



Weather and Climate Inventory

National Park Service

Southern Plains Network

Natural Resource Technical Report NPS/SOPN/NRTR—2007/040



ON THE COVER

Storm clouds over ruins at Pecos National Historical Park
Photograph copyrighted by National Park Service

Weather and Climate Inventory

National Park Service

Southern Plains Network

Natural Resource Technical Report NPS/SOPN/NRTR—2007/040
WRCC Report 2007-15

Christopher A. Davey, Kelly T. Redmond, and David B. Simeral
Western Regional Climate Center
Desert Research Institute
2215 Raggio Parkway
Reno, Nevada 89512-1095

May 2007

U.S. Department of the Interior
National Park Service
Natural Resource Program Center
Fort Collins, Colorado

The Natural Resource Publication series addresses natural resource topics that are of interest and applicability to a broad readership in the National Park Service and to others in the management of natural resources, including the scientific community, the public, and the National Park Service conservation and environmental constituencies. Manuscripts are peer-reviewed to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

The Natural Resources Technical Reports series is used to disseminate the peer-reviewed results of scientific studies in the physical, biological, and social sciences for both the advancement of science and the achievement of the National Park Service mission. The reports provide contributors with a forum for displaying comprehensive data that are often deleted from journals because of page limitations. Current examples of such reports include the results of research that address natural resource management issues; natural resource inventory and monitoring activities; resource assessment reports; scientific literature reviews; and peer-reviewed proceedings of technical workshops, conferences, or symposia.

Views and conclusions in this report are those of the authors and do not necessarily reflect policies of the National Park Service. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the National Park Service.

Printed copies of reports in these series may be produced in a limited quantity and they are only available as long as the supply lasts. This report is also available from the Natural Resource Publications Management website (<http://www.nature.nps.gov/publications/NRPM>) on the Internet or by sending a request to the address on the back cover.

Please cite this publication as follows:

Davey, C. A., K. T. Redmond, and D. B. Simeral. 2007. Weather and Climate Inventory, National Park Service, Southern Plains Network. Natural Resource Technical Report NPS/SOPN/NRTR—2007/040. National Park Service, Fort Collins, Colorado.

NPS/SOPN/NRTR—2007/040, May 2007

Contents

	Page
Figures	v
Tables	vi
Appendixes	vii
Acronyms	viii
Executive Summary	x
Acknowledgements	xii
1.0. Introduction	1
1.1. Network Terminology	1
1.2. Weather versus Climate Definitions	2
1.3. Purpose of Measurements	4
1.4. Design of Climate-Monitoring Programs	4
2.0. Climate Background	9
2.1. Climate and the SOPN Environment	9
2.2. Spatial Variability	10
2.3. Temporal Variability	10
2.4. Parameter Regression on Independent Slopes Model	16
3.0. Methods	19
3.1. Metadata Retrieval	19
3.2. Criteria for Locating Stations	21
4.0. Station Inventory	22
4.1. Climate and Weather Networks	22
4.2. Station Locations	25

Contents (continued)

	Page
5.0. Conclusions and Recommendations	41
5.1. Southern Plains Inventory and Monitoring Network	41
5.2. Spatial Variations in Mean Climate	41
5.3. Climate Change Detection	42
5.4. Aesthetics	42
5.5. Information Access	43
5.6. Summarized Conclusions and Recommendations	43
6.0. Literature Cited	44

Figures

	Page
Figure 1.1. Map of the Southern Plains Network	3
Figure 2.1. Mean annual precipitation, 1961–1990, for the SOPN	11
Figure 2.2. Mean monthly precipitation at selected locations in the SOPN	12
Figure 2.3. Mean annual temperature, 1961–1990, for the SOPN	13
Figure 2.4. Mean January minimum temperature, 1961–1990, for the SOPN	14
Figure 2.5. Mean July maximum temperature, 1961–1990, for the SOPN	15
Figure 2.6. Precipitation time series, 1895-2005, for selected regions in the SOPN	17
Figure 2.7. Temperature time series, 1895-2005, for selected regions in the SOPN	18
Figure 4.1. Station locations for the SOPN park units in Colorado, New Mexico, and northern Texas	31
Figure 4.2. Station locations for FOLS	34
Figure 4.3. Station locations for the SOPN park units in Oklahoma	37
Figure 4.4. Station locations for LYJO	40

Tables

	Page
Table 1.1. Park units in the Southern Plains Network	2
Table 3.1. Primary metadata fields for SOPN weather and climate stations	20
Table 4.1. Weather and climate networks represented within the SOPN	22
Table 4.2. Number of stations within or nearby SOPN park units	25
Table 4.3. Weather and climate stations for the SOPN park units in Colorado, New Mexico, and northern Texas	26
Table 4.4. Weather and climate stations for FOLS	35
Table 4.5. Weather and climate stations for the SOPN park units in Oklahoma	35
Table 4.6. Weather and climate stations for LYJO	39

Appendixes

	Page
Appendix A. Glossary	48
Appendix B. Climate-monitoring principles	50
Appendix C. Factors in operating a climate network	53
Appendix D. General design considerations for weather/climate-monitoring programs	56
Appendix E. Master metadata field list	76
Appendix F. Electronic supplements	78
Appendix G. Descriptions of weather/climate-monitoring networks	79

Acronyms

AASC	American Association of State Climatologists
ACIS	Applied Climate Information System
ALFL	Alibates Flint Quarries National Monument
ASOS	Automated Surface Observing System
AWOS	Automated Weather Observing System
BEOL	Bent's Old Fort National Historic Site
BLM	Bureau of Land Management
CAVO	Capulin Volcano National Monument
CDOT	Colorado Department of Transportation network
CHIC	Chickasaw National Recreation Area
CoAgMet	Colorado Agricultural Meteorological Network
COOP	Cooperative Observer Program
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
FOLS	Fort Larned National Historic Site
FOUN	Fort Union National Monument
GMT	Greenwich Mean Time
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
GPS-MET	NOAA ground-based GPS meteorology
I&M	NPS Inventory and Monitoring Program
LAMR	Lake Meredith National Recreation Area
LEO	Low Earth Orbit
LST	local standard time
LYJO	Lyndon B. Johnson National Historical Park
MDN	Mercury Deposition Network
NADP	National Atmospheric Deposition Program
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
OKMESO	Oklahoma Mesonet
PECO	Pecos National Historical Park
PRISM	Parameter Regression on Independent Slopes Model

RAWS	Remote Automated Weather Station network
RCC	regional climate center
SAND	Sand Creek Massacre National Historic Site
SAO	Surface Airways Observation network
SCAN	Soil Climate Analysis Network
SOD	Summary Of the Day
SOPN	Southern Plains Inventory and Monitoring Network
Surfrad	Surface Radiation Budget network
SNOTEL	Snowfall Telemetry network
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
UTC	Coordinated Universal Time
WABA	Washita Battlefield National Historic Site
WBAN	Weather Bureau Army Navy
WMO	World Meteorological Organization
WRCC	Western Regional Climate Center

Executive Summary

Climate is one of the 12 basic inventories to be completed for all National Park Service (NPS) Inventory and Monitoring Program (I&M) networks and it is a dominant factor driving the physical and ecologic processes affecting the Southern Plains Inventory and Monitoring Network (SOPN). The SOPN climate is typified by highly variable and stormy weather patterns. Moist air masses from the Pacific Ocean lose their moisture over the Rocky Mountains, causing precipitation over the mountains and drier conditions on the leeward side of the mountains. These drier conditions result in the short-grass ecosystem of the western plains. As these air masses continue across the broad flat plain they experience increasing interaction with arctic air masses from the north and more humid air masses to the east. The increased precipitation in these areas supports the mixed-grass of the central plains and the tall-grass prairie of the eastern plains. The organisms that live in this area must be adapted to surviving extreme climate conditions. In some cases, native SOPN plants actually take advantage of these climate extremes in order to colonize areas. Drought can lead to massive local extinctions of annual forbs and grasses that have invaded stands of perennial species. The impact of global climate change may be exacerbated in the SOPN due to the region's periodic droughts and the large number of habitat specialists. Species extinctions may occur due to the inability to re-colonize in response to future climate changes.

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

- Overview of broad-scale climatic factors and zones important to SOPN park units.
- Inventory of weather and climate station locations in and near SOPN 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.

Precipitation in the SOPN generally increases to the east, although localized higher precipitation amounts are also evident in the higher elevations of New Mexico. Mean annual precipitation ranges from around 300 mm near Bent's Old Fort National Historic Site (BEOL) to almost 1000 mm around Chickasaw National Recreation Area (CHIC). Precipitation in the SOPN generally peaks in mid- to late-summer, with some additional autumn maxima in central Texas. The general temperature gradient in the SOPN is from cooler temperatures in the northwest to warmer temperatures in the southeast. Mean annual temperatures in SOPN park units range from 8°C in the higher park units in New Mexico (e.g., Fort Union National Monument-FOUN, Pecos National Historical Park-PECO), up to almost 18°C at Lyndon B. Johnson National Historical Park (LYJO). Winter temperatures in the SOPN, like mean annual temperatures, generally follow a northwest-southeast gradient across the Great Plains. January minimum temperatures regularly are near -12°C at Sand Creek Massacre National Historic Site (SAND) and are as warm as 0°C for LYJO. July maximum temperatures are generally between 32°C and 35°C throughout the SOPN, except for the park units in New Mexico, where July maximum temperatures are

between 26°C and 29°C. The El Niño-Southern Oscillation (ENSO) causes interannual climate variations in the SOPN. El Niño conditions (warm ENSO phases) are associated with cooler, wetter conditions. Daily precipitation around the SOPN region during the last century shows no significant trend. Long-term time series of temperatures in the SOPN vary greatly throughout the network, with warming in some places (e.g., southeastern Colorado and Oklahoma) and neutral conditions in other places (e.g., central Texas).

Through a search of national databases and inquiries to NPS staff, we have identified six weather and climate stations within SOPN park units. Capulin Volcano National Monument (CAVO) and CHIC both have the most stations within park boundaries (two). Most of the weather and climate stations identified for SOPN park units had metadata and data records that are sufficiently complete and satisfactory in quality.

Most of the SOPN park units do not currently have any weather and climate stations within their boundaries. Only three park units (CAVO, CHIC, and PECO) have stations. Therefore, SOPN park units generally must rely on outside sources of weather and climate data in order to carry out their climate monitoring activities. These activities will benefit by encouraging the continued operation of active stations having longer climate records, as these records provide valuable documentation of ongoing climate changes within SOPN park units.

Those SOPN units which do not have any weather or climate stations within their boundaries could consider ways to add stations to their park units. The lack of weather and climate stations within SOPN park units is particularly evident for near-real-time weather stations. LYJO is the only park unit that has an automated weather station, the RAWS (Remote Automated Weather Station) site “Bird.” Although most of the SOPN park units have a few automated sites that are nearby, one of the park units, CAVO, has no automated station coverage within 40 km of their boundaries. We recommend that a RAWS station be considered for CAVO, due to its setting in the high desert/grassland environments of northern New Mexico. Even SAND may be able to benefit from improving the coverage of automated stations in its vicinity, as the closest automated site is 22 km from the park unit. The Oklahoma Mesonet is a reliable source of near-real-time data for those SOPN park units that are in Oklahoma. Many of the remaining park units outside of Oklahoma are located in intensive agricultural areas. Therefore, to expand near-real-time station coverage in or near these park units, one strategy may be to install SCAN (Soil Climate Analysis Network) stations in these areas. The SCAN network is intended primarily for weather and climate monitoring in agricultural areas in the U.S.

All of the SOPN park units do have at least a few sources of long-term climate records within 40 km of their boundaries. However, some of these long-term records should be used with caution. This includes the COOP (Cooperative Observer Program) station “Las Animas,” near BEOL. Another example of this can be found with the COOP station records we identified within CHIC (“Chickasaw NRA” and “Sulphur Platt Nl. Pk”), which may actually be from one station that has moved. If these two records are interpreted as coming from one station, care must be taken to interpret their combined records properly.

Acknowledgements

This work was supported and completed under Task Agreement H8R07010001, with the Great Basin Cooperative Ecosystem Studies Unit. We would like to acknowledge very helpful assistance from various National Park Service personnel associated with the Southern Plains Inventory and Monitoring Network in Johnson City, Texas. Particular thanks are extended to Heidi Sosinski and Dusty Perkins. We also thank John Gross, Margaret Beer, Grant Kelly, Greg McCurdy, and Heather Angeloff for all their help. Seth Gutman with the National Oceanic and Atmospheric Administration Earth Systems Research Laboratory provided valuable input on the GPS-MET station network. Portions of the work were supported by the NOAA Western Regional Climate Center.

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). 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; Rodriguez-Iturbe 2000; Perkins 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 Southern Plains Inventory and Monitoring Network (SOPN) 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 SOPN (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 SOPN park units.
- Inventory of locations for all weather stations in and near SOPN 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 to be addressed by climate- and weather-monitoring activities in SOPN are as follows (Perkins et al. 2005):

- A. Determine trends in air temperature and precipitation.
- B. Identify extreme climatic events.
- C. Determine how climate trends correlate with other network monitoring programs.

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 and climate station networks. See Appendix A for a full definition of these terms.

Table 1.1. Park units in the Southern Plains Network.

Acronym	Name
ALFL	Alibates Flint Quarries National Monument
BEOL	Bent's Old Fort National Historic Site
CAVO	Capulin Volcano National Monument
CHIC	Chickasaw National Recreation Area
FOLS	Fort Larned National Historic Site
FOUN	Fort Union National Monument
LAMR	Lake Meredith National Recreation Area
LYJO	Lyndon B. Johnson National Historical Park
PECO	Pecos National Historical Park
SAND	Sand Creek Massacre National Historic Site
WABA	Washita Battlefield National Historic Site

1.1.1. Weather and 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 network (RAWS) and the U.S. Department of Agriculture/Natural Resources Conservation Service (USDA/NRCS) Snowfall Telemetry (SNOTEL) and snowcourse networks. Usually a single agency, but sometimes a consortium of interested parties, will jointly support a particular weather 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.

1.2. Weather versus Climate Definitions

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



Geographic Location - Southern Great Plains Network

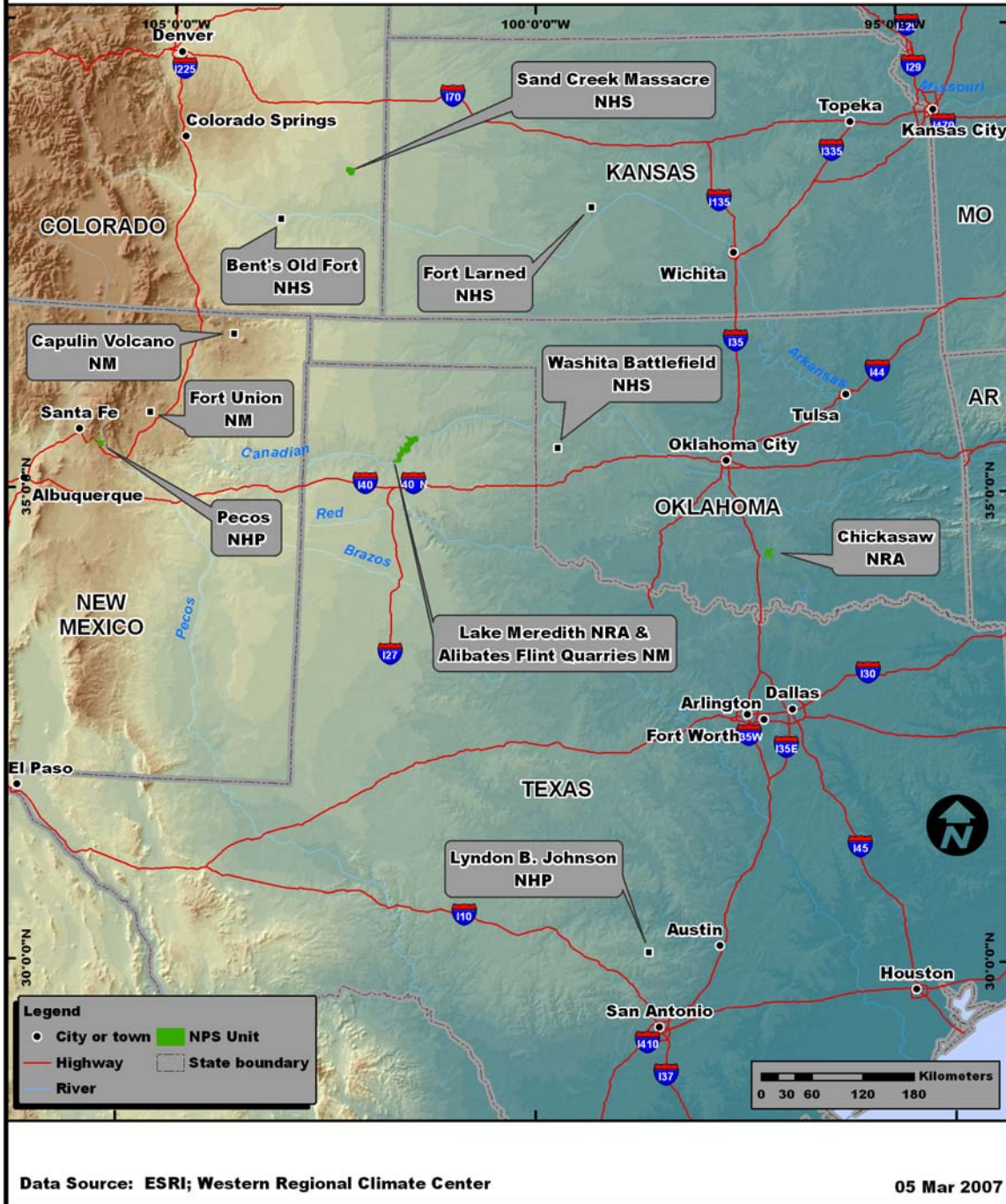


Figure 1.1. Map of the Southern Plains Network.

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/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 SOPN 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/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 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 driver of almost all physical and ecological processes in the SOPN. An understanding of both current climate patterns and climate history in the SOPN is important to understanding and interpreting change and patterns in ecosystem attributes (Perkins et al. 2005). It is essential that the SOPN 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 SOPN, as discussed in this chapter.

2.1. Climate and the SOPN Environment

The Great Plains climate is typified by highly variable and stormy weather patterns, with increasing precipitation from west to east (Parton et al. 1981; Risser et al. 1981) and increasing temperatures from northwest to southeast. Dry air masses from the west are modified by arctic air masses from the north and tropical air masses from the south and east. Westerly air masses that become saturated over the Pacific Ocean have been obstructed by the Rocky Mountains which cause precipitation over the mountains and drier conditions on the leeward side of the mountains. These drier conditions drive the short-grass ecosystem of the western plains. As these air masses continue across the broad flat plain they experience increasing interaction with more humid air masses to the east. The increased precipitation in these areas supports the mixed-grass prairie of the central plains and the tall-grass prairie of the eastern plains (Perkins et al. 2005).

The inherent unpredictability of SOPN climate has had an influence on the evolutionary processes of the Great Plains (Mock 1991). Organisms that live in this area must be adapted to surviving extreme climate conditions. Climate extremes in the SOPN are really “normal” events and many of the more common plants in SOPN are better adapted to persisting through these extremes. In some cases, native SOPN plants actually take advantage of these climate extremes in order to colonize areas (Weaver 1954). The Great Plains, particularly the short-grass prairie and the southern mixed-grass that make up SOPN, undergo frequent droughts from reduced precipitation, increased evapotranspiration, and increased water runoff (Weaver 1968; Wilhite and Hoffman 1979). Drought can lead to massive local extinctions of annual forbs and grasses that have invaded stands of perennial species, and recolonization can be slow (Tilman and El Haddi 1992). Climatic extremes like drought and severe winters have affected animal and plant abundances in the Great Plains for centuries, including bison (Roe 1951) and pronghorn populations (Perkins et al. 2005). Drought can affect some grazing species in the year of the drought, while having a lag effect of a year or more on fauna that feed on seeds (French et al. 1976).

Precipitation, evapotranspiration, temperature, and fire all combine to define the boundary where tree growth is possible in the SOPN (Perkins et al. 2005). These conditions result in a line along the eastern edge of the tall-grass prairie which largely prohibits tree growth through much of the SOPN. Climate and fire are thought to be most important processes to the spread and maintenance of grasslands (Anderson 1990).

The impact of global climate change may be exacerbated in the Southern Plains due to the region's periodic droughts and the large number of habitat specialists (e.g., prairie dogs and associated species) (Collins and Glenn 1995; Clark et al. 2002). Once these communities are

isolated as ‘islands’ such as those represented by the SOPN, species extirpations may occur due to the inability to re-colonize. Changes to weather patterns, especially outside the normal range of variability, can have significant impact on grassland vegetation (Clark et al. 2002). In Weaver’s (1943) classic vegetation study during and after the Dust Bowl of the 1930s he found that the mixed-grass prairie biome had moved a hundred miles to the east.

The unique weather patterns of the Great Plains present some challenges when designing a long-term monitoring program. The inter-year variability can increase the noise to signal ratio in monitoring projects. This can confound efforts to analyze and interpret temporal and spatial trends and to identify causative factors in changes in natural resources. In addition, there can be large local variation in precipitation, necessitating site-specific weather monitoring stations to obtain accurate information (Perkins et al. 2005).

2.2. Spatial Variability

Precipitation in the SOPN generally increases to the east, although localized higher precipitation amounts are also evident in the higher elevations of New Mexico. Mean annual precipitation (Figure 2.1) ranges from around 300 mm near BEOL to almost 1000 mm around CHIC. BEOL is located in one of the more severe rainshadow environments along the High Plains, the Arkansas River Valley, while CHIC is the easternmost park unit in SOPN. Precipitation in the SOPN generally peaks in mid- to late-summer, although some locations in central Texas see two precipitation maxima, one in late spring and the other in early autumn (Figure 2.2).

The general temperature gradient in the SOPN is from cooler temperatures in the northwest to warmer temperatures in the southeast (Perkins et al. 2005). Topography also influences mean annual temperatures in the extreme western portions of the network. Mean annual temperatures in SOPN park units range from 8°C in the higher park units in New Mexico (e.g., FOUN, PECO), up to almost 18°C at LYJO in central Texas (Figure 2.3). January minimum temperatures in the SOPN, like mean annual temperatures, generally follow a northwest-southeast gradient across the Great Plains, with strong topographical influences in westernmost SOPN (Figure 2.4). The coldest SOPN park unit is SAND, where January minimum temperatures regularly are near -12°C. In contrast, January minimum temperatures at LYJO are generally near 0°C. The northwest-southeast temperature gradient is no longer evident when one looks at summer maximum temperatures. July maximum temperatures, for instance, generally are between 32°C and 35°C throughout the SOPN (Figure 2.5). The exceptions to this are the park units in New Mexico, where daytime maximum temperatures are between 26°C and 29°C.

2.3. Temporal Variability

The El Niño-Southern Oscillation (ENSO) causes interannual climate variations in the SOPN (NAST 2001). El Niño conditions (warm ENSO phases) are associated with cooler, wetter conditions while La Niña conditions (cool ENSO phases) are associated with warmer, drier conditions.



Mean Annual Precipitation

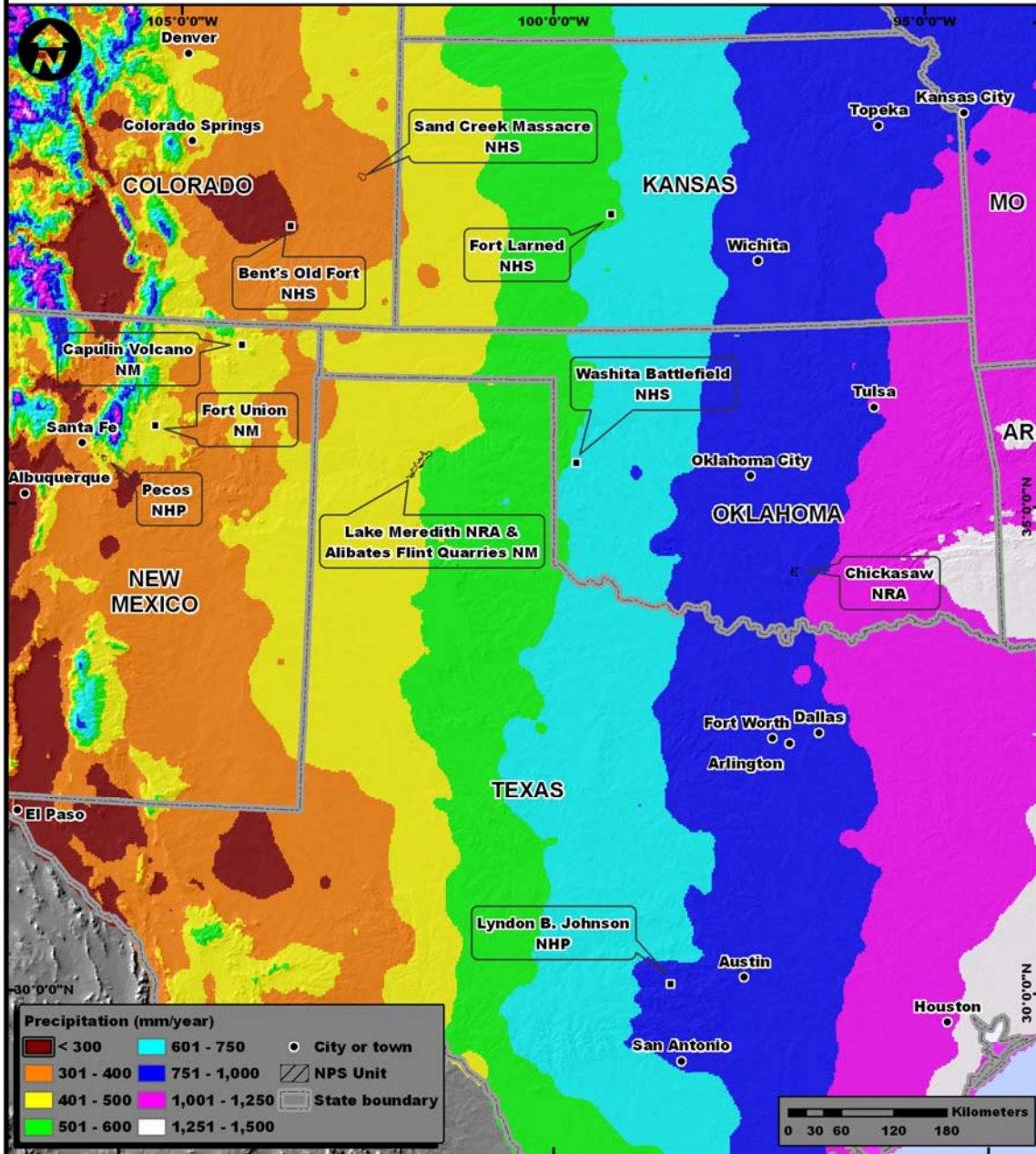
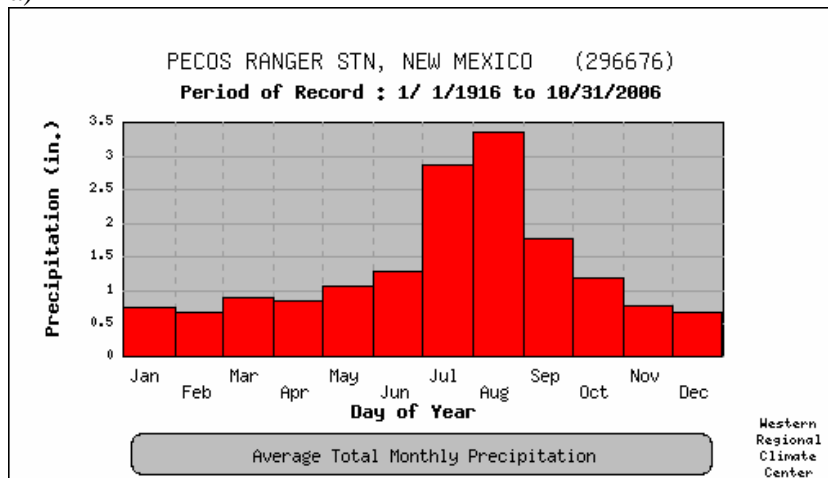
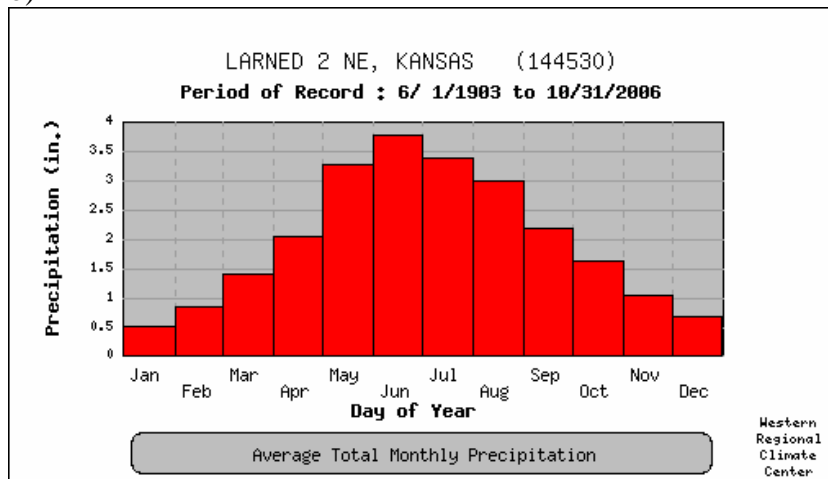


Figure 2.1. Mean annual precipitation, 1961-1990, for the SOPN.

a)



b)



c)

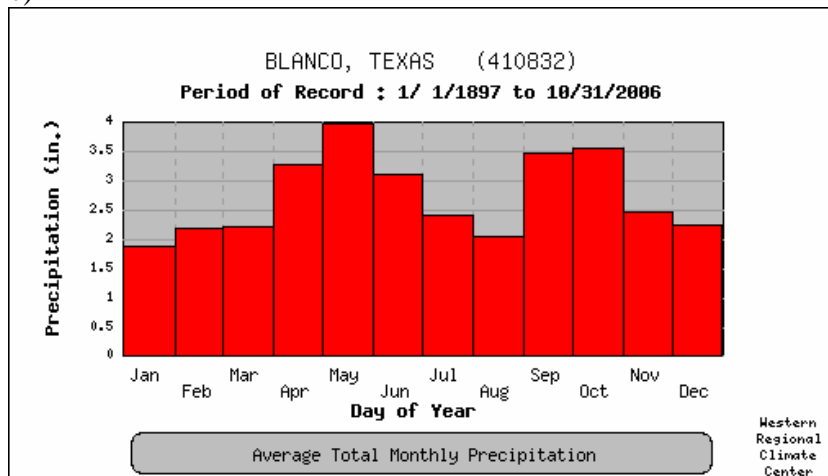


Figure 2.2. Mean monthly precipitation at selected locations in the SOPN, including Pecos Ranger Stn., near PECO (a); Larned 2 NE, near FOLS (b); and Blanco, near LYJO (c).



Mean Annual Temperature

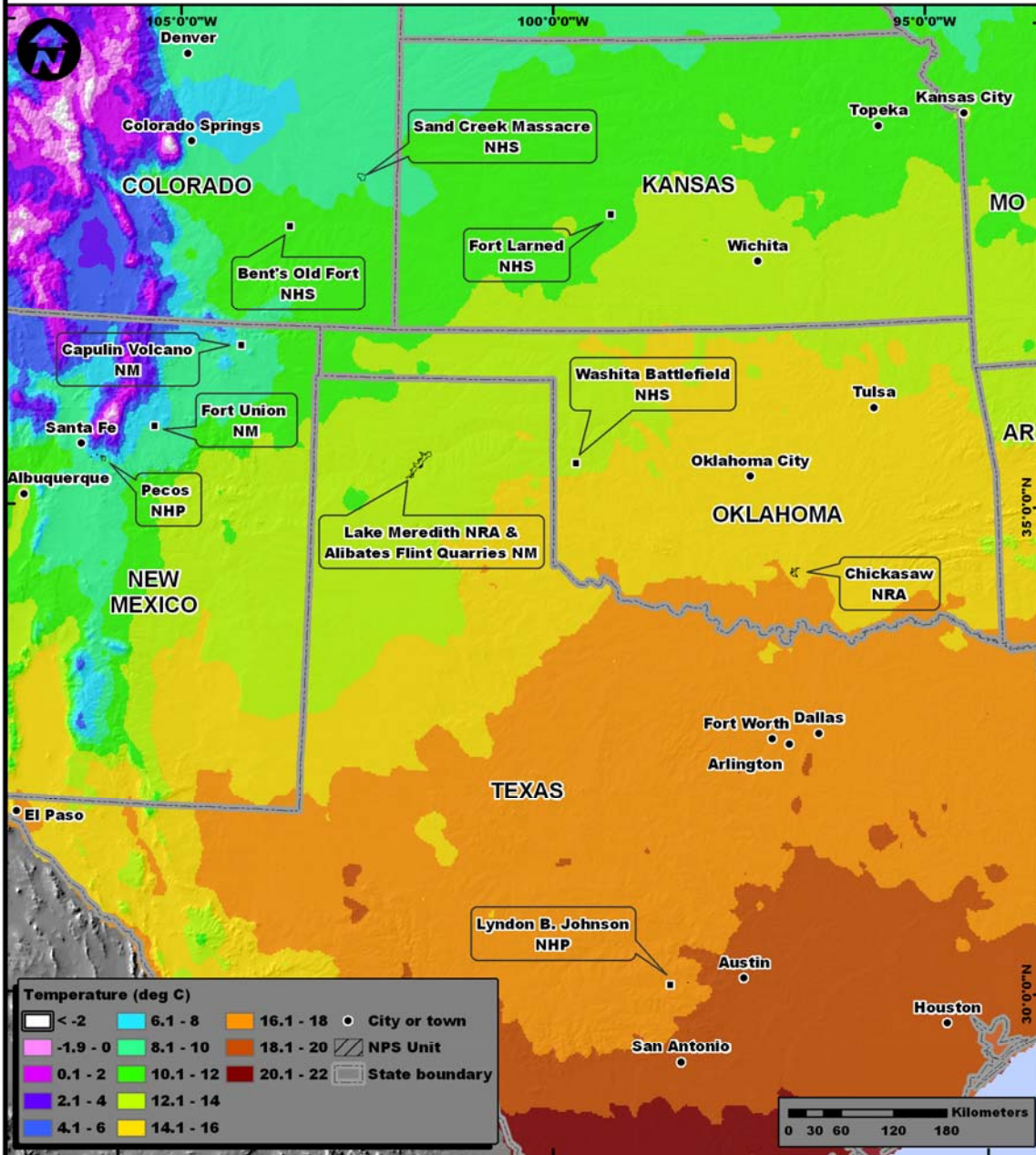


Figure 2.3. Mean annual temperature, 1961-1990, for the SOPN.

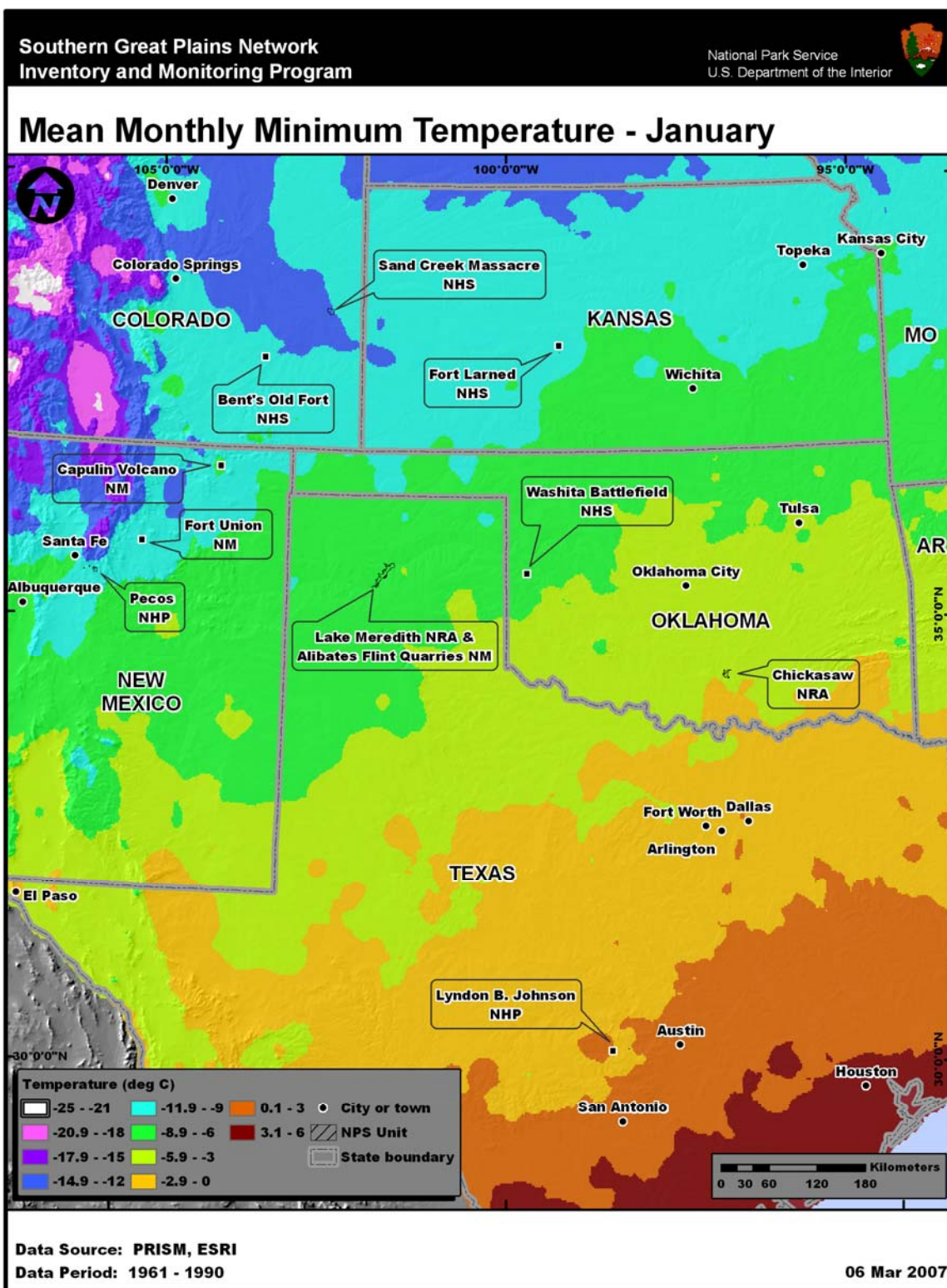


Figure 2.4. Mean January minimum temperature, 1961-1990, for the SOPN.

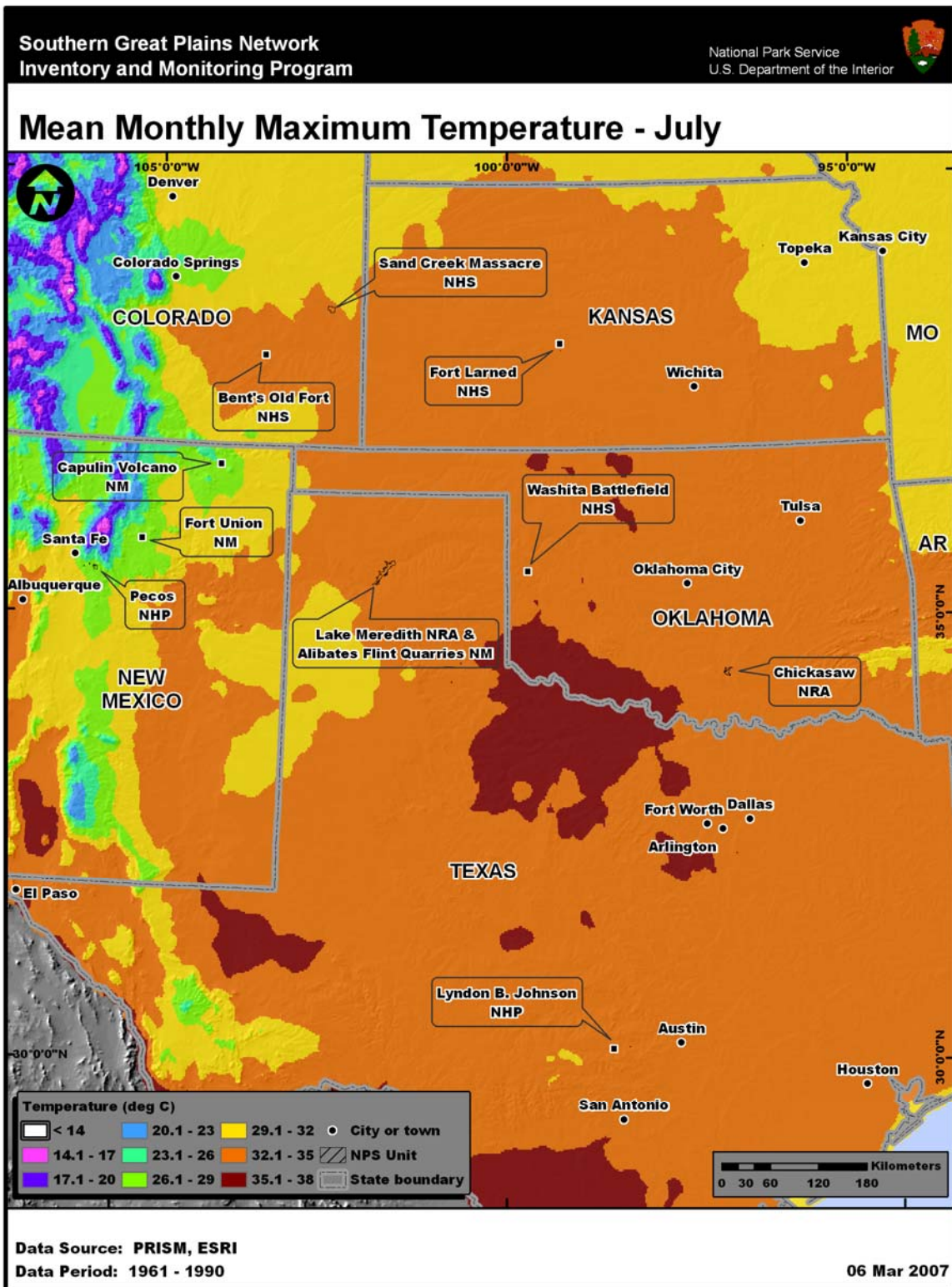


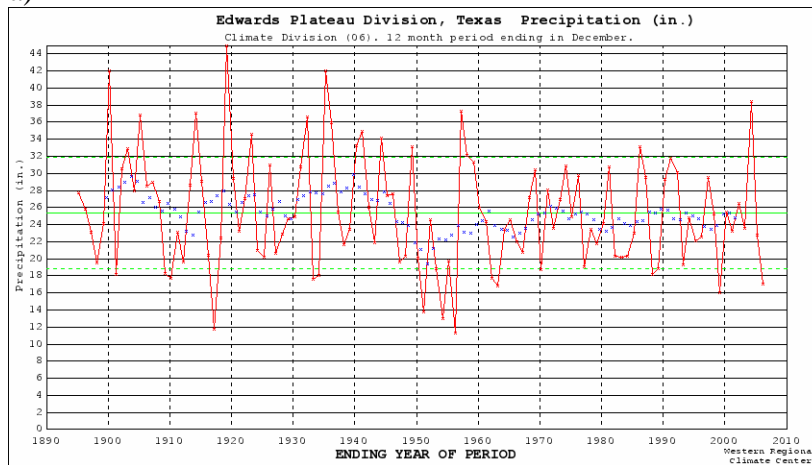
Figure 2.5. Mean July maximum temperature, 1961-1990, for the SOPN.

An investigation of daily precipitation amounts around the SOPN region over the last century (Figure 2.6) reveals little in the way of an overall trend. A somewhat drier period is apparent during the 1950s, especially in central Texas (Figure 2.6a) and southeastern Colorado (Figure 2.6b). Long-term time series of temperatures in the SOPN (Figure 2.7) vary greatly throughout the network. In southeastern Colorado (Figure 2.7b), for instance, temperatures appear to have warmed significantly over the past century. South-central Oklahoma (Figure 2.7c) also appears to show slight warming in the past century. In contrast to these patterns, however, central Texas (Figure 2.7a) does not indicate a clear warming or cooling trend. Much of the SOPN experienced a cooler period which peaked during the 1970s. Cooler conditions were also prevalent in the SOPN during the early part of the twentieth century.

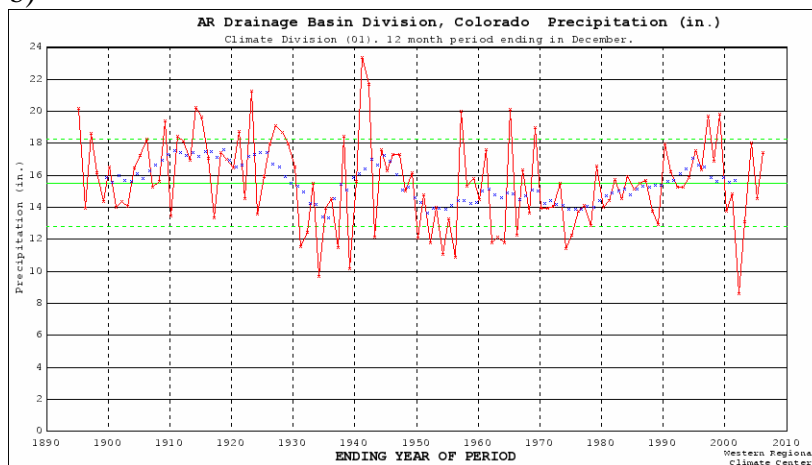
2.4. Parameter Regression on Independent Slopes Model (PRISM)

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. Originally, this model was developed to provide climate information at scales matching available land-cover maps to assist in ecologic modeling. The PRISM technique accounts for the scale-dependent effects of topography on mean values of climate elements. Elevation provides the first-order constraint for the mapped climate fields, with slope and orientation (aspect) providing second-order constraints. The model has been enhanced gradually to address inversions, coast/land gradients, and climate patterns in small-scale trapping basins. Monthly climate fields are generated by PRISM to account for seasonal variations in elevation gradients in climate elements. These monthly climate fields then can be combined into seasonal and annual climate fields. Since PRISM maps are grid maps, they do not replicate point values but rather, for a given grid cell, represent the grid-cell average of the climate variable in question at the average elevation for that cell. The model relies on observed surface and upper-air measurements to estimate spatial climate fields.

a)



b)



c)

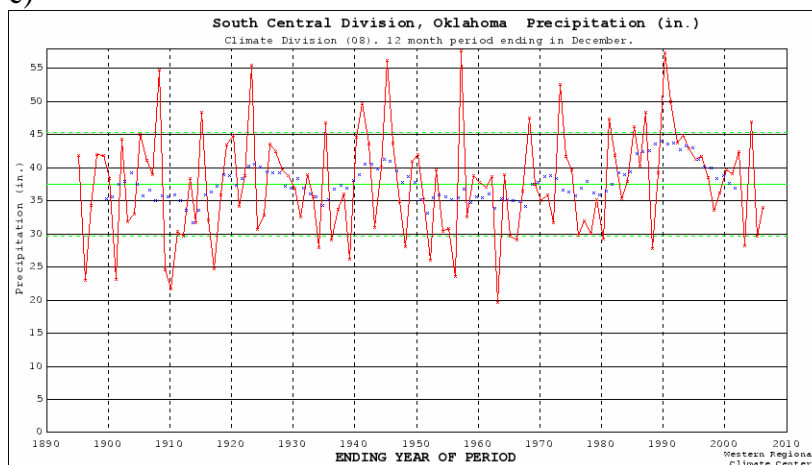
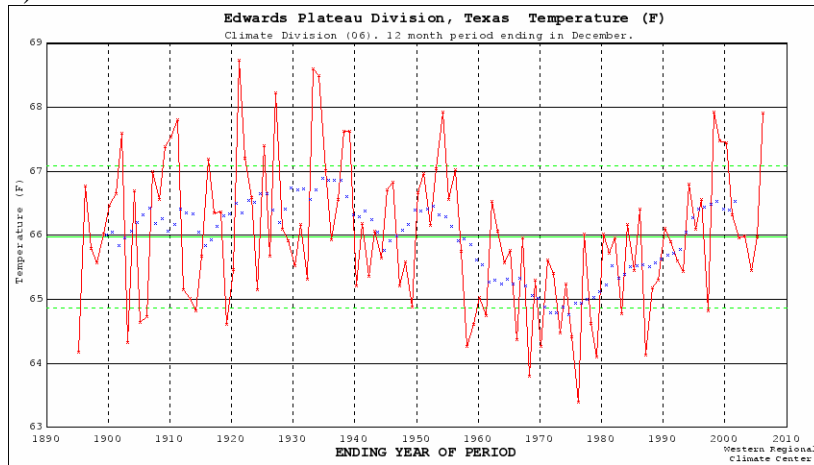
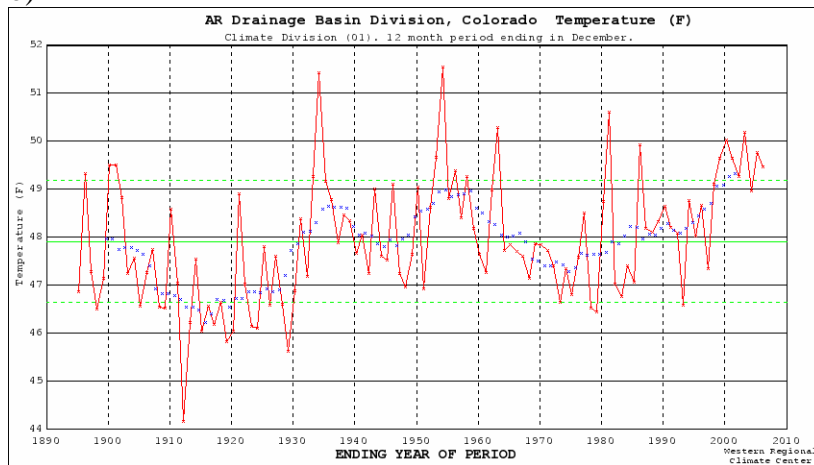


Figure 2.6. Precipitation time series, 1895-2005, for selected regions in the SOPN. These include twelve-month precipitation (ending in December) (red), 10-year running mean (blue), mean (green), and plus/minus one standard deviation (green dotted). Locations include west-central Texas (a), southeastern Colorado (b), and south-central Oklahoma (c).

a)



b)



c)

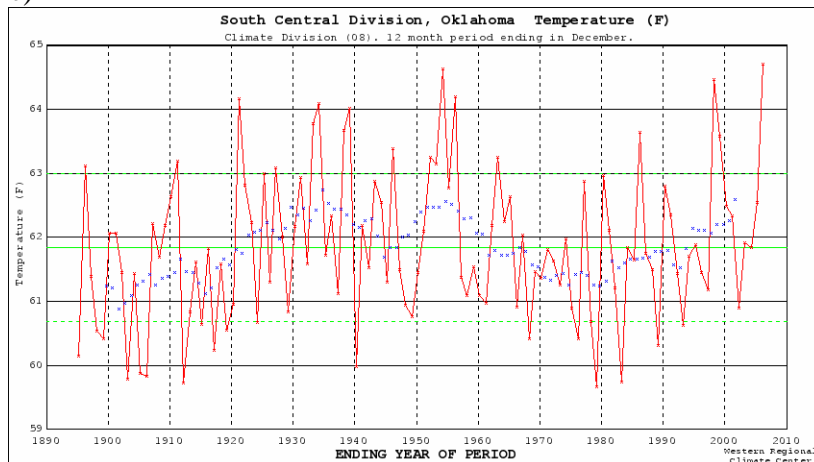


Figure 2.7. Temperature time series, 1895-2005, for selected regions in the SOPN. These include twelve-month average temperature (ending in December) (red), 10-year running mean (blue), mean (green), and plus/minus one standard deviation (green dotted). Locations include west-central Texas (a), southeastern Colorado (b), and south-central Oklahoma (c).

3.0. Methods

Having discussed the climatic characteristics of the SOPN, we now present the procedures that were used to obtain information for weather and climate stations within the SOPN. 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/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 SOPN weather and climate stations identified from the ACIS database are available in file “SOPN_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 SOPN 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.

Two types of information have been used to complete the SOPN 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 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 SOPN we selected only those stations located within 40 km of the SOPN park units. This buffer distance was selected in an attempt to include automated stations from major networks such as SAO, but also to keep the size of the stations lists down to a reasonable number.

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 SOPN. 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 SOPN region in relation to the boundaries of the NPS park units within the SOPN. 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 SOPN region are associated with at least one of 13 major climate and weather networks (Table 4.1). Brief descriptions of each weather or climate network are provided below (see Appendix G for greater detail).

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

Acronym	Name
CDOT	Colorado Department of Transportation network
CoAgMet	Colorado Agricultural Meteorological Network
COOP	NWS Cooperative Observer Program
CRN	NOAA Climate Reference Network
CWOP	Citizen Weather Observer Program
GPS-MET	NOAA ground-based GPS meteorology network
NADP	National Atmospheric Deposition Program
NRCS-SC	USDA/NRCS snowcourse network
OKMESO	Oklahoma Mesonet
RAWS	Remote Automated Weather Station network
SAO	NWS/FAA Surface Airways Observation network
SCAN	Soil Climate Analysis Network
SNOTEL	USDA/NRCS Snowfall Telemetry network

4.1.1. Colorado Department of Transportation (CDOT) Network

These weather stations are operated by CDOT in support of management activities for Colorado's transportation network. Measured meteorological elements include temperature, precipitation, wind, and relative humidity.

4.1.2. Colorado Agricultural Meteorological Network (CoAgMet)

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

4.1.3. 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.

4.1.4. NOAA 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. Standard meteorological elements are measured. CRN data are used in operational climate-monitoring activities and to place current climate patterns in historic perspective.

4.1.5. 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.

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

The GPS-MET network is the first network of its kind dedicated to GPS (Global Positioning System) meteorology (see Duan et al. 1996). GPS meteorology utilizes the radio signals broadcast by the GPS satellite array 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.

4.1.7. 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 USDA and the U.S. Geological Survey (USGS). Precipitation is the primary climate parameter measured at NADP sites. Mercury Deposition Network (MDN) sites are included in the NADP network.

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

The USDA/NRCS maintains a 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.

4.1.9. Oklahoma Mesonet (OKMESO)

The OKMESO network is administered through the Oklahoma Climatological Survey. Observations are taken every 5 minutes at OKMESO sites around the state of Oklahoma. The first stations in the OKMESO network were installed in the early 1990s. Meteorological elements that are measured at OKMESO sites include temperature, precipitation, wind, humidity/dewpoint, barometric pressure, solar radiation, and soil temperatures.

4.1.10. 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.

4.1.11. 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.

4.1.12. USDA/NRCS Soil Climate Analysis Network (SCAN)

The SCAN network is administered by NRCS and is intended to be a comprehensive nationwide soil moisture and climate information system to be used in supporting natural resource assessments and other conservation activities. These stations are usually located in the agricultural areas of the U.S. All SCAN sites are automated. The parameters measured at these sites include air temperature, precipitation, humidity, wind, barometric pressure, solar radiation, snow depth, and snow water content.

4.1.13. USDA/NRCS Snowfall Telemetry (SNOTEL) Network

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

4.1.14. 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 or 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.

4.1.15. 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. These networks could be present within SOPN but have not been identified in this report. Some of the commonly used networks include the following:

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

4.2. Station Locations

The major weather and climate networks in the SOPN (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.

Table 4.2. Number of stations within or nearby SOPN 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	ALFL	BEOL	CAVO	CHIC	FOLS	FOUN
CDOT	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)
CoAgMet	0(0)	3(0)	0(0)	0(0)	0(0)	0(0)
COOP	7(0)	9(0)	12(1)	16(2)	19(0)	17(0)
CRN	0(0)	1(0)	0(0)	0(0)	0(0)	0(0)
CWOP	2(0)	0(0)	0(0)	0(0)	2(0)	1(0)
GPS-MET	0(0)	0(0)	0(0)	0(0)	1(0)	0(0)
NADP	0(0)	1(0)	1(1)	0(0)	0(0)	0(0)
NRCS-SC	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)
OKMESO	0(0)	0(0)	0(0)	9(0)	0(0)	0(0)
RAWS	1(0)	0(0)	0(0)	0(0)	0(0)	1(0)
SAO	2(0)	1(0)	0(0)	1(0)	1(0)	1(0)
SCAN	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)
SNOTEL	0(0)	1(0)	0(0)	0(0)	0(0)	0(0)
Other	1(0)	1(0)	1(0)	0(0)	0(0)	0(0)
Total	13(0)	17(0)	14(2)	26(2)	23(0)	20(0)
Network	LAMR	LYJO	PECO	SAND	WABA	
CDOT	0(0)	0(0)	0(0)	1(0)	0(0)	
CoAgMet	0(0)	0(0)	0(0)	0(0)	0(0)	
COOP	15(0)	23(0)	35(1)	8(0)	17(0)	
CRN	0(0)	0(0)	0(0)	0(0)	0(0)	
CWOP	4(0)	5(0)	2(0)	1(0)	0(0)	
GPS-MET	1(0)	0(0)	0(0)	0(0)	0(0)	
NADP	0(0)	0(0)	0(0)	0(0)	0(0)	
NRCS-SC	0(0)	0(0)	2(0)	0(0)	0(0)	
OKMESO	0(0)	0(0)	0(0)	0(0)	2(0)	
RAWS	1(0)	1(1)	1(0)	0(0)	0(0)	
SAO	4(0)	1(0)	1(0)	0(0)	1(0)	
SCAN	1(0)	0(0)	0(0)	0(0)	0(0)	
SNOTEL	0(0)	0(0)	4(0)	0(0)	0(0)	
Other	2(0)	1(0)	1(0)	0(0)	0(0)	
Total	28(0)	31(1)	46(1)	10(0)	20(0)	

Lists of stations have been compiled for the SOPN. As noted previously, a station does not have to be within park unit 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.

4.2.1. Colorado, New Mexico, and Northern Texas

No weather or climate stations were identified within the boundaries of ALFL (Table 4.3; Figure 4.1). Seven COOP stations, three active, were identified within 40 km of ALFL. The COOP station “Panhandle” is located 34 km southeast of ALFL and provides the longest data record we identified for ALFL (1911-present). Notable data gaps at this station include from November 1972 to February 1973 and from October 1993 to March 1995. Another long-term record is found at the COOP station “Amarillo,” 39 km southwest of ALFL. This climate station’s data record goes back to 1932 and is largely complete with the exception of a gap from December 1992 to May 1993. The closest COOP station to ALFL is “Borger,” which is 19 km east of ALFL. This climate station has been active since 1949 and its data record is very reliable.

The closest station overall to ALFL is the RAWS station “Cedar,” which is 12 km north of the park unit (Figure 4.1) and provides automated weather data for the area. This weather station has been active since 1997 (Table 4.3) and has a very complete data record. The SAO stations at Amarillo (39 km southwest) and Borger (26 km east) also provide near-real-time data for the region around ALFL.

No weather or climate stations were identified within the boundaries of BEOL (Table 4.3; Figure 4.1). The CoAgMet station “LaJunta” is the closest weather station to BEOL, being located only 6 km southwest of the park unit. This station has been active since 2005. Another CoAgMet

Table 4.3. Weather and climate stations for the SOPN park units in Colorado, New Mexico, and northern Texas. Stations inside park units and within 40 km of the park unit boundaries are included. Missing entries are indicated by “M”.

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Alibates Flint Quarries National Monument (ALFL)							
Amarillo	35.219	-101.706	1093	COOP	4/1/1932	Present	No
Amarillo 19 N	35.467	-101.883	M	COOP	2/1/1965	1/31/1977	No
Borger	35.650	-101.400	949	COOP	4/1/1944	11/30/1961	No
Borger	35.636	-101.454	935	COOP	2/1/1949	Present	No
Panhandle	35.414	-101.342	1077	COOP	8/1/1911	Present	No
Plemons	35.767	-101.333	854	COOP	9/7/1906	1/22/1959	No
Stinnett	35.833	-101.450	954	COOP	2/1/1929	5/12/1992	No
AA5AW Borger	35.637	-101.454	978	CWOP	M	Present	No
CW2051 Panhandle	35.354	-101.388	1165	CWOP	M	Present	No
Cedar	35.667	-101.567	930	RAWS	10/1/1997	Present	No
Amarillo	35.219	-101.706	1093	SAO	4/1/1932	Present	No
Borger	35.695	-101.395	931	SAO	5/1/1951	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Amarillo AAF	35.233	-101.700	1100	WBAN	3/1/1943	12/31/1945	No
Bent's Old Fort National Historic Site (BEOL)							
CSU Exp. Stn. Rocky Ford	38.039	-103.695	1274	CoAgMet	6/4/1992	Present	No
CSU Exp. Stn. Rocky Ford NRCS	38.039	-103.695	1274	CoAgMet	1/1/1999	Present	No
La Junta	38.078	-103.366	1207	CoAgMet	3/17/2005	Present	No
Cheraw 1 N	38.115	-103.510	1264	COOP	8/1/1948	Present	No
Higbee 2 SW	37.750	-103.467	1296	COOP	5/1/1906	9/18/1980	No
La Junta	38.049	-103.512	1278	COOP	7/1/1939	Present	No
La Junta	37.986	-103.541	1278	COOP	6/1/1982	Present	No
La Junta 20 S	37.751	-103.478	1283	COOP	7/1/1982	Present	No
Las Animas	38.064	-103.215	1186	COOP	1/1/1893	Present	No
Las Animas #2	38.067	-103.217	1186	COOP	12/1/1963	11/30/1965	No
Ordway 2 ENE	38.222	-103.722	1315	COOP	7/1/1915	Present	No
Rocky Ford 2 SE	38.039	-103.693	1271	COOP	1/1/1893	Present	No
La Junta 17 WSW	37.864	-103.822	1347	CRN	8/3/2004	Present	No
Las Animas Fish Hatchery	38.118	-103.316	1213	NADP	10/4/1983	Present	No
La Junta	38.049	-103.512	1278	SAO	7/1/1939	Present	No
Patterson Hollow #1	38.033	-103.700	1271	SNOTEL	10/28/1992	9/30/1993	No
La Junta AAF	38.050	-103.517	1279	WBAN	11/1/1942	6/30/1945	No
Capulin Volcano National Monument (CAVO)							
Capulin Natl. Monument	36.783	-103.967	2223	COOP	2/1/1966	9/21/1979	Yes
Capulin Volcano NM	36.779	-103.981	2205	NADP	11/15/1984	Present	Yes
Branson	37.017	-103.883	1918	COOP	8/1/1918	4/30/1978	No
Capulin	36.739	-103.994	2085	COOP	6/1/1995	Present	No
Capulin 6 SSE	36.667	-103.950	2196	COOP	1/1/1930	11/1/1969	No
Cunico Ranch	36.683	-104.117	2080	COOP	6/1/1940	9/1/1970	No
Des Moines	36.750	-103.833	2018	COOP	4/1/1916	7/1/1994	No
Des Moines Brown Ranch	36.767	-103.633	1830	COOP	3/1/1941	6/30/1947	No
Folsom	36.867	-103.917	2013	COOP	12/1/1892	10/31/1949	No
Grenville	36.594	-103.619	1829	COOP	10/22/1940	Present	No
Hennigan Ranch	36.633	-104.133	2117	COOP	2/1/1971	10/1/1971	No
Johnsons Park	36.800	-104.250	1996	COOP	10/1/1909	10/31/1923	No
Long Canyon	37.000	-103.650	1623	COOP	2/22/1941	9/30/1959	No
Des Moines	36.733	-103.783	2019	WBAN	12/1/1938	2/28/1941	No
Fort Union National Monument (FOUN)							
Aurora	36.267	-105.050	2480	COOP	7/1/1909	8/31/1960	No
Chacon 2 S	36.121	-105.375	2455	COOP	9/19/1985	Present	No
Fort Union	35.900	-105.033	2099	COOP	9/1/1851	1/31/1919	No
Gascon	35.892	-105.448	2515	COOP	11/1/1953	Present	No
La Cueva	35.933	-105.217	2141	COOP	6/1/1940	9/30/1950	No
La Placita Ranch	35.733	-105.150	2044	COOP	4/24/1905	9/30/1948	No
Las Vegas	35.654	-105.143	2093	COOP	8/1/1932	11/1/2000	No
Las Vegas 2 NW	35.617	-105.267	2013	COOP	12/1/1892	6/16/1983	No
Las Vegas 4 NW	35.633	-105.267	2044	COOP	5/1/1967	6/30/1969	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Las Vegas Exp. Plot	35.583	-105.183	1983	COOP	9/1/1908	2/28/1945	No
Las Vegas Hot Springs	35.667	-105.300	2063	COOP	6/1/1890	7/31/1903	No
Levy	36.083	-104.683	1906	COOP	11/1/1908	1/31/1962	No
Ocate 2 NW	36.184	-105.061	2333	COOP	1/1/1897	Present	No
Onava	35.700	-105.117	2044	COOP	5/1/1929	12/31/1942	No
Optimo	35.900	-104.717	1952	COOP	6/1/1910	Present	No
Rociada	35.850	-105.433	2286	COOP	5/1/1904	6/30/1926	No
Valmora	35.817	-104.924	1928	COOP	7/17/1893	Present	No
CW2187 Las Vegas	35.600	-105.228	1966	CWOP	M	Present	No
Bartley	35.895	-105.461	2542	RAWS	1/1/2004	Present	No
Las Vegas	35.654	-105.143	2093	SAO	8/1/1932	11/1/2000	No

Lake Meredith National Recreation Area (LAMR)

Amarillo	35.219	-101.706	1093	COOP	4/1/1932	Present	No
Amarillo 19 N	35.467	-101.883	M	COOP	2/1/1965	1/31/1977	No
Borger	35.650	-101.400	949	COOP	4/1/1944	11/30/1961	No
Borger	35.636	-101.454	935	COOP	2/1/1949	Present	No
Boys Ranch	35.530	-102.256	973	COOP	6/12/1964	Present	No
Bushland 1 WSW	35.187	-102.080	1164	COOP	7/1/1947	Present	No
Channing 11 NE	35.767	-102.150	1135	COOP	3/1/1990	6/30/1991	No
Channing SCS 38	35.683	-102.167	M	COOP	1/1/1941	12/31/1942	No
Dumas	35.873	-101.973	1114	COOP	1/1/1937	Present	No
Dumas 8 NE	35.950	-101.883	1083	COOP	7/1/1947	12/7/1954	No
Morse	36.061	-101.475	969	COOP	9/1/1941	2/1/1998	No
Panhandle	35.414	-101.342	1077	COOP	8/1/1911	Present	No
Plemons	35.767	-101.333	854	COOP	9/7/1906	1/22/1959	No
Stinnett	35.833	-101.450	954	COOP	2/1/1929	5/12/1992	No
Sunray 4 SW	35.967	-101.867	1080	COOP	11/1/1932	8/31/1984	No
AA5AW Borger	35.637	-101.454	978	CWOP	M	Present	No
KC5JIF Amarillo	35.172	-101.933	1125	CWOP	M	Present	No
KB5WIO Amarillo	35.152	-101.876	1116	CWOP	M	Present	No
CW2051 Panhandle	35.354	-101.388	1165	CWOP	M	Present	No
Amarillo	35.150	-101.880	1124	GPS-MET	M	Present	No
Cedar	35.667	-101.567	930	RAWS	10/1/1997	Present	No
Amarillo	35.219	-101.706	1093	SAO	4/1/1932	Present	No
Borger	35.695	-101.395	931	SAO	5/1/1951	Present	No
Channing 11 NE	35.767	-102.150	1135	SAO	3/1/1990	6/30/1991	No
Dumas Moore Co. Arpt.	35.858	-102.013	1129	SAO	2/4/1960	Present	No
Bushland #1	35.170	-102.100	1164	SCAN	M	Present	No
Amarillo	35.217	-101.833	1117	WBAN	1/1/1892	12/31/1941	No
Amarillo AAF	35.233	-101.700	1100	WBAN	3/1/1943	12/31/1945	No

Pecos National Historical Park (PECO)

Pecos Natl. Monument	35.549	-105.689	2096	COOP	1/1/1916	Present	Yes
Big Tesuque Ski Course	35.783	-105.800	2974	COOP	7/1/1946	11/30/1976	No
Buckmans	35.667	-106.117	2591	COOP	8/1/1896	1/25/1899	No
Cerrillos	35.433	-106.117	1737	COOP	11/1/1905	8/31/1945	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Cow Springs	35.417	-105.800	1842	COOP	7/1/1947	9/30/1948	No
Cowles	35.817	-105.667	2471	COOP	7/1/1894	11/9/1964	No
Cowles 1 SE	35.817	-105.650	2684	COOP	10/1/1949	7/31/1976	No
Dyer Ranch	35.300	-105.750	2181	COOP	10/1/1948	3/31/1950	No
Elk Cabin	35.700	-105.817	2593	COOP	7/1/1946	11/30/1976	No
Galisteo	35.400	-105.950	1857	COOP	1/1/1894	12/31/1977	No
Gallinas Canyon	35.700	-105.433	2257	COOP	1/1/1906	11/30/1976	No
Glorieta	35.582	-105.773	2292	COOP	3/1/1915	Present	No
Harveys Upper Ranch	35.750	-105.467	2730	COOP	2/1/1909	7/31/1959	No
Holy Ghost Canyon	35.767	-105.700	2318	COOP	7/1/1946	9/30/1956	No
Irvins Ranch	35.783	-105.600	2959	COOP	5/1/1935	7/31/1945	No
Mineral Hill	35.600	-105.433	2149	COOP	11/1/1904	8/31/1923	No
Montezuma 8 NW	35.683	-105.383	2208	COOP	8/1/1971	10/1/1973	No
Pecos	35.438	-105.564	2073	COOP	7/1/1996	9/1/2001	No
Pecos 9 N	35.717	-105.683	2287	COOP	8/1/1978	12/1/1992	No
Rencona	35.283	-105.600	2135	COOP	12/1/1923	1/10/1972	No
Ribera	35.367	-105.450	1861	COOP	3/1/1950	4/15/1965	No
Santa Fe	35.617	-106.089	1934	COOP	3/1/1938	Present	No
Santa Fe	35.601	-105.932	2134	COOP	12/11/1997	Present	No
Santa Fe	35.543	-105.920	2079	COOP	3/26/1998	10/1/2006	No
Santa Fe	35.683	-105.900	2196	COOP	10/1/1867	3/21/1972	No
Santa Fe 2	35.619	-105.975	2059	COOP	3/1/1972	Present	No
Santa Fe 2 SE	35.683	-105.933	2208	COOP	5/1/1948	9/30/1951	No
Santa Fe Caja D R	35.717	-106.100	1952	COOP	7/1/1947	5/31/1950	No
Santa Fe Canyon	35.717	-105.800	2560	COOP	1/1/1910	11/27/1928	No
Santa Fe Lake	35.783	-105.767	3538	COOP	7/1/1946	11/30/1976	No
Santa Fe Synoptic	35.667	-105.967	M	COOP	M	Present	No
Serafina 6 WNW	35.417	-105.417	1983	COOP	6/1/1915	3/31/1950	No
Tererro	35.767	-105.667	2288	COOP	5/1/1946	8/31/1961	No
Turquoise Bonanza Cr.	35.550	-106.100	1867	COOP	6/1/1953	3/31/1996	No
Winsors	35.833	-105.667	2501	COOP	1/1/1897	10/31/1949	No
W5VBQ Santa Fe	35.709	-105.921	2218	CWOP	M	Present	No
W0RAT-2 Mineral Hill	35.625	-105.432	2195	CWOP	M	Present	No
Elk Cabin	35.700	-105.800	2515	NRCS-SC	1/1/1948	Present	No
Rio En Medio	35.800	-105.800	3139	NRCS-SC	1/1/1950	Present	No
Pecos	35.558	-105.483	2621	RAWS	6/1/1994	Present	No
Santa Fe	35.617	-106.089	1934	SAO	3/1/1938	Present	No
Elk Cabin	35.800	-105.700	2502	SNOTEL	M	Present	No
Panchuela	35.833	-105.667	2560	SNOTEL	6/3/1980	Present	No
Santa Fe	35.767	-105.783	3488	SNOTEL	M	Present	No
Wesner Springs	35.767	-105.533	3389	SNOTEL	10/1/1989	Present	No
Santa Fe	35.683	-105.950	2138	WBAN	12/1/1889	12/31/1941	No
Sand Creek Massacre National Historic Site (SAND)							
US-40 @ Firstview (92)	38.793	-102.483	1384	CDOT	M	Present	No
Arapahoe	38.684	-102.161	1248	COOP	6/1/2003	Present	No
Brandon	38.460	-102.436	1196	COOP	2/1/1955	1/1/2000	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Cheyenne	38.818	-102.361	1295	COOP	1/1/1893	Present	No
Chivington	38.433	-102.533	1190	COOP	3/1/1893	2/28/1955	No
Eads	38.478	-102.781	1285	COOP	4/1/1907	Present	No
Kit Carson	38.766	-102.803	1317	COOP	1/1/1893	Present	No
Kit Carson 9 NNE	38.887	-102.722	1405	COOP	11/1/1996	Present	No
Sheridan Lake	38.468	-102.295	1241	COOP	1/1/2000	Present	No
CW4436 Kit Carson	38.767	-102.792	1314	CWOP	M	Present	No

station, “CSU Exp. Stn. Rocky Ford,” is 23 km west of BEOL at the Colorado State University Agricultural Experiment Station near Rocky Ford and has been active since 1992. This weather station’s data record is fairly reliable.

Nine COOP stations, seven active, were identified within 40 km of BEOL (Table 4.3). The COOP station “Rocky Ford 2 SE” is located at the previously-mentioned agricultural experiment station near Rocky Ford and, along with “Las Animas,” provides the longest data record we identified for BEOL (1893-present). “Rocky Ford 2 SE” has a very reliable data record. In contrast, the reliability of the data record at “Las Animas” (18 km east of BEOL) is less certain. Although quite complete, the data record at “Las Animas” may be compromised by exposure problems which have been noted for this site (e.g., Davey and Pielke 2005). The closest COOP station to BEOL is “La Junta,” which is 7 km southwest of BEOL. This climate station has been active since 1939 and its data record is largely complete. Another long-term record is found at the COOP station “Ordway 2 ENE,” 32 km northwest of BEOL. This station’s data record goes back to 1915. Until 1980, only precipitation was measured at this site. Numerous gaps exist in the data record for “Ordway 2 ENE” in the late 1980s. The COOP station “Cheraw 1 N” is located 10 km northwest of BEOL and has a data record that goes back to 1948. This data record was unreliable until the early 1990s and has been very complete since that time.

A NADP station and a SAO station also operate within 40 km of BEOL. The NADP station “Las Animas Fish Hatchery” (1983-present) is 12 km east of BEOL (Figure 4.1). The SAO station “La Junta” (1939-present) is 7 km southwest of BEOL and provides near-real-time weather data for the region. A SNOTEL station (Patterson Hollow #1) operated briefly between 1992 and 1993. This station was 23 km southwest of BEOL.

We identified two stations within CAVO (Table 4.3; Figure 4.1). Only one of these stations is still operating. The NADP station “Capulin Volcano NM” has been active since 1984. A COOP station (Capulin Natl. Monument) operated in CAVO from 1966 to 1979. We identified 11 COOP stations within 40 km of the boundaries of CAVO; however, only two of these are still active. The COOP station “Capulin” is 4 km south of CAVO and provides a data record going back to 1995. The data record at “Capulin” had a gap in August 1998 but is otherwise complete. The COOP station “Grenville,” 37 km southeast of CAVO, provides the longest data record in the vicinity of CAVO, going back to 1940. This climate station measured only precipitation until 1948, at which point temperature measurements began. The data record at “Grenville” is very reliable.



Weather - Climate Observing Sites (CO, NM, & TX)

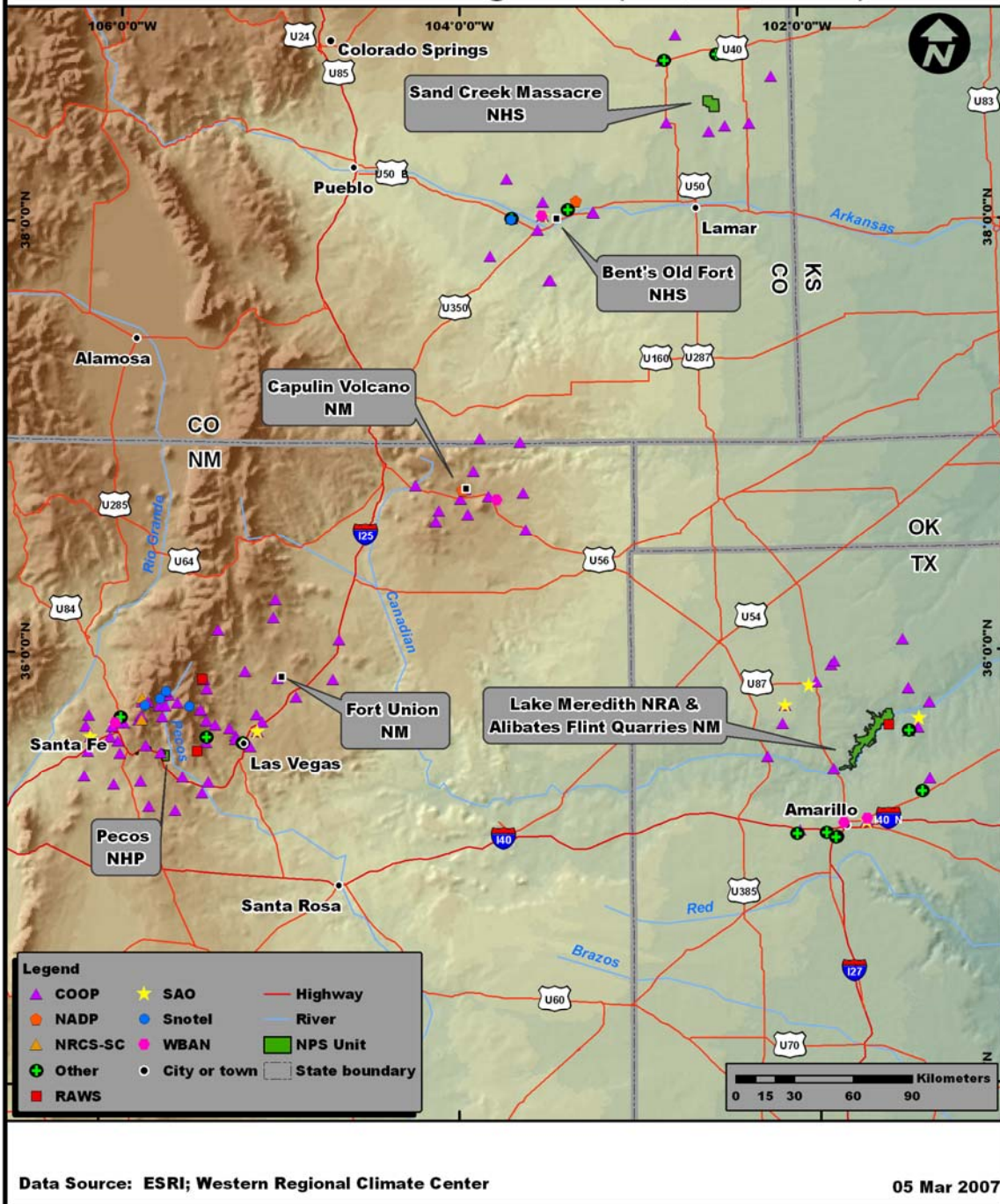


Figure 4.1. Station locations for the SOPN park units in Colorado, New Mexico, and northern Texas.

No weather or climate stations were identified within the boundaries of FOUN (Table 4.3; Figure 4.1). The only sources for near-real-time weather data within 40 km of FOUN are the CWOP station “CW2187 Las Vegas” and the RAWS station “Bartley.” “Bartley” has been active since January 2004 but has a data gap from February through May of 2004.

Seventeen COOP stations, five active, were identified within 40 km of FOUN (Table 4.3). The closest COOP station to FOUN is “Valmora,” which is 12 km southeast of FOUN. This station has been active since 1893, also making it the longest data record we identified among all the active COOP stations near FOUN. Its data record is fairly complete, with scattered data gaps. The COOP station “Ocate 2 NW” is 30 km north of FOUN. Although the station’s data record goes back to 1897, it has only been reliably complete since 1960. The COOP station “Optimo” (1910-present) is located 26 km east of FOUN. The data record at this station has been unreliable since 1960. The COOP station “Gascon” has a very reliable data record going back to 1953. This station is located 37 km west of FOUN.

No weather or climate stations were identified within the boundaries of LAMR (Table 4.3; Figure 4.1). Fifteen COOP stations, six of which are active, were identified within 40 km of LAMR. The closest COOP station to LAMR is “Borger,” which is 11 km east of LAMR. This station has been discussed previously. The longest period of record within 40 km of LAMR is found at the COOP station “Panhandle” (1911-present), which was discussed previously. This station is 36 km southeast of LAMR. The COOP station “Amarillo” (1932-present; discussed previously) is 28 km southwest of LAMR. The COOP station “Dumas” (1937-present) is located 30 km northwest of LAMR. Unfortunately, the data record at this station has numerous data gaps, especially during the 1940s and 1950s. This data record has been fairly unreliable since that time, with scattered, small data gaps. The last gap at “Dumas” occurred in May 2006. The COOP station “Bushland 1 WSW,” which is 37 km southwest of LAMR, has been active since 1947 but has an unreliable data record.

Several weather networks provide near-real-time data within 40 km of LAMR. The RAWS station “Cedar,” discussed previously, is only 2 km north of LAMR (Figure 4.1) and as such is likely the best source of near-real-time weather data for the park unit. Four SAO stations were identified within 40 km of LAMR (Table 4.3). Three of these stations are still active, including the aforementioned sites at Amarillo (28 km southwest) and Borger (13 km east). The SAO station “Dumas Moore Co. Arpt.” is 32 km northwest of LAMR and has been active since 1960. A SCAN station (Bushland #1) is located 40 km southwest of LAMR.

One station was identified at PECO (Table 4.3). The COOP station “Pecos Natl. Monument” has been operating since 1916 and has a data record that is largely complete with the exception of scattered, small gaps that are present throughout the record.

There are no near-real-time weather stations within PECO. However, at least 10 active near-real-time stations were identified within 40 km of the park unit (Table 4.3). Four of these are CWOP stations. The RAWS station “Pecos” (1994-present) is 15 km southeast of PECO. This station has data gaps in July 2001, July 2002, and March 2006. The SAO station “Santa Fe” is collocated with the Santa Fe COOP site that was discussed previously. Four SNOTEL stations

were identified within 40 km of PECO. Most of these are north and east of PECO (Figure 4.1). The closest SNOTEL station to PECO is “Santa Fe,” located 21 km north of PECO.

Two NRCS-SC stations were identified for PECO (Table 4.3). Both of these sites are located in the mountains to the north of PECO (Figure 4.1). We identified 34 COOP stations within 40 km of the boundaries of PECO; however, only five of these stations are still active. Of these active COOP stations, the station with the longest record is “Glorieta,” which is only 1 km west of PECO. This station, which measures only precipitation, has been operating since 1915. The data record has been very reliable since August 1949. The COOP station “Santa Fe” is 25 km west of PECO and has a reliable data record. The other three active COOP stations have much shorter data records.

No weather or climate stations were identified within SAND (Table 4.3). The only sources for near-real-time weather data within 40 km of SAND are the CDOT station “US-40 @ Firstview (92)” and the CWOP station “CW4436 Kit Carson.”

Eight COOP stations were identified within 40 km of SAND (Table 4.3). Five of these COOP stations are active. The closest COOP station to SAND is “Sheridan Lake,” which is 17 km southeast of SAND. This station has been active since 2000. The COOP stations “Cheyenne Wells,” 28 km northeast of SAND, and “Kit Carson,” 28 km northwest of SAND, have the longest data records in this region. Both data records go back to 1893. The record at “Cheyenne Wells” is quite complete; however, the reliability of the record at “Kit Carson” is uncertain. The COOP station “Eads” is 21 km southwest of SAND. This station’s data record goes back to 1907 and is largely complete, with scattered, small data gaps.

4.2.2. Kansas

No weather or climate stations were identified within the boundaries of FOLS (Figure 4.2; Table 4.4). Of the 19 COOP stations identified within 40 km of FOLS, six are active currently. The COOP station “Sanford 1 NW” (1954-present) is the closest active COOP station to FOLS, located 9 km west of the park unit. The COOP station “Larned” provides the longest data record we identified among these active COOP stations, with data going back to 1894. This data record is very complete. “Kinsley” is another long-term COOP station (1935-present) that we identified for FOLS. This climate station is 26 km southwest of FOLS and has a very reliable data record. The COOP station “Burdett 1 NW” (1941-present) is 26 km west of FOLS. This climate station measures precipitation only and it has a reliable data record. The COOP station “Albert” (1959-present) is 34 km northeast of FOLS. The primary source of near-real-time weather data we identified for FOLS is the SAO station “Great Bend” (1943-present), located 34 km northeast of FOLS. The closest source of near-real-time data for FOLS is the GPS-MET station “Parned,” which is 8 km east of the park unit. Two CWOP stations within 40 km of FOLS also provide near-real-time weather data.

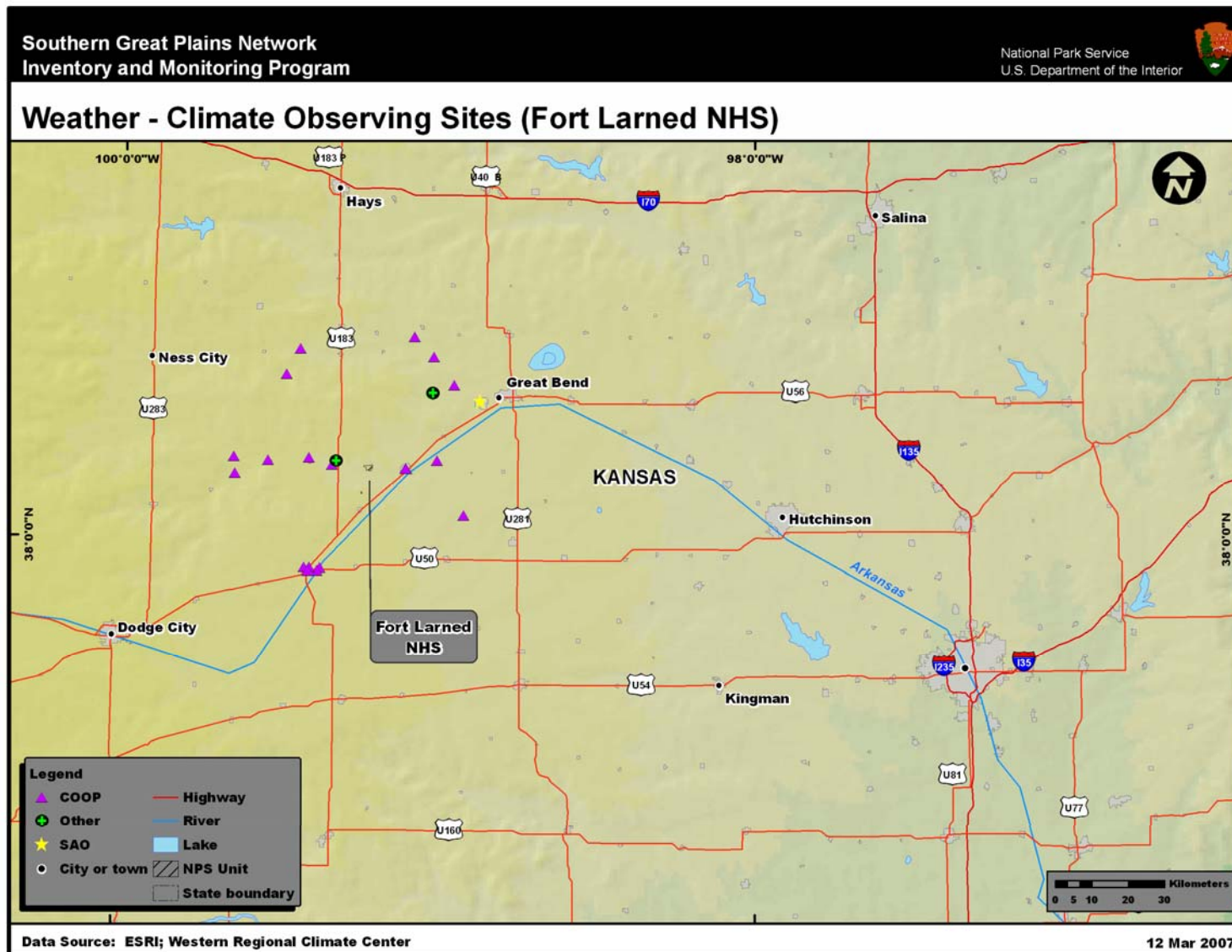


Figure 4.2. Station locations for FOLS.

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

Fort Larned National Historic Site (FOLS)							
Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Albert	38.461	-99.014	582	COOP	8/1/1959	Present	No
Albert	38.390	-98.950	582	COOP	9/29/1997	Present	No
Burdett	38.166	-99.638	650	COOP	6/11/1996	2/7/2000	No
Burdett	38.208	-99.642	651	COOP	6/11/1996	2/7/2000	No
Burdett 1 NW	38.201	-99.534	641	COOP	2/1/1941	Present	No
Kinsley	37.925	-99.404	660	COOP	11/1/1935	Present	No
Kinsley	37.926	-99.375	655	COOP	4/15/1998	2/7/2000	No
Kinsley 1 W	37.933	-99.417	M	COOP	M	12/31/1959	No
Kinsley DDC 3	37.933	-99.400	662	COOP	1/1/1958	12/31/1960	No
Kinsley River	37.933	-99.367	653	COOP	4/1/1966	9/12/1985	No
Larned	38.208	-99.406	634	COOP	10/31/1994	2/7/2000	No
Larned	38.204	-99.002	593	COOP	8/13/1998	2/7/2000	No
Larned	38.182	-99.099	608	COOP	4/1/1894	Present	No
Larned DDC 2	38.183	-99.100	610	COOP	1/1/1958	12/31/1960	No
Macksville 8 NNE	38.067	-98.917	607	COOP	2/1/1941	10/15/1977	No
Nekoma 5 SW	38.413	-99.480	655	COOP	7/1/1995	2/7/2000	No
Otis 2 SSW	38.510	-99.076	610	COOP	7/1/1995	2/7/2000	No
Rush Center 7 W	38.478	-99.437	617	COOP	11/2/1994	2/7/2000	No
Sanford 1 NW	38.190	-99.332	622	COOP	4/1/1954	Present	No
AB0XM-1 Great Bend	38.370	-99.017	596	CWOP	M	Present	No
WA0DOB-1 Great Bend	38.371	-99.017	596	CWOP	M	Present	No
Parned	38.200	-99.320	631	GPS-MET	M	Present	No
Great Bend	38.350	-98.867	573	SAO	8/1/1943	Present	No

4.2.3. Oklahoma

Two stations were identified within CHIC (Table 4.5; Figure 4.3). Both of these are COOP stations. While only one of these stations, “Chickasaw NRA,” is indicated to be active (with a reliable data record from 1978 until present), the other COOP station in CHIC, “Sulphur Platt Nl. Pk.,” operated until 1978. Therefore, it is possible that these two records may actually be from the same station, with a slight station move occurring in 1978.

Table 4.5. Weather and climate stations for the SOPN park units in Oklahoma. Stations inside park units and within 40 km of the park unit boundaries are included. Missing entries are indicated by “M”.

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Chickasaw National Recreation Area (CHIC)							
Chickasaw NRA	34.502	-96.972	322	COOP	11/1/1978	Present	Yes
Sulphur Platt Nl. Pk.	34.500	-96.967	302	COOP	2/1/1917	10/31/1978	Yes
Ardmore	34.171	-97.129	268	COOP	1/1/1901	Present	No
Ardmore	34.300	-97.150	264	COOP	1/1/1932	7/16/1961	No
Ardmore	34.300	-97.017	221	COOP	2/12/1951	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Ardmore #2	34.150	-97.150	259	COOP	10/1/1958	8/31/1994	No
Ardmore ACF 14	34.167	-97.133	265	COOP	M	1/31/1961	No
Dolberg 1 W	34.617	-96.933	345	COOP	11/1/1966	1/31/1981	No
Hennepin	34.517	-97.350	287	COOP	7/1/1947	5/6/1974	No
Hennepin 5 N	34.583	-97.346	296	COOP	10/1/1966	Present	No
Pauls Valley 2 WNW	34.755	-97.251	261	COOP	3/1/1961	Present	No
Pauls Valley 4 WSW	34.725	-97.281	287	COOP	1/1/1893	Present	No
Pontotoc	34.500	-96.628	312	COOP	9/1/1941	Present	No
Roff 2 WNW	34.640	-96.878	383	COOP	1/1/1901	2/24/2005	No
Tishomingo NWR	34.193	-96.644	196	COOP	12/1/1902	Present	No
Wynnewood OKC 26	34.567	-97.133	259	COOP	M	1/31/1961	No
Ardmore	34.193	-97.086	266	OKMESO	M	Present	No
Bee	34.191	-96.644	196	OKMESO	M	M	No
Byars	34.850	-97.003	345	OKMESO	M	Present	No
Fittstown	34.552	-96.718	352	OKMESO	M	Present	No
Newport	34.228	-97.201	283	OKMESO	M	Present	No
Pauls Valley	34.716	-97.229	291	OKMESO	M	Present	No
Sulphur	34.566	-96.951	320	OKMESO	M	Present	No
Tishomingo	34.333	-96.679	268	OKMESO	M	Present	No
Vanoss	34.789	-96.843	320	OKMESO	M	Present	No
Pauls Valley Muni. Arpt.	34.711	-97.223	295	SAO	M	Present	No

Washita Battlefield National Historic Site (WABA)

Allison	35.608	-100.100	792	COOP	1/1/1960	Present	No
Canadian 22 SE	35.647	-100.066	772	COOP	2/18/2000	Present	No
Cheyenne	35.600	-99.683	611	COOP	7/1/1923	1/1/1995	No
Cheyenne	35.754	-99.763	710	COOP	6/4/2003	Present	No
Cheyenne 1 N	35.626	-99.668	579	COOP	12/1/1966	Present	No
Elk City 2	35.417	-99.433	610	COOP	3/1/1976	10/8/1981	No
Elk City 4 W	35.393	-99.506	646	COOP	5/1/1904	Present	No
Elk City OKC 18	35.417	-99.417	M	COOP	M	1/31/1961	No
Hammon 3 SSW	35.585	-99.395	555	COOP	1/1/1920	12/1/2005	No
Mackie 4 NNW	35.748	-99.818	655	COOP	11/1/1959	1/1/2003	No
Mayfield	35.339	-99.877	611	COOP	7/1/1947	Present	No
Reydon	35.626	-99.911	727	COOP	11/15/1941	Present	No
Reydon 7 NNE	35.750	-99.867	662	COOP	7/1/1947	10/31/1965	No
Roll	35.783	-99.717	702	COOP	7/1/1947	1/24/1970	No
Sayre	35.306	-99.628	579	COOP	6/1/1936	Present	No
Sweetwater	35.422	-99.905	658	COOP	4/1/1967	Present	No
Thomas OKC 12	35.750	-99.750	531	COOP	M	1/31/1961	No
Butler	35.591	-99.271	520	OKMESO	M	Present	No
Cheyenne	35.546	-99.728	694	OKMESO	M	Present	No
Elk City	35.433	-99.400	610	SAO	6/1/1991	Present	No

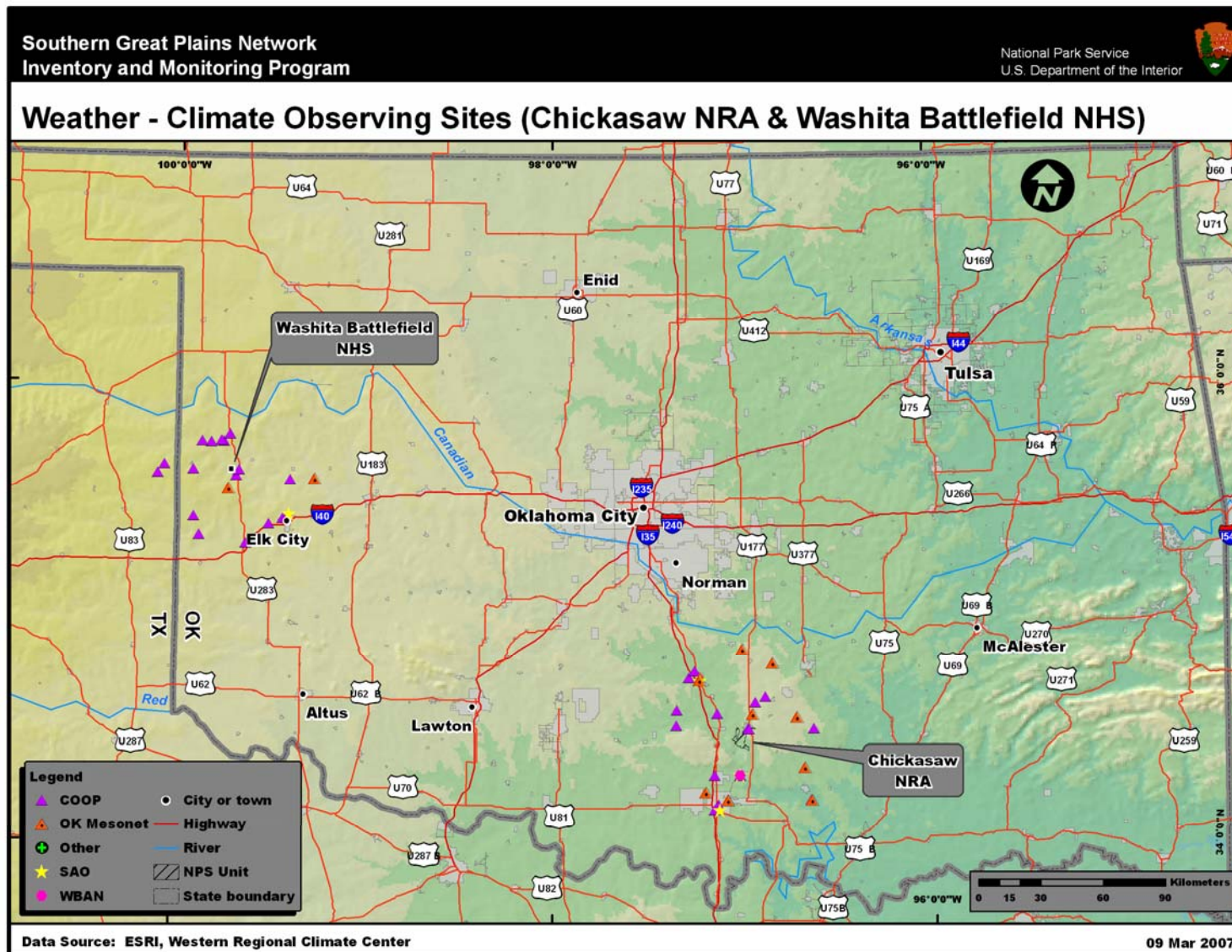


Figure 4.3. Station locations for the SOPN park units in Oklahoma.

We identified 14 COOP stations within 40 km of the boundaries of CHIC. Seven of these COOP stations are still active (Table 4.5). The longest record we identified was from the COOP station “Pauls Valley 4 WSW” (1893-present), which is 33 km northwest of CHIC. The data record at this climate station is largely complete, with scattered, small data gaps. The COOP station “Ardmore,” 13 km south of CHIC, has a data record (1901-present) which is largely complete except for occasional short data gaps. The COOP station “Tishomingo NWR” provides another long-term climate record for CHIC, with data going back to 1902. Since May 1975, this station has measured precipitation only. The COOP station “Pontotoc,” 28 km east of CHIC, has been active since 1941. This station measures precipitation only and has a largely complete data record, with scattered data gaps.

The OKMESO and SAO networks are the primary source of near-real-time weather data for CHIC. Nine OKMESO weather stations were identified for CHIC. One of these (Bee) is no longer active. We identified three active SAO stations within 40 km of CHIC (Table 4.5). “Ardmore” is the closest SAO station to CHIC, being located only 13 km south of the park unit (Figure 4.3). The SAO station “Ardmore Downtown Arpt.” is 32 km south of CHIC, while “Pauls Valley Muni. Arpt.” is 29 km southwest of CHIC.

No weather or climate stations were identified within WABA (Table 4.5). The only sources for near-real-time weather data within 40 km of WABA are the OKMESO stations “Butler” and “Cheyenne,” and the SAO station “Elk City.” The SAO station is 34 km southeast of WABA (Figure 4.3) and has been operating since 1991.

All of the remaining stations we identified for WABA are COOP stations. Seventeen such stations were identified within 40 km of WABA (Table 4.5). Nine of the COOP stations are active. The closest COOP station to WABA is “Cheyenne” (2003-present), which is only 3 km east of the park unit. The COOP station “Elk City 4 W,” 30 km southeast of WABA, has the longest data record in this region, going back to 1904. The record at “Elk City 4 W” is largely complete, with scattered data gaps. The COOP station “Sayre” (1936-present) is 35 km south of WABA. This climate station’s data record is very reliable. Only precipitation has been measured since 1975. The COOP station “Reydon” (1941-present) is 18 km west of WABA and has a data record which is largely complete, with scattered, small data gaps. The COOP station “Mayfield” (1947-present), located 34 km southwest of WABA, has an unreliable data record.

4.2.4. Central Texas

One weather station has been identified within LYJO (Table 4.6; Figure 4.4). The RAWS station “Bird” has been active since 2001 and provides a reliable data record. Besides this RAWS station, the primary source of near-real-time data for LYJO comes from CWOP stations. Five such weather stations have been identified within 40 km of LYJO.

Out of the 23 COOP stations identified within 40 km of the boundaries of LYJO, 17 are active (Table 4.6). The longest record among these climate stations is at the COOP station “Fischers Store” (1887-present), which is 36 km southeast of LYJO. The data record at this station, which measures precipitation only, is very reliable. The COOP station “Blanco” is 19 km south of LYJO and is quite reliable. A few isolated data gaps have occurred in the data record of “Blanco,” with the last gap occurring in December 2004. The COOP station “Fredericksburg”

Table 4.6. Weather/climate stations for LYJO. Stations inside LYJO and within 40 km of LYJO are included. Missing entries are indicated by "M".

Lyndon B. Johnson National Historical Park (LYJO)							
Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Bird	30.263	-98.629	457	RAWS	5/1/2001	Present	Yes
Bankersmith	30.141	-98.820	533	COOP	7/1/1947	Present	No
Blanco	30.101	-98.423	418	COOP	5/1/1896	Present	No
Canyon Dam	29.947	-98.301	347	COOP	1/1/1961	Present	No
Canyon Dam 5	29.917	-98.350	305	COOP	1/1/1961	10/28/1987	No
Canyon Dam No 3	29.946	-98.397	396	COOP	1/1/1961	Present	No
Canyon Dam No 4	29.911	-98.371	356	COOP	1/1/1961	Present	No
Comfort 2	29.962	-98.894	437	COOP	1/1/1961	Present	No
Cypress Mill	30.383	-98.250	281	COOP	7/1/1947	9/30/1964	No
Fischers Store	29.976	-98.265	354	COOP	4/10/1887	Present	No
Fredericksburg	30.239	-98.909	514	COOP	12/1/1896	Present	No
Gold	30.348	-98.686	500	COOP	7/1/1947	Present	No
Henly	30.200	-98.217	354	COOP	7/1/1947	12/31/1965	No
Hye	30.253	-98.571	444	COOP	7/1/1947	Present	No
Johnson City	30.284	-98.417	376	COOP	7/1/1964	Present	No
Kendalia	29.966	-98.512	415	COOP	1/27/1961	Present	No
Llano	30.501	-98.745	421	COOP	8/1/1997	Present	No
Marble Falls	30.567	-98.283	235	COOP	1/1/1908	7/31/1951	No
Moss Ranch	30.550	-98.700	360	COOP	7/1/1947	8/1/1997	No
Round Mountain	30.425	-98.349	411	COOP	7/1/1947	Present	No
Sandy 2 S	30.333	-98.467	378	COOP	7/1/1947	12/31/1965	No
Sisterdale	29.977	-98.730	427	COOP	1/1/1961	Present	No
Spicewood	30.483	-98.160	259	COOP	1/1/1968	Present	No
Teague Ranch	30.432	-98.810	497	COOP	7/1/1947	Present	No
CW5227 Dripping Springs	30.264	-98.150	388	CWOP	M	Present	No
CW5354 Henly	30.252	-98.218	400	CWOP	M	Present	No
K5MCL Johnson City	30.306	-98.397	371	CWOP	M	Present	No
KC4WFA Johnson City	30.300	-98.400	366	CWOP	M	Present	No
N5ZTW Austin	30.227	-98.196	448	CWOP	M	Present	No
Stonewall	30.250	-98.617	461	SAO	12/1/1963	1/31/1969	No
Fredericksburg	30.267	-98.867	525	WBAN	5/1/1940	12/31/1948	No

(1896-present) is 25 km west of LYJO. Observations were not taken at this site from May 1915 until January 1939. Several other COOP stations within 40 km of LYJO have data records that go back to the 1940s.



Weather - Climate Observing Sites (Lyndon B. Johnson NHP)

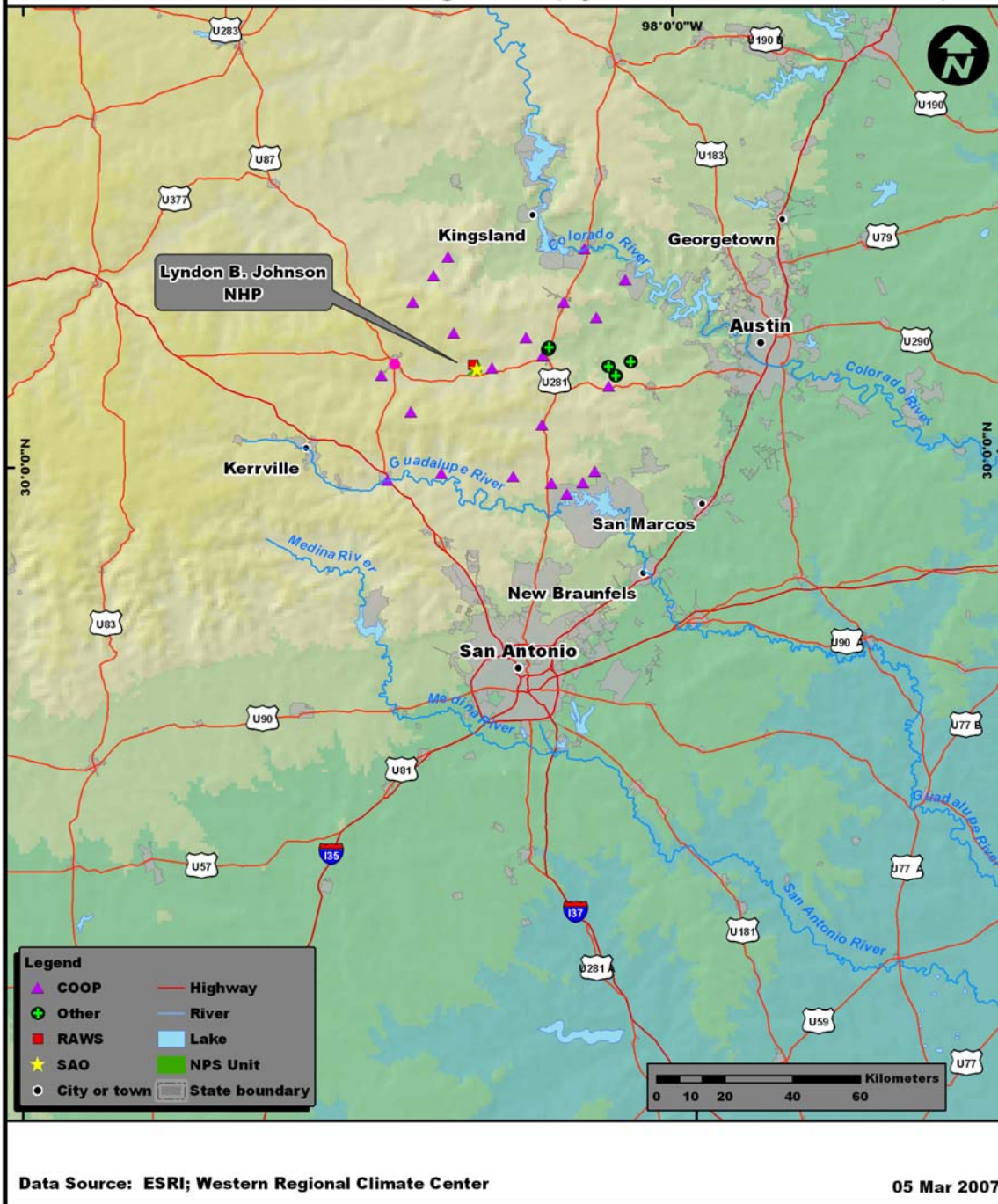


Figure 4.4. Station locations for LYJO.

5.0. Conclusions and Recommendations

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

5.1. Southern Plains Inventory and Monitoring Network

Most of the SOPN park units do not currently have any weather or climate stations within their boundaries. Only three park units (CAVO, CHIC, and PECO) have stations. Therefore, SOPN park units must rely heavily on outside sources of weather/climate data in order to carry out their climate monitoring activities. Climate monitoring efforts within the SOPN will benefit by encouraging the continued operation of these active stations having longer climate records, as these records provide valuable documentation of ongoing climate changes within SOPN park units.

As these partnerships are being developed, those SOPN units which do not have any weather or climate stations within their boundaries could consider ways to add such stations to their park units. The lack of stations within SOPN park units is particularly evident for near-real-time weather stations. The only park unit that has an automated weather station is LYJO (the RAWS station “Bird”). Although most of the SOPN park units have a few automated sites that are nearby, one of the park units, CAVO, has no automated station coverage within 40 km of their boundaries. We recommend that a RAWS station be considered for CAVO, due to its setting in the high desert/grassland environment of northern New Mexico. Even SAND may be able to benefit from improving the coverage of automated weather stations in its vicinity, as the closest automated site (the CDOT station “US-40 @ Firstview (92)”) is 22 km from the park unit. The Oklahoma Mesonet is a reliable source of near-real-time data for those SOPN park units that are in Oklahoma. Many of the remaining park units outside of Oklahoma are located in intensive agricultural areas. Therefore, to expand near-real-time station coverage in or near these park units, one strategy for the SOPN may be to work with USDA/NRCS to install SCAN stations in these areas. The SCAN network is intended primarily for weather/climate monitoring in agricultural areas in the U.S.

All of the SOPN park units do have at least a few sources of long-term climate records within 40 km of their boundaries. However, some of these long-term records should be used with caution. This includes the COOP station “Las Animas,” near BEOL, as discussed previously (also see Davey and Pielke 2005). Another example of this can be found with the COOP station records we identified within CHIC (“Chickasaw NRA” and “Sulphur Platt Nl. Pk.”), which may actually be from one station, as discussed previously. If these two records are interpreted as coming from one station, care must be taken to interpret their combined records properly.

5.2. Spatial Variations in Mean Climate

Convective summer precipitation events introduce a high level of spatial variability to precipitation characteristics in SOPN park units. With local variations over short horizontal and vertical distances, topography introduces considerable fine-scale structure to mean climate (temperature and precipitation) within some SOPN park units, particularly in New Mexico.

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 SOPN ecosystems in response to possible future climate change. In particular, there are concerns about habitat shifts and abilities of plant and animal communities to migrate in response to climate changes (Perkins et al. 2005). The SOPN region is strongly affected by ENSO cycles. Future climate changes could affect the frequency, intensity, and duration of ENSO events in the area, which would in turn impact SOPN ecosystems.

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.

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/climate stations. Most weather/climate stations, therefore, tend to be “hidden” but many of these hidden locations have inferior exposures. Some measure of compromise is nearly always called for in siting weather and climate stations.

The public has vast interest 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 SOPN 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 SOPN park units but also to climate-monitoring efforts for SOPN. These pages can be found through <http://www.wrcc.dri.edu/nps>.

Additional access to more standard climate information is accessible through 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

- Most of the SOPN park units do not currently have any weather or climate stations within their boundaries. These park units must rely heavily on outside weather/climate data sources. Climate monitoring efforts will benefit as SOPN park units work closely with local observers to continue operating long-term climate sites.
- Lack of station coverage within SOPN park units is particularly evident for near-real-time stations. Some SOPN park units have virtually no near-real-time weather data within 40 km of their boundaries (e.g. CAVO).
- A RAWs station installation could be very useful for climate monitoring efforts within CAVO. Many of the other SOPN park units with no near-real-time station coverage are located in agricultural areas. SCAN station installations would be suitable in or near these park units.
- Although most SOPN park units have at least a few nearby long-term climate records, some records should be used with caution. These include the “Las Animas” COOP station near BEOL and the two COOP stations within CHIC.

6.0 Literature Cited

- American Association of State Climatologists. 1985. Heights and exposure standards for sensors on automated weather stations. *The State Climatologist* **9**.
- Anderson, R. C. 1990. The historic role of fire in the North American grassland. Pages 8-18 *in* S. L. Collins and L. L. Wallace, editors. *Fire in North American Tallgrass Prairies*. University of Oklahoma Press, Norman, Oklahoma.
- Bevis, M., S. Businger, T. A. Herring, C. Rocken, R. A. Anthes, and R. H. Ware. 1992. GPS meteorology: remote sensing of the atmospheric water vapor using the global positioning system. *Journal of Geophysical Research* **97**:75–94.
- Bonan, G. B. 2002. *Ecological Climatology: Concepts and Applications*. Cambridge University Press.
- Bureau of Land Management. 1997. Remote Automatic Weather Station (RAWS) and Remote Environmental Monitoring Systems (REMS) standards. RAWS/REMS Support Facility, Boise, Idaho.
- Chapin III, F. S., M. S. Torn, and M. Tateno. 1996. Principles of ecosystem sustainability. *The American Naturalist* **148**:1016-1037.
- Clark, J. S., E. C. Grimm, J. J. Donovan, S. C. Fritz, D. R. Engstrom, and J. E. Almendinger. 2002. Drought cycles and landscape responses to past aridity on prairies of the Northern Great Plains. *Ecology* **83**:595-601.
- Collins, S. L., and S. M. Glenn. 1995. Grassland ecosystem and landscape dynamics. Pages 128-156 *in* Joern, A., and K. H. Keeler, editors. *The changing prairie: North American Grasslands*. Oxford University Press, New York.
- Daly, C., R. P. Neilson, and D. L. Phillips. 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *Journal of Applied Meteorology* **33**:140-158.
- Daly, C., W. P. Gibson, G. H. Taylor, G. L. Johnson, and P. Pasteris. 2002. A knowledge-based approach to the statistical mapping of climate. *Climate Research* **22**:99-113.
- Davey, C. A., and R. A. Pielke, Sr. 2005. Microclimate exposures of surface-based weather stations - implications for the assessment of long-term temperature trends. *Bulletin of the American Meteorological Society* **86**:497–504.
- Doggett, M., C. Daly, J. Smith, W. Gibson, G. Taylor, G. Johnson, and P. Pasteris. 2004. High-resolution 1971-2000 mean monthly temperature maps for the western United States. Fourteenth AMS Conf. on Applied Climatology, 84th AMS Annual Meeting. Seattle,

- Washington, American Meteorological Society, Boston, Massachusetts, January 2004, Paper 4.3, CD-ROM.
- Duan, J., M. Bevis, P. Fang, Y. Bock, S. Chiswell, S. Businger, C. Rocken, F. Solheim, T. van Hove, R. Ware, and others. 1996. GPS meteorology: direct estimation of the absolute value of precipitable water. *Journal of Applied Meteorology* **35**:830-838.
- Environmental Protection Agency. 1987. On-site meteorological program guidance for regulatory modeling applications. EPA-450/4-87-013. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina.
- Finklin, A. I., and W. C. Fischer. 1990. Weather station handbook –an interagency guide for wildland managers. NFES No. 2140. National Wildfire Coordinating Group, Boise, Idaho.
- French, N. R., W. E. Grant, W. Grodzinski, and D. M. Smith. 1976. Small mammal energetics in grassland ecosystems. *Ecological Monographs* **46**:201-220.
- Gibson, W. P., C. Daly, T. Kittel, D. Nychka, C. Johns, N. Rosenbloom, A. McNab, and G. Taylor. 2002. Development of a 103-year high-resolution climate data set for the conterminous United States. Thirteenth AMS Conf. on Applied Climatology. Portland, Oregon, American Meteorological Society, Boston, MA, May 2002:181-183.
- I&M. 2006. I&M Inventories home page. <http://science.nature.nps.gov/im/inventory/index.cfm>.
- Jacobson, M. C., R. J. Charlson, H. Rodhe, and G. H. Orians. 2000. *Earth System Science: From Biogeochemical Cycles to Global Change*. Academic Press, San Diego.
- 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.
- Mock, C. J. 1991. Drought and precipitation fluctuations in the Great Plains during the late nineteenth century. *Great Plains Research* **1**:26-57.
- National Assessment Synthesis Team. 2001. *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*, Report for the U.S. Global Change Research Program. Cambridge University Press, Cambridge, UK.
- National Research Council. 2001. *A Climate Services Vision: First Steps Toward the Future*. National Academies Press, Washington, D.C.
- National Wildfire Coordinating Group. 2004. National fire danger rating system weather station standards. Report PMS 426.3. National Wildfire Coordinating Group, Boise, Idaho.

- Neilson, R. P. 1987. Biotic regionalization and climatic controls in western North America. *Vegetatio* **70**:135-147.
- Oakley, K. L., L. P. Thomas, and S. G. Fancy. 2003. Guidelines for long-term monitoring protocols. *Wildlife Society Bulletin* **31**:1000-1003.
- Parton, W. J., W. K. Lauenroth, and F. M. Smith. 1981. Water loss from a short-grass steppe. *Agricultural Meteorology* **24**:97-109.
- Perkins, D. W., H. Sosinski, K. Cherwin, and T. F. Zettner. 2005. Southern Plains Network Vital Signs Monitoring Plan: Phase I. National Park Service, Southern Plains Network, Johnson City, Texas.
- Redmond, K. T., D. B. Simeral, and G. D. McCurdy. 2005. Climate monitoring for southwest Alaska national parks: network design and site selection. Report 05-01. Western Regional Climate Center, Reno, Nevada.
- Risser, P. G., E. C. Birney, H. D. Blocker, S. W. May, W. J. Parton, and J. A. Wiens. 1981. The true prairie ecosystem. Hutchinson Ross Publishing Company, Stroudsburg, Pennsylvania.
- Rodriguez-Iturbe, I. 2000. Ecohydrology: A hydrologic perspective of climate-soil-vegetation dynamics. *Water Resources Research* **36**:3-9.
- Roe, F. G. 1951. The North American buffalo. University of Toronto Press, Toronto, Ontario, Canada.
- Schlesinger, W. H. 1997. Biogeochemistry: An Analysis of Global Change. Academic Press, San Diego.
- Tanner, B. D. 1990. Automated weather stations. *Remote Sensing Reviews* **5**:73-98.
- Tilman, D. and A. El Haddi. 1992. Drought and biodiversity in grasslands. *Oecologia* **89**:257-264.
- Weaver, J. E. 1943. Resurvey of grasses, forbs,, and underground plant parts at the end of the great drought. *Ecological Monographs* **13**:63-117.
- Weaver, J. E. 1954. North American prairie. Johnsen Publishing Company, Lincoln, Nebraska.
- Weaver, J. E. 1968. Prairie plants and their environment. University of Nebraska Press, Lincoln, Nebraska.
- Wilhite, D. A. and R. O. Hoffman. 1979. Drought in the Great Plains: A bibliography. Institute of Agriculture and Natural Resources, University of Nebraska, Lincoln, Nebraska.

- World Meteorological Organization. 1983. Guide to meteorological instruments and methods of observation, No. 8, 5th edition, World Meteorological Organization, Geneva, Switzerland.
- World Meteorological Organization. 2005. Organization and planning of intercomparisons of rainfall intensity gauges. World Meteorological Organization, Geneva, Switzerland.
- Yuan, L. L., R. A. Anthes, R. H. Ware, C. Rocken, W. D. Bonner, M. G. Bevis, and S. Businger. 1993. Sensing climate change using the global positioning system. *Journal of Geophysical Research* **98**:14925-14937.

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; NRC 2001). Because climate measurements are accumulated over a long time, they should be treated as multi-purpose and should be undertaken in a manner that serves the widest possible applications. Some applications remain constant, while others rise and fall in importance. An insistent issue today may subside, while the next pressing issue of tomorrow barely may be anticipated. The notion that humans might affect the

climate of the entire Earth was nearly unimaginable when the national USDA (later NOAA) cooperative weather network began in the late 1800s. Abundant experience has shown, however, that there always will be a demand for a history record of climate measurements and their properties. Experience also shows that there is an expectation that climate measurements will be taken and made available to the general public.

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

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

Thus, individuals who observe the climate should be able to record observations accurately and depict both rapid and slow changes. In particular, an array of artificial influences easily can confound detection of slow changes. The record as provided can contain both real climate variability (that took place in the atmosphere) and fake climate variability (that arose directly from the way atmospheric changes were observed and recorded). As an example, trees growing near a climate station with an excellent anemometer will make it appear that the wind gradually slowed down over many years. Great care must be taken to protect against sources of fake climate variability on the longer-time scales of years to decades. Processes leading to the observed climate are not stationary; rather these processes draw from probability distributions that vary with time. For this reason, climatic time series do not exhibit statistical stationarity. The implications are manifold. There are no true climatic “normals” to which climate inevitably must return. Rather, there are broad ranges of climatic conditions. Climate does not demonstrate exact repetition but instead continual fluctuation and sometimes approximate repetition. In addition,

there is always new behavior waiting to occur. Consequently, the business of climate monitoring is never finished, and there is no point where we can state confidently that “enough” is known.

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 (Parameter Regression on Independent Slopes Model) maps (Daly et al. 1994; 2002; Gibson et al. 2002; Doggett et al. 2004) were probably the best available. An analysis by Simpson et al. (2005) further discussed many issues in the mapping of Alaska’s climate and resulted in the same conclusion about PRISM.

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 observations 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 (Climate Reference Network): the DFIR (Double-Fence Intercomparison Reference) shield with 2.4-m (8-ft.) vertical, wooden slatted fences in two concentric octagons with diameters of 8 m and 4 m (26 ft and 13 ft, respectively) and an inner Alter shield (flapping vanes). Numerous tests have shown this is the only way to achieve complete catch of snowfall (e.g., Yang et al. 1998, 2001). The DFIR shield is large and bulky; it is recommended that all precipitation gauges have at least Alter shields on them.

Near 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 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).

D.4. Literature Cited

- American Association of State Climatologists. 1985. Heights and exposure standards for sensors on automated weather stations. *The State Climatologist* **9**.
- Brock, F. V., K. C. Crawford, R. L. Elliott, G. W. Cuperus, S. J. Stadler, H. L. Johnson and M. D. Eilts. 1995. The Oklahoma Mesonet: A technical overview. *Journal of Atmospheric and Oceanic Technology* **12**:5-19.
- Daly, C., R. P. Neilson, and D. L. Phillips. 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *Journal of Applied Meteorology* **33**:140-158.
- Daly, C., W. P. Gibson, G. H. Taylor, G. L. Johnson, and P. Pasteris. 2002. A knowledge-based approach to the statistical mapping of climate. *Climate Research* **22**:99-113.
- Doggett, M., C. Daly, J. Smith, W. Gibson, G. Taylor, G. Johnson, and P. Pasteris. 2004. High-resolution 1971-2000 mean monthly temperature maps for the western United States. Fourteenth AMS Conf. on Applied Climatology, 84th AMS Annual Meeting. Seattle, WA, American Meteorological Society, Boston, MA, January 2004, Paper 4.3, CD-ROM.
- Geiger, R., R. H. Aron, and P. E. Todhunter. 2003. *The Climate Near the Ground*. 6th edition. Rowman & Littlefield Publishers, Inc., New York.
- Gibson, W. P., C. Daly, T. Kittel, D. Nychka, C. Johns, N. Rosenbloom, A. McNab, and G. Taylor. 2002. Development of a 103-year high-resolution climate data set for the conterminous United States. Thirteenth AMS Conf. on Applied Climatology. Portland, OR, American Meteorological Society, Boston, MA, May 2002:181-183.
- Goodison, B. E., P. Y. T. Louie, and D. Yang. 1998. WMO solid precipitation measurement intercomparison final report. WMO TD 982, World Meteorological Organization, Geneva, Switzerland.

- National Research Council. 1998. Future of the National Weather Service Cooperative Weather Network. National Academies Press, Washington, D.C.
- National Research Council. 2001. A Climate Services Vision: First Steps Toward the Future. National Academies Press, Washington, D.C.
- Redmond, K. T. 1992. Effects of observation time on interpretation of climatic time series - A need for consistency. Eighth Annual Pacific Climate (PACCLIM) Workshop. Pacific Grove, CA, March 1991:141-150.
- Redmond, K. T. 2004. Photographic documentation of long-term climate stations. Available from <ftp://ftp.wrcc.dri.edu/nps/photodocumentation.pdf>. (accessed 15 August 2004)
- Redmond, K. T. and D. B. Simeral. 2004. Climate monitoring comments: Central Alaska Network Inventory and Monitoring Program. Available from <ftp://ftp.wrcc.dri.edu/nps/alaska/cakn/npscakncomments040406.pdf>. (accessed 6 April 2004)
- Redmond, K. T., D. B. Simeral, and G. D. McCurdy. 2005. Climate monitoring for southwest Alaska national parks: network design and site selection. Report 05-01. Western Regional Climate Center, Reno, Nevada.
- Redmond, K. T., and G. D. McCurdy. 2005. Channel Islands National Park: Design considerations for weather and climate monitoring. Report 05-02. Western Regional Climate Center, Reno, Nevada.
- Sevruk, B., and W. R. Hamon. 1984. International comparison of national precipitation gauges with a reference pit gauge. Instruments and Observing Methods, Report No 17, WMO/TD – 38, World Meteorological Organization, Geneva, Switzerland.
- Simpson, J. J., Hufford, G. L., C. Daly, J. S. Berg, and M. D. Fleming. 2005. Comparing maps of mean monthly surface temperature and precipitation for Alaska and adjacent areas of Canada produced by two different methods. *Arctic* **58**:137-161.
- Whiteman, C. D. 2000. Mountain Meteorology: Fundamentals and Applications. Oxford University Press, Oxford, UK.
- Wilson, E. O. 1998. Consilience: The Unity of Knowledge. Knopf, New York.
- World Meteorological Organization. 1983. Guide to meteorological instruments and methods of observation, No. 8, 5th edition, World Meteorological Organization, Geneva Switzerland.
- World Meteorological Organization. 2005. Organization and planning of intercomparisons of rainfall intensity gauges. World Meteorological Organization, Geneva Switzerland.
- Yang, D., B. E. Goodison, J. R. Metcalfe, V. S. Golubev, R. Bates, T. Pangburn, and C. Hanson. 1998. Accuracy of NWS 8" standard nonrecording precipitation gauge: results and

application of WMO intercomparison. *Journal of Atmospheric and Oceanic Technology* **15**:54-68.

Yang, D., B. E. Goodison, J. R. Metcalfe, P. Louie, E. Elomaa, C. Hanson, V. Bolubev, T. Gunther, J. Milkovic, and M. Lapin. 2001. Compatibility evaluation of national precipitation gauge measurements. *Journal of Geophysical Research* **106**:1481-1491.

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 SOPN:
http://www.wrcc.dri.edu/nps/pub/SOPN/metadata/SOPN_from_ACIS.tar.gz.

Appendix G. Descriptions of weather/climate monitoring networks

G.1. Colorado Department of Transportation (CDOT) Network

- Purpose of network: provide weather data to support management of Colorado's transportation network.
- Primary management agency: CDOT.
- Data website: <http://www.met.utah.edu/jhorel/html/mesonet>.
- Measured weather/climate elements:
 - Air temperature.
 - Relative humidity.
 - Barometric pressure.
 - Wind speed and direction.
 - Wind gust and direction.
- Sampling frequency: unknown.
- Reporting frequency: unknown.
- Estimated station cost: unknown.
- Network strengths:
 - Real-time data.
- Network weaknesses:
 - Coverage is limited to the state of Colorado.

These weather stations are operated by CDOT in support of management activities for Colorado's transportation network. Measured meteorological elements generally include temperature, precipitation, wind, and relative humidity.

G.2. Colorado Agricultural Meteorological Network (CoAgMet)

- Purpose of network: provide weather data in support of Colorado agricultural activities.
- Primary management agencies: Colorado State University Extension Service; Colorado Climate Center.
- Data website: <http://ccc.atmos.colostate.edu/~coagmet>.
- Measured weather/climate elements:
 - Air temperature.
 - Relative humidity.
 - Precipitation.
 - Wind.
 - Solar radiation.
 - Soil temperature.
- Sampling frequency: unknown.
- Reporting frequency: hourly or daily.
- Estimated station cost: unknown.
- Network strengths:
 - Real-time data.
- Network weaknesses:

- Coverage is limited to the state of Colorado.

The CoAgMet network is a weather monitoring network originally started in the early 1990s by the Agricultural Research Service branch of the USDA and the Plant Pathology extension service at Colorado State University. Data are managed by the Colorado Climate Center.

G.3. 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.4. 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.
 - 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.5. 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.6. 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.7. 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.

G.8. 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.9. Oklahoma Mesonet (OKMESO)

- Purpose of network: provide dense coverage of near-real-time weather observations for the state of Oklahoma.
- Primary management agency: Oklahoma Climatological Service.
- Data website: <http://www.mesonet.ou.edu>.
- Measured weather/climate elements:
 - Air temperature.
 - Relative humidity/dewpoint temperature.

- Precipitation.
- Barometric pressure.
- Wind.
- Solar Radiation.
- Sampling frequency: unknown.
- Reporting frequency: five minutes.
- Estimated station cost: unknown.
- Network strengths:
 - Dense coverage within state of Oklahoma.
 - Sites are well-maintained.
 - Data quality is excellent.
 - Metadata is extensive.
- Network weaknesses:
 - Geographic coverage – limited to Oklahoma.

The OKMESO network is administered through the Oklahoma Climatological Survey. The first stations in the OKMESO network were installed in the early 1990s, with much of the current network coverage being established during the late 1990s and early 2000s. The OKMESO network now consists of over 110 stations around Oklahoma, with at least one station in each of the 77 counties of the state.

G.10. 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 and direction.
 - Wind gust and 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.11. 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.12. USDA/NRCS Soil Climate Analysis Network (SCAN)

- Purpose of network: comprehensive soil-climate network used in natural resource assessments and other conservation activities in the U.S.
- Primary management agency: USDA/NRCS.
- Data website: <http://www.wcc.nrcs.usda.gov/scan/>.
- Measured weather/climate elements:
 - Air temperature.
 - Precipitation.
 - Relative humidity.
 - Wind speed.
 - Wind direction.
 - Barometric pressure.
 - Solar radiation.
 - Snow water content.
 - Snow depth.
 - 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: \$25000, with maintenance costs approximately \$1000/year.
- Network strengths:
 - Sites are well-maintained.
 - Data are of high quality and are largely complete.
 - Very reliable automated system.
- Network weaknesses:
 - Short data records.
 - Network is still in development.

The SCAN network is intended to be a comprehensive nationwide soil moisture and climate information system to be used in supporting natural resource assessments and other conservation activities. These stations are usually located in the agricultural areas of the U.S. All SCAN sites

are automated. The parameters measured at these sites include air temperature, precipitation, humidity, wind, barometric pressure, solar radiation, snow depth, and snow water content.

G.13. 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.

The U.S. Department of the Interior (DOI) is the nation's principal conservation agency, charged with the mission “*to protect and provide access to our Nation’s natural and cultural heritage and honor our trust responsibilities to Indian tribes and our commitments to island communities.*” More specifically, DOI protects America’s treasures for future generations, provides access to our Nation’s natural and cultural heritage, offers recreational opportunities, honors its trust responsibilities to American Indians and Alaskan Natives and its responsibilities to island communities, conducts scientific research, provides wise stewardship of energy and mineral resources, fosters sound use of land and water resources, and conserves and protects fish and wildlife. The work that we do affects the lives of millions of people; from the family taking a vacation in one of our national parks to the children studying in one of our Indian schools.

**National Park Service
U.S. Department of the Interior**

**Natural Resource Program Center
Fort Collins, Colorado**



**Natural Resource Program Center
1201 Oakridge Drive, Suite 150
Fort Collins, Colorado 80525**

www.nps.gov