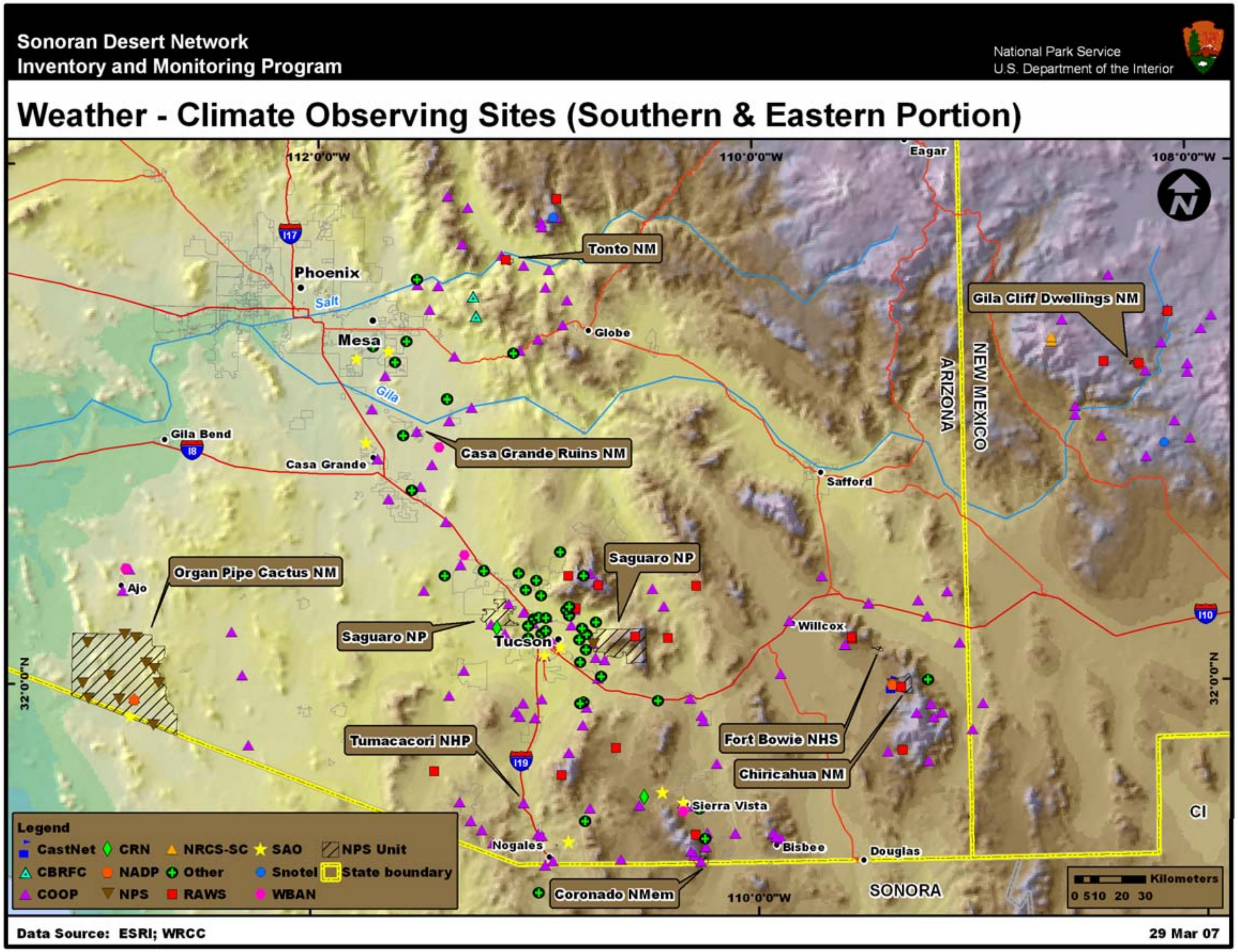


Figure 4.2. Station locations for the southern SODN park units.

We identified 13 COOP stations within 40 km of the boundaries of CHIR (Table 4.4). Only four of these sites are active currently. “Rucker Canyon,” 26 km southwest of CHIR, has the longest data record among these COOP sites (1893-present). This site measures only precipitation. The data record at “Rucker Canyon” had a significant gap from 1897 until 1917. Other than this gap, the data record is very complete. The COOP station “San Simon,” 26 km northeast of CHIR, also has data going back to the 1890s (1898-present). Unfortunately, the data record at “San Simon” is unreliable before January 1987. The COOP station “Bowie” (1899-present) is 33 km north of CHIR. Two big gaps have occurred in the data record at “Bowie.” No temperature observations were taken between October 1939 and February 1951. A second gap occurred for the period 1966-1968, where no temperature or precipitation observations were made. Numerous other small gaps occur in the data record for “Bowie.” The COOP station “Portal 4 SW” (1951-present) is 14 km southeast of CHIR and has a very complete data record.

We identified one station within CORO (Table 4.4). This is a COOP station (Coronado NM Hqs.) which has been active since 1960 and has a very complete data record. Thirteen COOP stations, five active, have been identified within 40 km of the boundaries of CORO. The COOP station “San Rafael Ranch S.P.,” located 31 km west of CORO, provides the longest record among these COOP stations, having been active since 1892; unfortunately, its data record is not reliable. The COOP station “Canelo 1 NW” (1910-present) is 31 km northwest of CORO and was quite reliable from the late 1950s through October 2003. Since 2003, the data record has become much less reliable. The COOP station “Y Lightning Ranch” (1939-present) is 9 km north of CORO and has a very reliable precipitation record (no temperature measurements).

The CRN station “Elgin 5 S” is 33 km northwest of CORO (Figure 4.2) and has provided near-real-time data since 2002 (Table 4.4). It is intended that this station will provide a valuable climate record in the coming decades. Two CWOP stations, one in Hereford and the other in Sierra Vista, provide near-real-time data. The RAWS station “Carr” has been active since 1999 and is 9 km north of CORO. An active SAO station is located at Fort Huachuca’s Pioneer Airfield. Another source of near-real-time data is the WBAN site “Ft. Huachuca” (1989-present).

No weather or climate stations were identified within FOBO. Many of the same stations that were identified for CHIR have also been identified for FOBO. The CASTNet station “Chiricahua NM” is 15 km south of FOBO (Figure 4.2). The NPS station “Sugarloaf” is 17 km south of FOBO. The RAWS station “Chiricahua” is 18 km south of FOBO. Of the five active COOP stations we identified for FOBO, four were also identified with CHIR (Bowie; Chiricahua NM; Portal 4 SW; San Simon). The closest active COOP station to FOBO is “Chiricahua NM,” which is 17 km south of the park unit. Like “San Simon,” the longest COOP data record we found for FOBO, the COOP station “Willcox” also provides a data record going back to 1898. This station is 37 km west of FOBO and its data record has had no major data gaps since the 1950s.

One weather station was identified within the boundaries of GICL (Table 4.4). This is an active RAWS station, “Gila Center,” whose near-real-time data record (1998-present) has been very complete except for a gap in February 2003. The NADP station “Gila Cliff Dwellings N M” (1985-present) is just outside of the park unit. Two other sources of near-real-time weather data are located within 40 km of GICL boundaries. The RAWS station “Beaverhead” is 25 km northeast of GICL (Figure 4.2) and has been active since 1986, although a large gap occurred in this data record between May 1996 and May 2001. The SNOTEL station "Signal Peak" is 35 km southeast of GICL and has been active since 1980.

The closest active COOP station to GICL is "Gila Hot Springs," which is 4 km southeast of the park unit and has a reliable data record going back to 1957 (Table 4.4). The COOP station "Mimbres R.S.," 38 km southeast of GICL, has the longest data record (1905-present) among the active COOP sites within 40 km of GICL. This site's data record is largely complete, being very reliable up until the 1990s. From the 1990s onward, no weekend observations have been recorded at "Mimbres R.S." The COOP station "Beaverhead R.S." (1916-present), 26 km northeast of GICL, has numerous large gaps in its data record.

Two NRCS-SC stations were identified within 40 km of GICL, both starting observations in 1964 (Table 4.4). "Hummingbird" is 35 km northwest of GICL and "Whitewater" is 34 km northwest of GICL (Figure 4.2).

We identified 13 weather and climate stations, all active, within the boundaries of ORPI (Table 4.4; Figure 4.2). The COOP station "Organ Pipe Cactus NM" is located near park headquarters and has a very reliable climate record that goes back to 1944. The NADP station "Organ Pipe Cactus NM" is also located at park headquarters and has been active since 1980. In addition to these two stations, Charles Conner and Jeff Balmat have administered a network of 11 near-real-time weather stations across ORPI. Many of these stations started operating in the 1990s. Outside of ORPI, the only active station within 40 km of the park unit is the COOP station "Ajo," which is 19 km north of ORPI. "Ajo" has been active since 1914 and its data record is very reliable except for a lack of weekend observations starting in the mid-1980s.

We identified 14 weather and climate stations within the boundaries of SAGU (Table 4.4; Figure 4.2). All of these stations are active currently. The COOP station "Saguaro NM" is located in the eastern unit of SAGU but the reliability of its data record is not certain. The COOP station "Tucson 17 NW" has been operating since 1982 in the western unit of SAGU and has a data record that is largely complete, with only scattered, small data gaps. Like ORPI, Charles Conner and Jeff Balmat administer nine weather stations within SAGU. All of these stations are located in the eastern unit of SAGU. The RAWS station "Rincon" is located in the eastern unit of SAGU and has been active since 1994. "Rincon" has had a few gaps in its data record; one gap occurred from December 2000 through January 2001 and another occurred in April 2001.

Several networks have near-real-time weather stations located within 40 km of SAGU units. Two active AZMET stations were identified within 40 km of the boundaries of SAGU (Table 4.4). The closest AZMET station is "Tucson," only 12 km from SAGU boundaries. The CRN station "Tucson 11 W" is only one kilometer away from the western SAGU unit and has provided data since 2002. Numerous CWOP stations are located in the greater Tucson metropolitan area. Two GPS-MET stations operate currently in Tucson, near the University of Arizona campus. Both Davis Monthan Air Force Base and Tucson International Airport host SAO stations. Finally, four active RAWS stations are located within 40 km of SAGU boundaries. "Empire" is 36 km south of the eastern unit of SAGU and "Muleshoe Ranch" is 28 km northeast of the eastern unit of SAGU. Both of these stations began taking observations and 1988 and both have reliable data records. “Saguaro” (1995-present) is 13 km from SAGU boundaries and is the closest active RAWS station outside of SAGU.

We identified 37 COOP stations within 40 km of the boundaries of SAGU (Table 4.4). Seventeen of these sites are active currently. The COOP station “Tucson Camp Ave. Exp. Farm,” 12 km from SAGU, has the longest data record among these COOP sites (1893-present). This site’s data record was not reliable before February 1949. After 1949, this site has had a very reliable data record. The COOP station “Tucson WFO” is 11 km from SAGU and has data going back to 1894. This data record is largely complete, with scattered, small data gaps. The COOP station “Silver Bell” (1906-present) has an unreliable data record. The most complete record we identified was at the COOP station “Tucson Intl. Arpt.,” which is 17 km from SAGU and has data going back to 1946.

No weather or climate stations were identified within TONT. The AZ ALERT station “Saguaro Lake” provides near-real-time precipitation data 39 km southwest of TONT. Two CRBFC stations are located southwest of TONT; “Fish Creek NR Globe” is 26 km from TONT, while “Sunflower NR Payson” is 20 km from TONT. A CWOP station is located at Superior. Two active RAWS stations provide near-real-time data within 40 km of TONT. The RAWS station “Roosevelt” is within a kilometer of TONT (Figure 4.2) and has a very complete data record going back to 1992. The RAWS station “Tonto P#2 (Cherry Creek)” is 32 km northeast of TONT. This site’s observations have been unreliable since June 2006. The SNOTEL station “Workman Creek” (1982-present) is 24 km northeast of TONT.

Of the 21 COOP stations we identified within 40 km of TONT, nine are active (Table 4.4). The closest active COOP station to TONT is “Roosevelt 1 WNW,” which is 3 km northwest of the park unit. This station has been active since 1905 and has a very complete data record. Another reliable long-term climate record comes from the COOP station “Miami” (1914-present), which is 34 km southeast of TONT. The COOP station “Mormon Flat” (1923-present), 30 km west of TONT, has become unreliable in the past 10 years. The COOP station “Punkin Center” (1915-present) is located 28 km northwest of TONT and has a data record that is largely complete, with scattered data gaps throughout. The COOP station “Sierra Ancha” (1913-present) is 20 km northeast of TONT. “Sierra Ancha” has not had reliable observations since September 1979. The COOP station “Stewart Mountain” (1939-present) is 39 km southwest of TONT. The precipitation data record at “Stewart Mountain” has been very reliable since July 1948, while the temperature record has only been reliable since April 1961. The COOP station “Superior” has been active since 1920 and is located 38 km south of TONT. This station’s data record is quite complete for precipitation but temperatures have only been reliable since October 1953. A data gap occurred at “Superior” from April to October of 1998.

We identified one climate station within the boundaries of TUMA (Table 4.4). This is an active COOP station, “Tumacacori NM,” whose data record (1946-present) has been very reliable. In addition to this COOP station, six active COOP stations are located within 40 km of TUMA. The COOP station “Canelo 1 NW,” discussed previously, is 39 km east of TUMA. The COOP station “San Rafael Ranch S.P.” is 28 km southeast of the park unit and is the longest data record within 40 km of TUMA (1892-present), although this data record has significant problems (see previous discussion on this station). The COOP station “Patagonia” (1921-present), 21 km east of TUMA, measures only precipitation and has a reliable data record. The COOP station “Santa Rita Exp. Range” is 28 km northeast of TUMA and has been active since 1950. The data record at this site is largely complete, with scattered gaps. The COOP station “Nogales 6 N” (1952-present) is just outside of the park unit and has a very reliable data record.

We identified four weather stations that provide near-real-time data within 40 km of TUMA. A CWOP station is located in Patagonia, 16 km southeast of TUMA. The SAO station “Nogales Intl. Arpt.” is 5 km southeast of TUMA (Figure 4.2) and has been active since 1950 (Table 4.4). Two RAWS stations provide near-real-time data in the vicinity of TUMA. “Hopkins” (2001-present) is 19 km northeast of TUMA and has a very reliable data record. “Sasabe” (1992-present) is 40 km northwest of TUMA and also has a very reliable data record.

5.0. Conclusions and Recommendations

We have based our findings on an examination of available climate records within SODN 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 SODN.

5.1. Sonoran Desert Inventory and Monitoring Network

Much of the desert environment around SODN park units has little or no weather or climate station coverage, particularly for those units that are not near major cities such as Phoenix and Tucson. For example, we only identified six stations within 40 km of the boundaries of ORPI. Fortunately, ORPI has an active network of weather stations within its boundaries, providing valuable weather data across the desert landscape of ORPI.

Many of the SODN park units are quite small and must therefore rely heavily on outside sources of weather and climate data. This is particularly true for near-real-time weather data. The only park units within which near-real-time data are observed include CHIR, GICL, ORPI, and SAGU. Two park units, FOBO and TONT, have no weather or climate stations within their boundaries. Both a COOP station and a RAWS station are located within 3 km of TONT, providing long-term climate data and near-real-time weather data. There are no near-real-time stations within 15 km of FOBO. If near-real-time weather data is desired from FOBO, the park unit could consider working with local agencies (e.g., BLM) to install a RAWS station, as the RAWS network already has a notable presence in the area. Due to the relatively close proximity of CHIR and FOBO to each other, FOBO can also rely on stations identified in and near CHIR for its weather and climate data. Two SODN park units, CAGR and SAGU, are located near more urban settings (CAGR – southeast Phoenix/Mesa; SAGU – Tucson) and can therefore take advantage of weather and climate data provided by numerous stations in these areas.

Despite the limited station coverage in and around many SODN park units, many of these same park units (CAGR, CHIR, MOCA, ORPI, TUMA, and TUZI) have at least one reliable long-term climate station located within their boundaries. This situation is very helpful in meeting the SODN climate monitoring objective of documenting long-term trends in temperature and precipitation, as laid out in Section 1.1. Other climate monitoring objectives of the SODN, as presented in Section 1.1., include better documentation of spatial weather and climate variations, particularly at local scales with respect to topographical variations in and around SODN park units. Some park units, such as ORPI and the eastern unit of SAGU, are already actively establishing weather station networks to help meet this objective. However, other larger park units in the SODN, such as the western unit of SAGU, are still lacking sufficient station coverage to begin addressing spatial weather and climate characteristics. We identified no automated weather stations within the western unit of SAGU. The closest automated data for this unit comes from the CRN station “Tucson 11 W.” Although observations from this site are probably sufficient at the present time to document overall near-real-time weather conditions within the western unit of SAGU, additional stations would be needed to better understand local-scale characteristics such as the spatial distribution of precipitation during convective storms in the summer monsoon season. Expansion of the NPS-operated networks of weather stations such as those already in place in ORPI and eastern SAGU could help address this issue.

5.2. Spatial Variations in Mean Climate

With local variations over short horizontal and vertical distances, topography introduces considerable fine-scale structure to mean climate (temperature and precipitation) within the SODN park units. Issues encountered in mapping mean climate are discussed in Appendix D and in Redmond et al. (2005).

For areas where new stations will be installed, if only a few new 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

There is much interest in the adaptation of SODN ecosystems in response to possible future climate change. In particular, there are concerns about the potential impact of global warming on species extinctions and the ability of species to adapt to future climate changes. If temperatures continue to warm, local extinction of some species is likely.

The desire for credible, accurate, complete, and long-term climate records—from any location—cannot be overemphasized. Thus, 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 consequence of diversity within SODN in both topography and in land use patterns.

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. In many settings (such as heavily forested areas) 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 and climate stations. Most weather and 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 and curiosity 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 SODN 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 SODN park units but also to climate-monitoring efforts for SODN. 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 Web pages, as well as through http://www.wrcc.dri.edu/summary. These summaries are generally for COOP stations.

5.6. Summarized Conclusions and Recommendations

- The desert environment around many SODN park units has little or no station coverage, particularly near-real-time weather station coverage.
- Some SODN park units are near more heavily populated areas and thus have denser station coverages available outside their boundaries (e.g., Phoenix for CAGR and Tucson for SAGU).
- Many SODN park units have at least one reliable long-term climate record within their boundaries.
- Both ORPI and the eastern unit of SAGU contain valuable arrays of NPS-operated near-real-time weather stations.
- FOBO has no near-real-time data within 15 km of its boundaries. The park unit may consider new RAWS installation as well as utilizing stations in and near CHIR.

- No near-real-time weather stations are present in the western unit of SAGU. The CRN station just outside this unit provides useful near-real-time data. In addition, NPS may consider expanding network of stations already present in ORPI and eastern SAGU to include stations in western SAGU.

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Appendix A. 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 B. 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.)

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

B.1.1. 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.1.2. Processing algorithms and changes in these algorithms must be well documented. Documentation should be carried with the data throughout the data-archiving process.

B.1.3. 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.

B.1.4. 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.

B.1.5. 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.

B.1.6. Where feasible, some level of "low-technology" backup to "high-technology" observing systems should be developed to safeguard against unexpected operational failures.

B.1.7. 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.

B.1.8. 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.

B.1.9. 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.

B.1.10. 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.

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

B.2.1. 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.2.2. 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)

B.2.3. 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)

B.2.4. 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)

B.2.5. 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)

B.2.6. Maintain long-term weather and climate stations.

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

B.2.7. 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)

B.2.8. 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)

B.2.9. Carefully consider the transition from research-observing system to long-term operation.

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

B.2.10. 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)

B.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 C. Factors in operating a weather/ 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. 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.

D.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.

D.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; 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.

D.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.

D.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.

D.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.

D.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”).

D.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.

D.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.

D.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 a 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.

D.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* (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.

D.1.10. Frozen Precipitation

Frozen precipitation is more difficult to measure than liquid precipitation, especially with automated techniques. Sevruk and Harmon (1984), Goodison et al. (1998), 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. 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.

D.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.) 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.

D.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.

D.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.

D.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.

D.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.

D.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.

D.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 U.S.

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 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.

D.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 climate-change issue is quite complex because it encompasses more than just greenhouse gasses.

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.

D.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.

D.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.

D.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.

D.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.

D.3.1. Equipment and Exposure Factors

D.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.

D.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.

D.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.

D.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.

D.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.

D.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.

D.3.2. Element-Specific Factors

D.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.

D.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.

D.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: 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 oceans, 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.

D.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.

D.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.

D.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.

D.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.

D.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.

D.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.

D.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.

D.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.

D.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.

D.3.3. Long-Term Comparability and Consistency

D.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.

D.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 E. 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.
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 F. Electronic supplements

F.1. ACIS metadata file for weather and climate stations associated with the SODN: http://www.wrcc.dri.edu/nps/pub/SODN/metadata/SODN_from_ACIS.tar.gz.

F.2. SODN metadata files for weather and climate stations associated with the SODN: http://www.wrcc.dri.edu/nps/pub/SODN/metadata/SODN_NPS.tar.gz.

Appendix G. Descriptions of weather/climate monitoring networks

G.1. The Arizona ALERT Network (AZ ALERT)

- Purpose of network: provide weather data to monitor possible flooding events in central Arizona.
- Data website: http://rfcd.pima.gov/alertsys/index.cfm.
- Measured weather/climate elements:
  - Precipitation.
  - Humidity (some sites).
  - Temperature (some sites).
  - Wind speed and direction (some sites).
  - Barometric pressure (some sites).
- Sampling frequency:
  - Precipitation: every 12 hours, except every increment (tip of tipping bucket) during precipitation events.
  - Humidity: 5 minutes.
  - Temperature: 5 minutes.
  - Wind speed and direction: each 3 km of wind run.
  - Pressure: every 17 minutes.
- Reporting frequency: 12 hours.
- Estimated station cost: unknown.
- Network strengths:
  - Data are in near-real-time.
  - High-quality data and metadata.
- Network weaknesses:
  - Limited geographic extent (central Arizona).

The AZ ALERT network provides timely information primarily for Pima County residents on possible flooding events. This network measures precipitation, stormwater runoff, and other weather conditions. This network started in 1983 and has grown to 84 precipitation gauges, 30 stream stage sensors, and four automatic weather stations in eastern Pima County and adjoining counties. Data is sent in near-real-time to NWS to ground-truth radar precipitation estimates and assist in issuing flood watches and warnings. This data is also used to reconstruct past storm events.

G.2. The Arizona Meteorological Network (AZMET)

- Purpose of network: provide weather data to agricultural and horticultural interests in southern and central Arizona.
- Data website: http://ag.arizona.edu/azmet.
- Measured weather/climate elements:
  - Air temperature.
  - Relative humidity and dewpoint temperature.
  - Precipitation.

  - Wind speed and direction.
  - Solar radiation.
  - Soil temperature.
- Sampling frequency: hourly.
- Reporting frequency: hourly.
- Estimated station cost: unknown.
- Network strengths:
  - Data are in near-real-time.
  - High-quality data and metadata.
- Network weaknesses:
  - Limited geographic extent (southern and central Arizona).

The Arizona Meteorological Network (AZMET) provides near-real-time weather data that is used primarily for agricultural applications in southern and central Arizona. This network began operating stations in January, 1987.

G.3. 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: $13000.
- Network strengths:
  - High-quality data.
  - Sites are well-maintained.
- Network weaknesses:
  - Density of station coverage is low.
  - Shorter periods of record for western U.S.

The CASTNet network is 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.

G.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: $2000 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 U.S. 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.

G.5. Colorado River Basin Forecast Center (CRBFC) Network

- Purpose of network: provide weather data for river forecasting efforts in Colorado River Basin.
- Data website: http://www.met.utah.edu/jhorel/html/mesonet.
- Measured weather/climate elements:

  - Air temperature.
  - Precipitation.
- Sampling frequency: hourly.
- Reporting frequency: hourly.
- Estimated station cost: unknown.
- Network strengths:
  - Data are in near-real-time.
- Network weaknesses:
  - Instrumentation platforms do sometimes vary.

The CRBFC network has over 100 weather stations in the Colorado River Basin. The primary purpose of CRBFC stations is to collect meteorological data in support of efforts by the CRBFC to monitor potential flood conditions in the Colorado River Basin.

G.6. 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: $30000 with maintenance costs around $2000/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 U.S. 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.

G.7. Citizen Weather Observer Program (CWOP)

- Purpose of network: collect observations from private citizens and make these data available for homeland security and other weather applications, providing constant feedback to the observers to maintain high data quality.
- Primary management agency: NOAA MADIS program.
- Data Website: http://www.wxqa.com.
- Measured weather/climate elements:
  - Air temperature.
  - Dewpoint temperature.
  - Precipitation.
  - Wind speed and direction.
  - Barometric pressure.
- Sampling frequency: 15 minutes or less.
- Reporting frequency: 15 minutes.
- Estimated station cost: unknown.
- Network strengths:
  - Active partnership between public agencies and private citizens.
  - Large number of participant sites.
  - Regular communications between data providers and users, encouraging higher data quality.
- Network weaknesses:
  - Variable instrumentation platforms.
  - Metadata are sometimes limited.

The CWOP network is a public-private partnership with U.S. citizens and various agencies including NOAA, NASA (National Aeronautics and Space Administration), and various universities. There are over 4500 registered sites worldwide, with close to 3000 of these sites located in North America.

G.8. NPS Gaseous Pollutant Monitoring Program (GPMP)

- Purpose of network: measurement of ozone and related meteorological elements.
- Primary management agency: NPS.
- Data website: http://www2.nature.nps.gov/air/monitoring.
- Measured weather/climate elements:
  - Air temperature.
  - Relative humidity.
  - Precipitation.
  - Wind speed and direction.
  - Solar radiation.
  - Surface wetness.
- Sampling frequency: continuous.
- Reporting frequency: hourly.
- Estimated station cost: unknown.

- Network strengths:
  - Stations are located within NPS park units.
  - Data quality is excellent, with high data standards.
  - Provides unique measurements that are not available elsewhere.
  - Records are up to 2 decades in length.
  - Site maintenance is excellent.
  - Thermometers are aspirated.
- Network weaknesses:
  - Not easy to download the entire data set or to ingest live data.
  - Station spacing and coverage: station installation is episodic, driven by opportunistic situations.

The NPS web site indicates that there are 33 sites with continuous ozone analysis run by NPS, with records from a few to about 16-17 years. Of these stations, 12 are labeled as GPMP sites and the rest are labeled as CASTNet sites. All of these have standard meteorological measurements, including a 10-m mast. Another nine GPMP sites are located within NPS units but run by cooperating agencies. A number of other sites (1-2 dozen) ran for differing periods in the past, generally less than 5-10 years.

G.9. NOAA Ground-Based GPS Meteorology (GPS-MET) Network

- Purpose of network:
  - Measure atmospheric water vapor using ground-based GPS receivers.
  - Facilitate use of these data operational and in other research and applications.
  - Provides data for weather forecasting, atmospheric modeling and prediction, climate monitoring, calibrating and validation other observing systems including radiosondes and satellites, and research.
- Primary management agency: NOAA Earth System Research Laboratory.
- Data website: http://gpsmet.noaa.gov/jsp/index.jsp.
- Measurements:
  - Dual frequency carrier phase measurements every 30 seconds.
- Ancillary weather/climate observations:
  - Air temperature.
  - Relative humidity.
  - Barometric pressure.
- Reporting frequency: currently 30 min.
- Estimated station cost: \$0-\$10000, depending on approach. Data from dual frequency GPS receivers installed for conventional applications (e.g. high accuracy surveying) can be used without modification.
- Network strengths:
  - Frequent, high-quality measurements.
  - High reliability.
  - All-weather operability.
  - Many uses.
  - Highly leveraged.
  - Requires no calibration.

    - Measurement accuracy improves with time.
- Network weakness:
    - Point measurement.
    - Provides no direct information about the vertical distribution of water vapor.

The GPS-MET network is the first network of its kind dedicated to GPS meteorology (see Duan et al. 1996). The GPS-MET network was developed in response to the need for improved moisture observations to support weather forecasting, climate monitoring, and other research activities. GPS-MET is a collaboration between NOAA and several other governmental and university organizations and institutions.

GPS meteorology utilizes the radio signals broadcast by the satellite Global Positioning System for atmospheric remote sensing. GPS meteorology applications have evolved along two paths: ground-based (Bevis et al. 1992) and space-based (Yuan et al. 1993). Both applications make the same fundamental measurement (the apparent delay in the arrival of radio signals caused by changes in the radio-refractivity of the atmosphere along the paths of the radio signals) but they do so from different perspectives.

In ground-based GPS meteorology, a GPS receiver and antenna are placed at a fixed location on the ground and the signals from all GPS satellites in view are continuously recorded. From this information, the exact position of the GPS antenna can be determined over time with high (millimeter-level) accuracy. Subsequent measurements of the antenna position are compared with the known position, and the differences can be attributed to changes in the temperature, pressure and water vapor in the atmosphere above the antenna. By making continuous measurements of temperature and pressure at the site, the total amount of water vapor in the atmosphere at this location can be estimated with high accuracy under all weather conditions. For more information on ground based GPS meteorology the reader is referred to http://gpsmet.noaa.gov.

In space-based GPS meteorology, GPS receivers and antennas are placed on satellites in Low Earth Orbit (LEO), and the signals transmitted by a GPS satellite are continuously recorded as a GPS satellite “rises” or “sets” behind the limb of the Earth. This process is called an occultation or a limb sounding. The GPS radio signals bend more as they encounter a thicker atmosphere and the bending (which causes an apparent increase in the length of the path of the radio signal) can be attributed to changes in temperature, pressure and water vapor along the path of the radio signal through the atmosphere that is nominally about 300 km long. The location of an occultation depends on the relative geometries of the GPS satellites in Mid Earth Orbit and the satellites in LEO. As a consequence, information about the vertical temperature, pressure and moisture structure of the Earth’s atmosphere as a whole can be estimated with high accuracy, but not at any one particular place over time. The main difference between ground and space-based GPS meteorology is one of geometry. A space-based measurement can be thought of as a ground-based measurement turned on its side. For more information on space based GPS meteorology, the reader is referred to http://www.cosmic.ucar.edu/gpsmet/.

G.10. Mexico Weather/Climate Stations (MEXICO)

- Purpose of network: provide weather/climate data for forecasting and climate-monitoring efforts in Mexico.

- Primary management agency: Servicio Meteorológico Nacional.
- Data website: http://smn.cna.gob.mx.
- Measured weather/climate elements:
    - Air temperature.
    - Barometric pressure.
    - Relative humidity and dewpoint temperature.
    - Precipitation.
    - Wind speed and direction.
    - Wind gust and direction.
    - Solar radiation.
    - Sky Cover.
    - Ceiling.
    - Visibility.
- Sampling frequency: hourly.
- Reporting frequency: hourly.
- Estimated station cost: unknown.
- Network strengths:
    - Near-real-time data.
    - Some periods of record are relatively long.
- Network weaknesses:
    - Sites are only in Mexico, so usefulness limited to NPS park units in extreme southern U.S.
    - Limited data access.

These include various automated weather/climate station networks from Mexico. Servicio Meteorológico Nacional operates many of these stations, including airport sites. The data measured at these sites generally include temperature, precipitation, humidity, wind, pressure, sky cover, ceiling, visibility, and current weather. Most of the data records are of high quality.

G.11. National Atmospheric Deposition Program (NADP)

- Purpose of network: measurement of precipitation chemistry and atmospheric deposition.
- Primary management agencies: USDA, but multiple collaborators.
- Data website: http://nadp.sws.uiuc.edu.
- Measured weather/climate elements:
    - Precipitation.
- Sampling frequency: daily.
- Reporting frequency: daily.
- Estimated station cost: unknown.
- Network strengths:
    - Data quality is excellent, with high data standards.
    - Site maintenance is excellent.
- Network weaknesses:
    - A very limited number of climate parameters are measured.

Stations within the NADP network monitor primarily wet deposition through precipitation chemistry at selected sites around the U.S. and its territories. The network is a collaborative effort among several agencies including USGS and USDA. Precipitation is the primary climate parameter measured at NADP sites. The NADP network includes MDN sites.

G.12. USDA/NRCS Snowcourse Network (NRCS-SC)

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

G.13. Remote Automated Weather Station (RAWS) Network

- 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: $12000 with satellite telemetry ($8000 without satellite telemetry); maintenance costs are around $2000/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 U.S. 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 1100 real-time sites in this network and about 1800 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.

G.14. NWS/FAA Surface Airways Observation Network (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: $100000–$200000, with maintenance costs approximately $10000/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.

G.15. USDA/NRCS Snowfall Telemetry (SNOTEL) network

- Purpose of network: collect snowpack and related climate data to assist in forecasting water supply in the western U.S.
- 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: $20000 with maintenance costs approximately $2000/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.

G.16. Weather For You Network (WX4U)

- Purpose of network: allow volunteer weather enthusiasts around the U.S. to observe and share weather data.
- 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.
    - Wind gust and direction.
- Sampling frequency: 10 minutes.
- Reporting frequency: 10 minutes.
- Estimated station cost: unknown.
- Network strengths:
    - Stations are located throughout the U.S.
    - Stations provide near-real-time observations.
- Network weaknesses:
    - Instrumentation platforms can be variable.
    - Data are sometimes of questionable quality.

The WX4U network is a nationwide collection of weather stations run by local observers. Meteorological elements that are measured usually include temperature, precipitation, wind, and humidity.

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