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Weather and Climate Inventory National Park Service Greater Yellowstone Network

Natural Resource Technical Report NPS/GRYN/NRTR—2006/001

ON THE COVER
Mt. Moran—Grand Teton National Park

Weather and Climate Inventory
National Park Service
Greater Yellowstone Network

Natural Resource Technical Report NPS/GRYN/NRTR—2006/001
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Acronyms

AASC	American Association of State Climatologists
ACIS	Applied Climate Information System
AgriMet	Pacific Northwest Cooperative Agricultural Network
ASOS	Automated Surface Observing System
AWOS	Automated Weather Observing System
BICA	Bighorn Canyon National Recreation Area
BLM	Bureau of Land Management
CASTNet	Clean Air Status and Trends Network
COOP	Cooperative Observer Program
CRN	Climate Reference Network
DFIR	Double-Fence Intercomparison Reference
DST	daylight savings time
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FIPS	Federal Information Processing Standards
GMT	Greenwich Mean Time
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
GRTE	Grand Teton National Park
GRYN	Greater Yellowstone Inventory and Monitoring Network
I&M	NPS Inventory and Monitoring Program
JODR	John D. Rockefeller, Jr., Memorial Parkway
LST	local standard time
NADP	National Atmospheric Deposition Program
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
PDO	Pacific Decadal Oscillation
PRISM	Parameter Regression on Independent Slopes Model
RAWS	Remote Automated Weather Station Network
RCC	regional climate center
SAO	Surface Airways Observation Network
Surfrad	Surface Radiation Budget Network
SNOTEL	NRCS Snowfall Telemetry Network
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
UTC	Coordinated Universal Time
WBAN	Weather Bureau Army Navy
WMO	World Meteorological Organization
WRCC	Western Regional Climate Center

YELL	Yellowstone National Park

Executive Summary

Climate is a dominant factor driving the physical and ecologic processes that affect the Greater Yellowstone Inventory and Monitoring Network (GRYN). Climate variations are responsible for short- and long-term changes in ecosystem fluxes of energy and matter and have profound effects on underlying geomorphic and biogeochemical processes. Climate is a major determinant in vegetation zonation and thus the distribution of animal habitats in the Greater Yellowstone Ecosystem. Major wildfires in GRYN have highlighted vulnerabilities to drought and other inter-annual climate variations. Because of its influence on the ecology of GRYN park units and the surrounding areas, climate was identified as a high-priority, vital sign for GRYN, and climate is one of the 12 basic inventories to be completed for all National Park Service (NPS) Inventory and Monitoring Program (I&M) networks.

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

- Overview of broad-scale climatic factors and zones important to GRYN park units.
- Inventory of weather and climate station locations in and near GRYN 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 (e.g. length of record).
- Initial evaluation of the adequacy of coverage for existing weather stations and recommendations for improvements in monitoring weather and climate.

The GRYN climate is complex, encompassing environments ranging from alpine zones to lower-elevation basins exhibiting sharp transitions in various places. Mean annual temperature ranges from near 20°C in Bighorn Canyon National Recreation Area (BICA) to nearly 0°C in most alpine areas. Mean annual precipitation ranges from less than 200 mm in BICA to almost 2000 mm in portions of the Teton Range. The region experiences two main precipitation seasons. One is an orographic winter pattern that especially influences the Teton Range and southwestern parts of Yellowstone National Park (YELL). The other season occurs in late spring, primarily over the eastern portions of GRYN. Dry conditions are common in mid- and late summer as the southwestern monsoon of New Mexico and Arizona becomes established. Winter precipitation in GRYN is very sensitive to climate indices such as the El Niño Southern Oscillation and the Pacific Decadal Oscillation. El Niño conditions and/or positive phases of the Pacific Decadal Oscillation generally lead to drier winter conditions in the GRYN. Mild winters and droughts have been common in recent years.

Through a search of national databases and inquiries to NPS staff, we have identified 57 weather and climate stations within GRYN park units. These include 40 stations in YELL, 12 stations in Grand Teton National Park (GRTE), and 6 stations in BICA. The current and past weather and climate stations in GRYN sample atmospheric conditions over a large portion of the land area and ecosystem zones. However, weather and climate

stations are not present in large portions of the mountains of eastern YELL, southwestern YELL, and mountains of GRTE. There are no automated weather or climate stations within BICA.

Metadata and data records for most of the weather and climate stations within GRYN are sufficiently complete and of satisfactory quality. However, there are at least two stations where data quality is questionable. These include the National Weather Service Cooperative Observer Program (COOP) site at Moose, Wyoming, and the Surface Airways Observation Network (SAO) weather station at West Yellowstone.

Alpine areas within GRYN are noticeably deficient in weather and climate stations. Additional stations in these areas would enhance hydrologic applications and support monitoring of climate changes. We have not identified automated weather stations higher than 2865 m (Parker Peak in YELL), although there are manual stations located at both Mount Holmes (3142 m) and Mount Sheridan (3126 m) in YELL. One of these alpine sites could be augmented by installing an enhanced Snowfall Telemetry Network (SNOTEL) site, which measures elements such as snowfall, solar radiation, and wind. A possible third location for this alpine station would be the summit of Mount Washburn.

The Teton Range and portions of southwestern YELL are among the wettest regions of GRYN. However, there are very few weather and climate stations sampling this unique climate zone. Installing a SNOTEL station here would allow GRYN to monitor climate and the resulting hydrologic processes in the Teton Range. There is a suitable location in GRTE at the head of the Cascade Creek Basin, which is reasonably accessible from the NPS facilities near Jenny Lake.

For BICA, retaining the existing manual site at Yellowtail Dam for long-term climate monitoring would be advantageous. Augmenting the existing manual site near Yellowtail Dam with an automated weather station would complement the existing Remote Automated Weather Station (RAWS) at Hillsboro by providing data to evaluate climate gradients along the canyon.

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 Greater Yellowstone Inventory and Monitoring Network. Particular thanks are extended to Robert Bennetts, Rob Daley, Cathie Jean. We also thank John Gross, Margaret Beer, and Steve Garman for their contributions to this report. Grant Kelly, Heather Angeloff, and Greg McCurdy from the Western Regional Climate Center have provided valuable assistance in the production of this report. Jennifer Lease with Desert Research Institute provided valuable assistance with proofreading, editing, and formatting this report. Portions of the work also were supported by the Western Regional Climate Center under the auspices of the National Oceanic and Atmospheric Administration.

1.0. Introduction

Weather and climate are key drivers in ecosystem structure and function. Global- and regional-scale climate variations will have a tremendous impact on natural systems (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 climate regime (Neilson 1987).

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 Greater Yellowstone Inventory and Monitoring Network (GRYN) have an effective climate-monitoring system in place to track climate changes and to aid in management decisions relating to these changes. The two primary objectives for climate- and weather-monitoring in GRYN are as follows (Jean et al. 2005):

A. Measure precipitation and air temperature in GRYN, including Bighorn Canyon National Recreation Area (BICA), Grand Teton National Park (GRTE), Yellowstone National Park (YELL), and surrounding areas.
B. Measure secondary climate elements including wind speed/direction, relative humidity, soil temperatures, and incoming solar radiation in GRYN, as well as BICA, GRTE, YELL, and surrounding areas.

The purpose of this report is to determine the current status of weather and climate monitoring within GRYN (Figure 1.1). This includes the following NPS units: BICA, GRTE, John D. Rockefeller, Jr., Memorial Parkway (JODR), and YELL. In this report, we provide the following informational elements:

- Overview of broad-scale climatic factors and zones important to GRYN park units.
- Inventory of locations for all weather stations in and near GRYN 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.

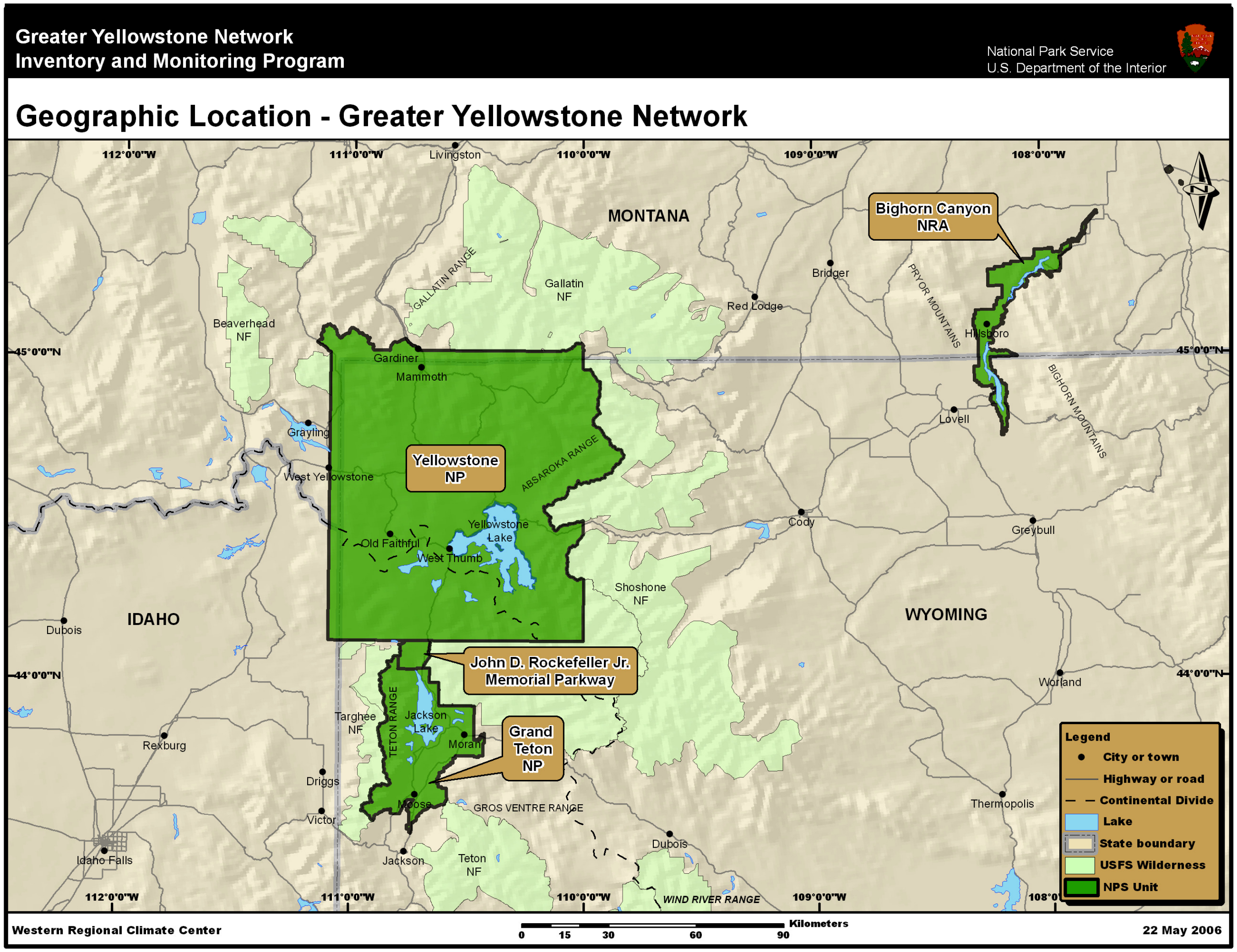

Figure 1.1. Map of the Greater Yellowstone Inventory and Monitoring Network (GRYN).

1.1. Network Terminology

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

1.1.1. Weather/Climate Station Networks

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

1.1.2. NPS I&M Networks

Within the NPS, the system for monitoring various attributes in the participating park units (about 280–290 in total) is divided into 32 NPS I&M networks. These networks are collections of park units grouped together around a common theme, typically geographical.

1.2. Weather versus Climate Definitions

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

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

1.3. Purpose of Measurements

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

- What is the purpose of weather and climate measurements?

Evaluation of past, present, or planned weather/climate monitoring activities must be based on the answer to this question. Within the context of the NPS, the following services constitute the main purposes for recording weather and climate observations:

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

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

1.4. Design of Climate-Monitoring Programs

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

- Define park- and network-specific monitoring needs and objectives.
- Identify locations and data repositories of existing and historic stations.
- Acquire existing data when necessary or practical.
- Evaluate the quality of existing data.
- Evaluate the adequacy of coverage of existing stations.

- Develop a protocol for monitoring weather and climate, including the following:
  - Standardized summaries and reports of weather/climate data.
  - Data management (quality assurance and quality control, archiving, data access, etc.).
- Develop and implement a plan for installing or modifying stations, as necessary.

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

1.4.1. Need for Consistency

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

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

1.4.2. Metadata

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

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

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

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

1.4.3. Maintenance

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

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

1.4.4. Automated versus Manual Stations

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

Nearly all newer stations are automated. Automated stations provide better time resolution, increased (though imperfect) reliability, greater capacity for data storage, and improved accessibility to large amounts of data. The purchase cost for automated stations is higher than for manual stations. A common expectation and serious misconception is that an automated station can be deployed and left to operate on its own. In reality, automation does not eliminate the need for people but rather changes the type of person that is needed. Skilled technical personnel are needed and must be readily available, especially if live communications exist and data gaps are not wanted. Site visits are needed at least annually and spare parts must be maintained. Typical annual costs for sensors and maintenance are $1.5–2.5K per station per year.

1.4.5. Communications

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

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

1.4.6. Quality Assurance and Quality Control

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

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

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

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

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

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

1.4.7. Standards

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

1.4.8. Who Makes Measurements?

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

2.0. Climate Background

The GRYN region is complex topographically and includes alpine areas, high-elevation plateaus, and lower-elevation basins and canyons. Topographic features interact with large-scale air masses that bring cold air from the north and moist air masses from the south or west. The interaction between topography and atmospheric features at multiple scales creates a complex pattern of temperature and precipitation gradients that define the climate zones in GRYN. Climate is a major determinant in the distribution of vegetation and animal habitats in the Greater Yellowstone Ecosystem (Whitlock 1993; Koteen 2001). Drought cycles have been linked to fire activity in the region and weakened plant communities, making them more susceptible to disease and insect infestation (Romme and Despain 1989; Heyerdahl et al. 2002; Hessl et al. 2004; Gray 2005). The resulting impacts on the biogeographic properties of the park have been extensive and may indicate the larger impacts that climate change could have on the biogeography of this region (Romme and Turner 1991; Bartlein et al. 1997; Koteen 2001; Jean et al. 2005). Similar impacts have occurred in response to past climate changes (Whitlock 1993; Whitlock and Bartlein 1993).

2.1. Spatial Variability

The climatic characteristics of the GRYN region are spatially variable, largely in response to topographic constraints (Whitlock and Bartlein 1993; Gray 2005). Orographic precipitation processes contribute significantly to extreme spatial heterogeneity in the region (Elder et al. 1994; Farnes 1995). Annual precipitation on the west slopes of the Teton Range can approach 2000 mm (Figure 2.1), much of which falls as snowfall during the winter (Figure 2.2). Compared to other mountain ranges in the GRYN region, the Teton Range has relatively few mountain ranges on its windward side. Thus, there are no major impediments to moisture coming from the west and southwest as it crosses the Snake River Plain, and this moisture is deposited as precipitation on the windward side of the Teton Range. This is contrasted with the lee side of the Teton Range, where locations typically only see about 500 mm of precipitation per year.

Other mountain ranges in the region, such as the Absaroka and Beartooth ranges, receive less annual precipitation than the Teton Range due to influences from upwind mountains, especially in the winter. Superimposed on these patterns is an increase in precipitation with elevation. Most of the precipitation at the higher elevations in GRYN falls during the winter months, while most of the precipitation at lower elevations falls during late spring and summer (Farnes 1995). The lowest elevations of the GRYN region are found in the Bighorn Basin, including BICA, and can experience annual precipitation totals under 200 mm (Figure 2.1).

Spatial variability of the GRYN climate is enhanced further by the intersection of two primary climate regimes (Despain 1987; Farnes 1995). The influences of these two regimes can be seen in Figure 2.3. One climate regime is characterized by heavier winter precipitation and dominates the southern and western sections of YELL along with much of GRTE.

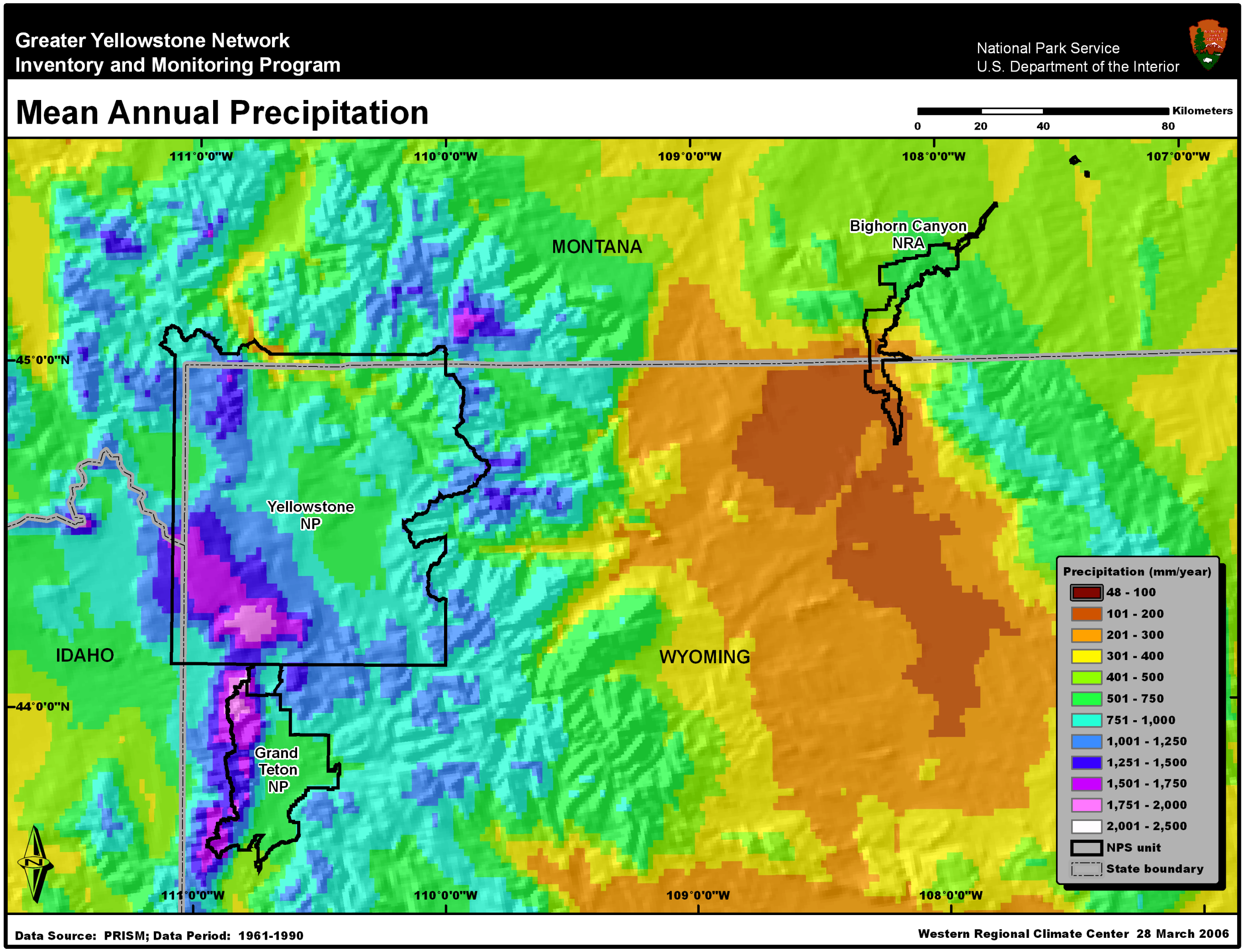

Figure 2.1. Mean annual precipitation, 1961–1990, within the GRYN region.

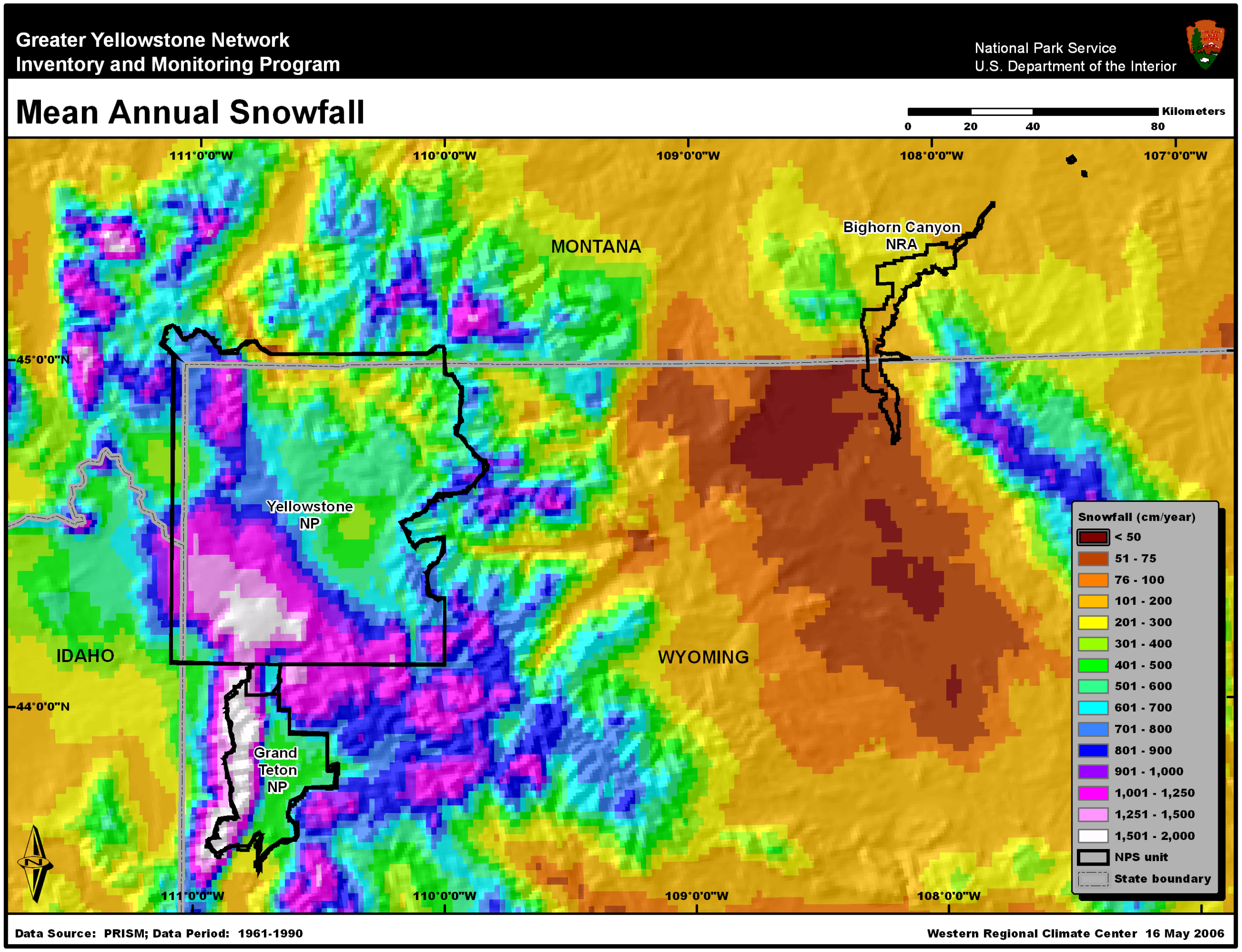

Figure 2.2. Mean annual snowfall, 1961-1990, within the GRYN region.

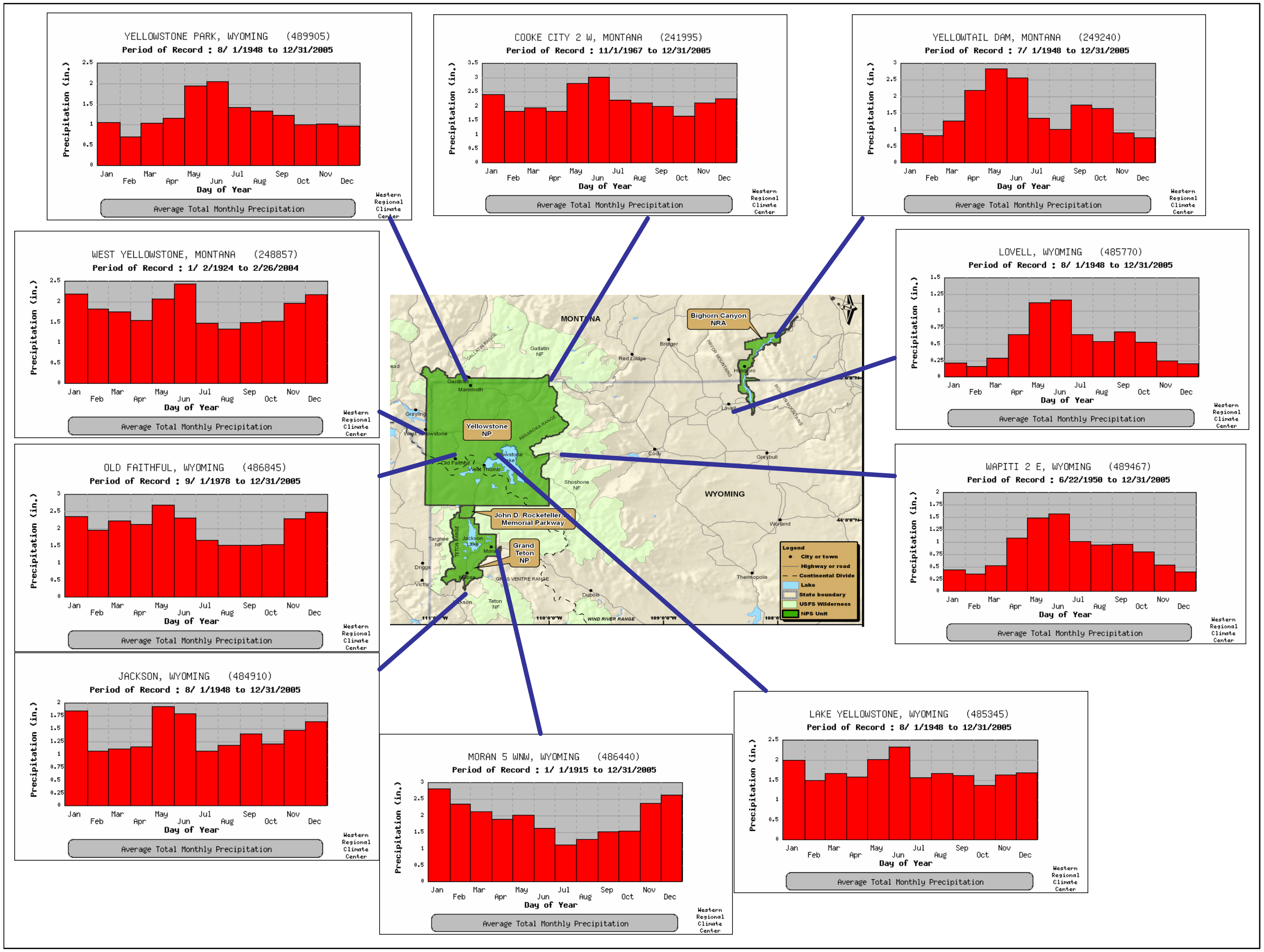

Figure 2.3. Spatial variation in annual precipitation cycles in the GRYN region. Illustrated using selected long-term climate stations.

This winter precipitation, typically snowfall (see Figure 2.2), is generated primarily by organized synoptic (spatial domain greater than 1000 km) winter storms approaching from the Pacific Ocean. In these areas, wintertime precipitation accounts for almost 50 percent of the total annual precipitation, whereas the precipitation during the spring and summer months accounts for less than 20 percent. The other climate regime is characterized by significant spring and early summer precipitation, typically rainfall, and is present in the eastern sections of GRYN. The precipitation in this regime is more convective in nature and individual storms have domains of 10 km or less. The springtime precipitation regime also influences the Teton Range, though not as strongly as in areas in the eastern GRYN. These areas see almost 50 percent of their annual precipitation during the spring and summer, while less than 20 percent occurs in the winter. Summer precipitation generally decreases throughout GRYN in July due to the onset of the Southwestern Monsoon in New Mexico and Arizona, which creates precipitation-inhibiting subsidence around the northern and western fringes of GRYN (Higgins et al. 1998).

Temperatures in the GRYN region also are influenced heavily by topography (Figure 2.4). The coldest regions in GRYN are generally the mountain areas and the high-plateau areas of central YELL. These areas have mean annual temperatures at or below 0°C. Temperatures on the coldest winter days can approach -50°C in the mountain valleys. The highest mountains in the northern and western portions of GRYN are warmer than their southern and eastern counterparts. The northern and western mountain ranges are generally lower in altitude and also tend to be less influenced by polar air masses from Canada in the winter months and more influenced by relatively mild Pacific air masses. The warmest locations in the GRYN region are found in the Bighorn Basin and the north entrance to YELL. These regions have mean annual temperatures as high as 20°C and summertime daily maximum temperatures that reach 40°C.

2.2. Temporal Variability

Investigations of both paleoclimatic records (e.g., Graumlich et al. 2003; Gray et al. 2004) and more recent instrumental climate records (e.g., Cayan et al. 1998) have demonstrated links between Pacific Basin climate indices, such as the El Niño Southern Oscillation and the Pacific Decadal Oscillation (Mantua et al. 1997; Mantua 2000), and precipitation patterns in the western United States. For GRYN, these influences are exerted primarily on winter precipitation, much of which is snowfall (Figure 2.2). Precipitation in GRYN tends to be lower during El Niño events and/or during positive phases of the Pacific Decadal Oscillation, or PDO (Redmond and Koch 1991; Mock 1996; Cayan et al. 1998; Gray et al. 2004). For example, during the 2004–2005 El Niño events, portions of YELL received less than 70% of their normal mean annual precipitation. Conversely, precipitation tends to be higher during La Niña events and/or during negative phases of the PDO.

Drought cycles, largely associated with the aforementioned climate variations, have been linked to increased fire activity in GRYN and to increased susceptibility of plant communities to diseases and insect infestations (Romme and Despain 1989; Heyerdahl et al. 2002; Hessl et al. 2004).

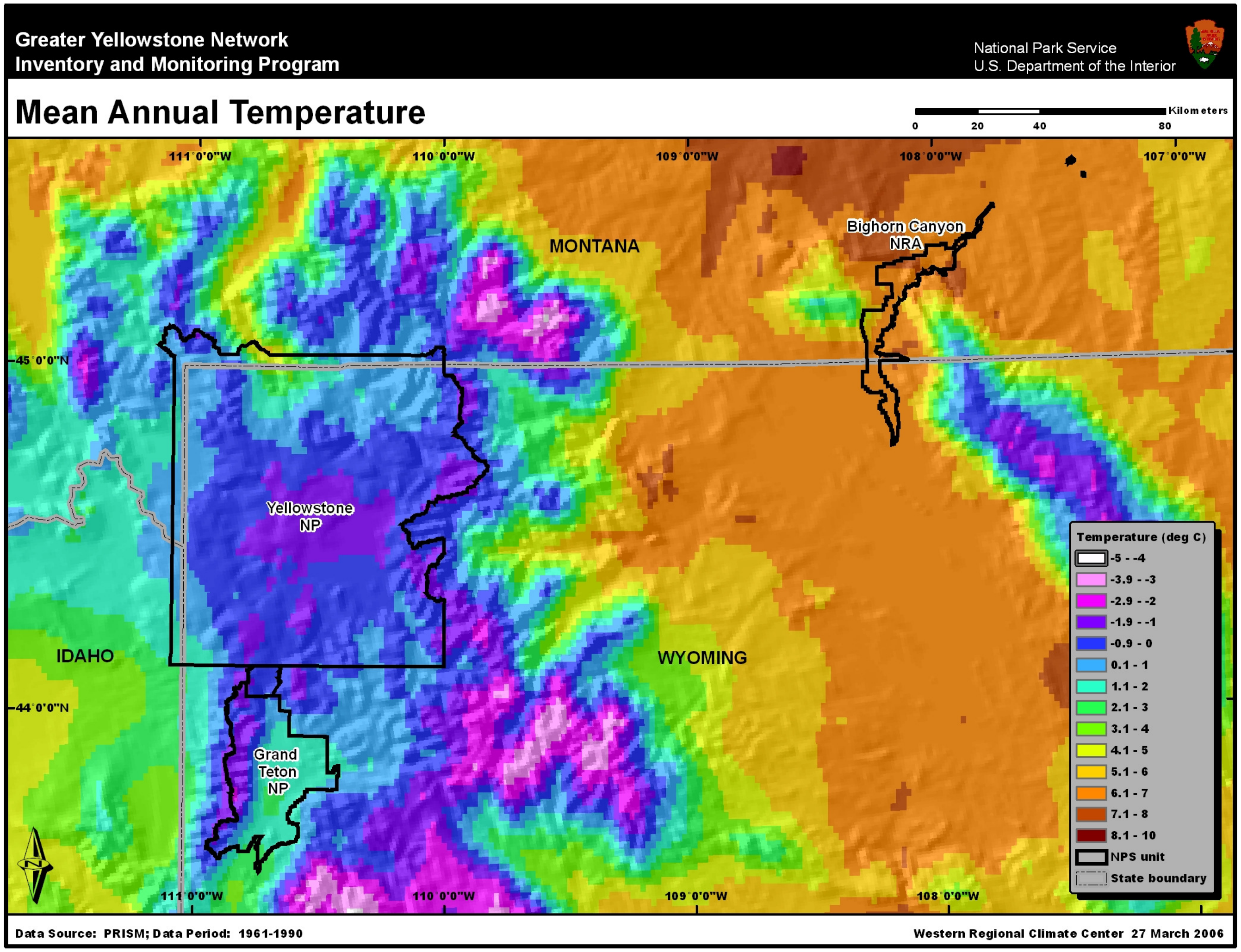

Figure 2.4. Mean annual temperature, 1961–1990, within the GRYN region.

Precipitation in the Upper Yellowstone River Basin (Figure 2.5) has shown no systematic trend, but wet and dry spells are readily apparent. The severe single-year deficit during the fire year of 1988 is among the driest years on record, and the 6-year drought from 1999–2005 represents the longest drought since the Dust Bowl drought of the 1930s. Much of the precipitation deficit associated with the 1999–2005 drought can be attributed to below-average winter snowfall.

Like most locations in the western U.S., temperatures in the Upper Yellowstone River Basin (Figure 2.6) have risen steadily since the late 1970s. During this period, temperatures have warmed by about 1.4°C (2.5°F). The last few winters in GRYN have been some of the warmest winters on record.

2.3. Parameter Regression on Independent Slopes Model (PRISM)

The climate maps presented here were generated using the Parameter Regression on Independent Slopes Model (PRISM). This model was developed to address the extreme spatial and elevation gradients exhibited by the climate of the western United States (Daly et al. 1994; 2002; Gibson et al. 2002; Doggett et al. 2004). The maps produced through PRISM have undergone rigorous evaluation across 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. Elevation provides the first-order constraint for the mapped climate fields, with orientation (aspect) providing a second-order constraint. The PRISM technique specifically accounts for different time-integrated climate elements whose behavior depends on spatial scale. The model has been enhanced gradually to address inversions, coast/land gradients,

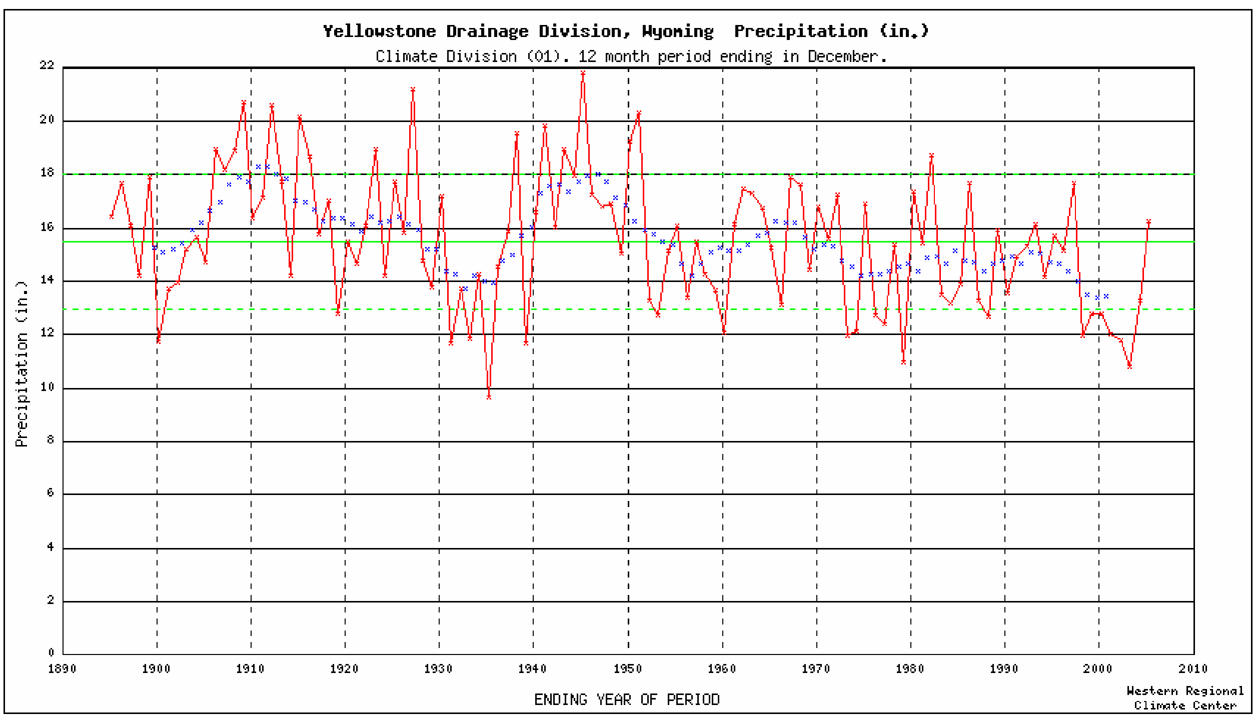

Figure 2.5. Upper Yellowstone River Basin 12-month average precipitation ending in December (red), 10-year running mean (blue), mean (green), and plus/minus one standard deviation (green dotted), 1895–2005.

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 pixel. The model relies on observed surface and upper-air measurements to estimate spatial climate fields.

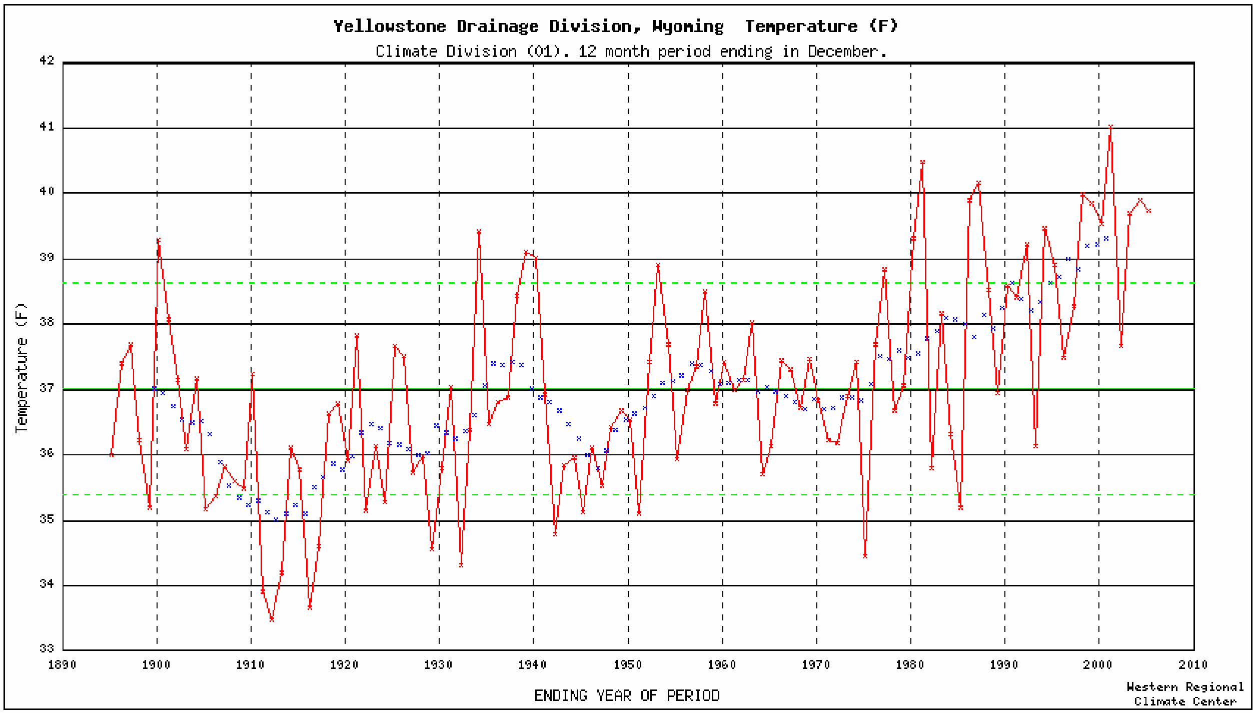

Figure 2.6. Upper Yellowstone River Basin 12-month average temperature ending in December (red), 10-year running mean (blue), mean (green), and +plus/minus one standard deviation (green dotted), 1895–2005.

3.0. Methods

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

3.1. Metadata Retrieval

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

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

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

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

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

This report has relied primarily on metadata stored in the Applied Climate Information System (ACIS), a joint effort among RCCs and other NOAA entities. Metadata for GRYN weather/climate stations identified from the ACIS database are available in file “GRYN_from_ACIS.tar.gz” (see Appendix G). 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. The available metadata from many smaller networks also have been entered but in most cases the data from these smaller networks have not yet been entered. Data sets are in the NetCDF (Network Common Data Form) format, but the design allows for integration with legacy systems, including non-NetCDF files (used at WRCC) and additional metadata (added for this project). The ACIS also supports a suite of products to visualize or summarize data from these data sets. National climate-monitoring maps are updated daily using the ACIS data feed. The developmental phases of ACIS have utilized metadata supplied by the NCDC and NWS with many tens of thousands of entries, screened as well as possible for duplications, mistakes, and omissions.

In addition to obtaining GRYN weather/climate station metadata from ACIS, metadata also were obtained from Selkowitz (2003). The NPS staff from the GRYN office in Bozeman, Montana, assisted in providing weather/climate station metadata information in the region for stations that were not in the ACIS database. The metadata provided from the GRYN office are available in file “GRYN_cli_sta.tar.gz” (see Appendix G). Note that there is some overlap between metadata provided from GRYN and metadata obtained from ACIS. The Wyoming state climate office (Phone: 307.766.6659; E-mail: stateclim@wrds.uwyo.edu) also was contacted for station metadata. In addition, we have relied on information supplied at various times in the past by the BLM, NPS, NCDC, and NWS.

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

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

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

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

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

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

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

3.2. Criteria for Locating Stations

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

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

4.0. Station Inventory

An objective of this report is to show the locations of weather/climate stations for the GRYN region in relation to the boundaries of the NPS park units within GRYN. 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 GRYN region are associated with at least one of eight major weather/climate networks (Table 4.1). Brief descriptions of each weather/climate network are provided below (see Appendix F for greater detail).

Table 4.1. Weather/climate networks represented within GRYN.

Acronym	Name
AgriMet	Pacific Northwest Cooperative Agricultural Network
CASTNet	Clean Air Status and Trends Network
COOP	NWS Cooperative Observer Program
CRN	NOAA Climate Reference Network
NRCS-SC	USDA/NRCS Snowcourse Network
RAWS	Remote Automated Weather Station Network
SAO	NWS/FAA Surface Airways Observation Network
SNOTEL	USDA/NRCS Snowfall Telemetry Network

4.1.1. Pacific Northwest Cooperative Agricultural Network (AgriMet)

AgriMet is a network of automated weather stations operated by the U.S. Bureau of Reclamation. The stations in AgriMet are located primarily in irrigated agricultural areas throughout the Pacific Northwest.

4.1.2. Clean Air Status and Trends Network (CASTNet)

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

4.1.3. 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. Temperature and precipitation are the primary meteorological elements are measured. Wind, solar radiation, and ground surface temperature are also measured. Data from the CRN are intended for use in operational climate-monitoring activities and to place current climate patterns in historic perspective.

4.1.5. Remote Automated Weather Station Network (RAWS)

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

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

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

4.1.7. 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.

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

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

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

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

4.2. Station Locations

The major weather/climate networks in GRYN (discussed in Section 4.1) have approximately several dozen stations in each park unit (Table 4.2). Most stations are located in YELL.

Table 4.2. Number of stations in or near GRYN (listed by park unit and/or weather/climate network).

Weather/Climate Network	Number of Stations
Yellowstone National Park (YELL)	
CASTNet	1
COOP	50
NRCS-SC	35
RAWS	13
SAO	4
SNOTEL	33
Grand Teton National Park (GRTE)	
AgriMet	1
COOP	21
CRN	1
NRCS-SC	13
RAWS	6
SAO	2
SNOTEL	5
Bighorn Canyon National Recreation Area (BICA)	
COOP	26
RAWS	9
SAO	5
SNOTEL	1

4.2.1. Yellowstone National Park (YELL)

Automated and manual weather/climate stations are distributed fairly evenly throughout YELL. There is generally at least one station present every 20–30 km within the park. The majority of identified weather and climate stations within YELL (Table 4.3) are located along primary roadways, and many are located near important road junctions and/or visitor centers (Figure 4.1). Away from the main roads, there are 10 sites along the southern boundary (two COOP sites, two RAWS sites, four SNOTEL sites, and two NRCS-SC sites), one SNOTEL site along the northeastern boundary, one RAWS site in the Gallatin Mountain Range in the northwest quadrant of YELL, and two NRCS-SC sites east of Mammoth Hot Springs.

Table 4.3. Weather/climate stations for YELL. Stations inside YELL and within 40 km of the YELL boundary are included. Each listing includes station name, location, and elevation; weather/climate network associated with station; start/end dates for station; and flag to indicate if station is located inside YELL boundaries. Missing entries are indicated by "M".

Yellowstone National Park (YELL)							
Name	**Lat.**	**Lon.**	**Elev. (m)**	**Network**	**Start**	**End**	**In Park?**
Yellowstone NP Wyoming	44.56	-110.40	732	CASTNet	06/26/1996	Present	YES
Bechler River RS	44.15	-111.05	1959	COOP	04/01/1911	Present	YES
Gallatin	45.02	-111.08	2105	COOP	01/01/1931	12/31/1941	YES
Grassy Lake Dam	44.13	-110.83	2208	COOP	09/01/1942	11/30/1953	YES
Lake Yellowstone	44.56	-110.40	2399	COOP	01/01/1904	Present	YES
Lamar RS	44.90	-110.24	1998	COOP	02/11/1881	Present	YES
Mount Holmes Lookout	44.82	-110.85	3142	COOP	07/01/1953	Present	YES
Mount Sheridan Lookout	44.27	-110.52	3126	COOP	06/01/1953	Present	YES
Old Faithful	44.46	-110.83	2243	COOP	05/01/1904	Present	YES
Snake River	44.13	-110.67	2098	COOP	06/21/1905	Present	YES
Tower Falls	44.92	-110.42	1910	COOP	08/01/1948	Present	YES
West Yellowstone	44.67	-111.08	M	COOP	M	Present	YES
West Yellowstone USFS	44.67	-111.10	2030	COOP	09/01/1981	Present	YES
Yellowstone NP Cyn RS	44.74	-110.50	2417	COOP	05/29/2002	Present	YES
Yellowstone NP E Ent	44.49	-110.00	2119	COOP	11/01/1999	Present	YES
Aster Creek	44.28	-110.63	2362	NRCS-SC	01/01/1919	Present	YES
Grassy Lake	44.13	-110.83	2214	NRCS-SC	01/01/1940	Present	YES
Lake Camp	44.55	-110.40	2371	NRCS-SC	01/01/1936	Present	YES
Lewis Lake Divide	44.20	-110.67	2393	NRCS-SC	01/01/1919	Present	YES
Lupine Creek	44.92	-110.62	2249	NRCS-SC	01/01/1938	Present	YES
Norris Basin	44.75	-110.70	2301	NRCS-SC	01/01/1936	Present	YES
Old Faithful	44.45	-110.82	2256	NRCS-SC	01/01/1975	Present	YES
Snake River Station	44.13	-110.67	2109	NRCS-SC	01/01/1919	Present	YES
Thumb Divide	44.37	-110.57	2432	NRCS-SC	01/01/1938	Present	YES
Twenty-One Mile	44.90	-111.05	2179	NRCS-SC	01/01/1937	Present	YES
Bechler	44.15	-111.05	1951	RAWS	10/01/1999	Present	YES
Quadrant	44.93	-110.99	2416	RAWS	04/01/1995	Present	YES
Thorofare	44.16	-110.08	2554	RAWS	11/01/1989	Present	YES
Yellowstone Lake	44.54	-110.42	2388	SAO	08/01/1978	Present	YES
Yellowstone Mammoth	44.98	-110.70	1899	SAO	12/01/1903	Present	YES
Canyon	44.72	-110.53	2466	SNOTEL	10/01/1980	Present	YES
Coulter Creek	44.17	-110.57	2140	SNOTEL	10/01/1980	Present	YES
Grassy Lake	44.13	-110.83	2214	SNOTEL	10/01/1980	Present	YES

Yellowstone National Park (YELL)							
Name	**Lat.**	**Lon.**	**Elev. (m)**	**Network**	**Start**	**End**	**In Park?**
Lewis Lake Divide	44.20	-110.67	2393	SNOTEL	10/01/1980	Present	YES
Parker Peak	44.73	-109.92	2865	SNOTEL	07/23/1980	Present	YES
Snake River Station	44.13	-110.67	2109	SNOTEL	10/01/1989	Present	YES
Sylvan Lake	44.48	-110.15	2566	SNOTEL	10/01/1980	Present	YES
Sylvan Road	44.47	-110.03	2170	SNOTEL	10/01/1987	Present	YES
Thumb Divide	44.37	-110.57	2432	SNOTEL	10/01/1987	Present	YES
Two Ocean Plateau	44.15	-110.22	2816	SNOTEL	10/01/1980	Present	YES
Big Sky 2 WNW	45.28	-111.32	2009	COOP	06/01/1967	Present	NO
Big Springs	44.50	-111.25	1964	COOP	09/01/1963	Present	NO
Bishop Mountain Look	44.33	-111.55	2196	COOP	07/01/1955	Present	NO
Circle H Ranch	44.50	-109.53	1922	COOP	03/01/1951	11/30/1957	NO
Cooke City 2 W	45.01	-109.97	2274	COOP	10/01/1967	Present	NO
Corwin Springs	45.13	-110.82	1565	COOP	05/01/1951	04/30/1972	NO
Corwin Springs River	45.12	-110.80	1549	COOP	01/01/1956	04/1/1987	NO
Crandall Creek	44.87	-109.64	1984	COOP	06/01/1913	Present	NO
Crandall Creek Near	44.83	-109.67	2074	COOP	01/01/1931	01/31/1939	NO
East Gate Y N P	44.50	-110.00	2123	COOP	07/01/1949	11/30/1953	NO
Emigrant	45.37	-110.72	1525	COOP	06/01/1950	06/1/1968	NO
Gallatin Gateway 32	45.12	-111.23	1952	COOP	07/01/1948	05/19/1959	NO
Gallatin Gateway 10 SSW	45.45	-111.23	1670	COOP	06/01/1950	Present	NO
Gallatin Gateway 26 S	45.23	-111.25	1876	COOP	10/01/1952	06/22/1967	NO
Gardiner	45.03	-110.70	1608	COOP	04/01/1956	Present	NO
Hebgen Dam	44.87	-111.34	1978	COOP	06/01/1904	Present	NO
Island Park	44.42	-111.37	1917	COOP	02/01/1937	Present	NO
Jardine	45.07	-110.63	1967	COOP	06/01/1951	09/20/1977	NO
Lone Mountain	45.27	-111.30	1888	COOP	05/01/1970	04/30/1975	NO
Mystic Lake	45.24	-109.73	1995	COOP	08/01/1924	Present	NO
Nye	45.38	-109.88	1534	COOP	02/01/1954	12/31/1962	NO
Nye Mouat Mine	45.38	-109.90	2114	COOP	12/01/1953	09/30/1962	NO
Pahaska	44.50	-109.96	2041	COOP	09/01/1996	Present	NO
Pahaska (River-ARC)	44.50	-109.97	2028	COOP	05/09/1991	Present	NO
Pahaska 5 N	44.57	-109.97	2114	COOP	08/01/1951	08/31/1976	NO
Red Lodge 18 SW	45.02	-109.53	2626	COOP	08/01/1951	08/31/1976	NO
Sawtelle Peak	44.53	-111.42	2355	COOP	12/01/1966	09/30/1976	NO
Sunlight Basin	44.76	-109.46	1983	COOP	09/01/1996	Present	NO
Valley 5 NE	44.20	-109.55	1891	COOP	07/01/1949	07/01/1958	NO
Valley 6 W	44.15	-109.73	2745	COOP	09/01/1951	8/31/1976	NO
Wapiti 4 W	44.47	-109.50	1750	COOP	04/21/1987	07/01/1988	NO
Wapiti 5 WNW	44.42	-109.58	2068	COOP	08/01/1977	01/15/1987	NO
Wapiti 9 W	44.48	-109.60	M	COOP	07/01/1949	06/30/1950	NO
West Yellowstone	44.65	-111.10	2031	COOP	06/01/1939	Present	NO
West Yellowstone 9 NNW	44.79	-111.13	2003	COOP	12/20/1999	Present	NO
West Yellowstone RS	44.65	-111.10	2034	COOP	06/01/1953	Present	NO
Arch Falls	45.42	-110.95	2240	NRCS-SC	01/01/1963	Present	NO

Yellowstone National Park (YELL)							
Name	**Lat.**	**Lon.**	**Elev. (m)**	**Network**	**Start**	**End**	**In Park?**
Bear Basin	45.32	-111.37	2484	NRCS-SC	01/01/1963	Present	NO
Big Springs	44.48	-111.27	1951	NRCS-SC	01/01/1936	Present	NO
Box Canyon	45.28	-110.25	2033	NRCS-SC	01/01/1976	Present	NO
Carrot Basin	44.97	-111.28	2743	NRCS-SC	01/01/1967	Present	NO
Colley Creek	45.27	-110.47	1920	NRCS-SC	01/01/1973	Present	NO
Crevice Mountain	45.03	-110.60	2560	NRCS-SC	01/01/1935	Present	NO
Fisher Creek	45.07	-109.95	2774	NRCS-SC	01/01/1966	Present	NO
Hebgen Dam	44.87	-111.33	1996	NRCS-SC	01/01/1934	Present	NO
Independence	45.22	-110.25	2393	NRCS-SC	01/01/1940	Present	NO
Lake Creek	44.83	-111.58	1859	NRCS-SC	01/01/1965	Present	NO
Latham Springs	44.47	-111.15	2326	NRCS-SC	01/01/1961	Present	NO
Little Park	45.30	-111.33	2256	NRCS-SC	01/01/1963	Present	NO
Lone Mountain	45.28	-111.43	2707	NRCS-SC	01/01/1971	Present	NO
Lucky Dog	44.48	-111.22	2091	NRCS-SC	01/01/1963	Present	NO
Madison Plateau	44.58	-111.12	2362	NRCS-SC	01/01/1968	Present	NO
Mill Creek	45.25	-110.40	2286	NRCS-SC	01/01/1967	Present	NO
Monument Peak	45.22	-110.23	2697	NRCS-SC	01/01/1961	Present	NO
Potomageton Park	44.92	-111.37	2179	NRCS-SC	01/01/1965	Present	NO
Rock Creek Meadow	45.18	-111.08	2487	NRCS-SC	01/01/1976	Present	NO
Shower Falls	45.40	-110.95	2469	NRCS-SC	01/01/1965	Present	NO
Valley View	44.63	-111.32	2036	NRCS-SC	01/01/1936	Present	NO
West Yellowstone	44.67	-111.10	2042	NRCS-SC	01/01/1934	Present	NO
Whiskey Creek	44.60	-111.15	2073	NRCS-SC	01/01/1967	Present	NO
White Mill	45.05	-109.90	2652	NRCS-SC	01/01/1967	Present	NO
Crandell	44.85	-109.61	2015	RAWS	05/01/1993	Present	NO
Eagle	44.49	-109.90	2286	RAWS	06/01/1999	Present	NO
Four Mile	45.33	-110.22	1737	RAWS	06/01/2001	Present	NO
Hebgen Lake	44.67	-111.10	2032	RAWS	05/01/2001	Present	NO
Island Park	44.42	-111.38	1915	RAWS	09/01/1999	Present	NO
Squaw Creek–FTS	45.45	-111.22	1637	RAWS	05/01/2001	Present	NO
Wicked Creek	45.27	-110.54	2318	RAWS	07/01/2002	Present	NO
Yellow Mule	45.17	-111.35	2804	RAWS	06/01/2001	Present	NO
West Yellowstone	44.68	-111.12	2026	SAO	06/01/1939	Present	NO
Beartooth Lake	44.78	-109.57	2827	SNOTEL	07/30/1980	Present	NO
Beaver Creek	44.95	-111.35	2393	SNOTEL	01/01/1970	Present	NO
Black Bear	44.50	-111.12	2484	SNOTEL	10/01/1971	Present	NO
Blackwater	44.38	-109.80	2981	SNOTEL	05/01/1981	Present	NO
Box Canyon	45.28	-110.25	2042	SNOTEL	10/01/1978	Present	NO
Carrot Basin	44.97	-111.28	2743	SNOTEL	10/01/1970	Present	NO
Cashe Creek	45.08	-111.38	2377	SNOTEL	08/14/1980	09/30/1991	NO
Eaglehead	45.23	-111.12	3039	SNOTEL	10/18/1987	Present	NO
Evening Star	44.65	-109.78	2804	SNOTEL	07/30/1980	Present	NO
Fisher Creek	45.07	-109.95	2774	SNOTEL	10/01/1970	Present	NO
Island Park	44.42	-111.38	1917	SNOTEL	10/06/1981	Present	NO

Yellowstone National Park (YELL)							
Name	**Lat.**	**Lon.**	**Elev. (m)**	**Network**	**Start**	**End**	**In Park?**
Lone Mountain	45.28	-111.43	2707	SNOTEL	10/01/1988	Present	NO
Madison Plateau	44.58	-111.12	2362	SNOTEL	01/01/1970	Present	NO
Monument Peak	45.22	-110.23	2697	SNOTEL	08/13/1980	Present	NO
Shower Falls	45.40	-110.95	2469	SNOTEL	01/01/1970	Present	NO
Trout Ck	44.58	-109.45	2560	SNOTEL	10/01/1980	07/28/1987	NO
West Yellowstone	44.67	-111.10	2042	SNOTEL	08/24/1998	Present	NO
Whiskey Creek	44.60	-111.15	2073	SNOTEL	10/1/1971	Present	NO
White Elephant	44.53	-111.42	2350	SNOTEL	10/21/1981	Present	NO
White Mill	45.05	-109.90	2652	SNOTEL	10/01/1973	Present	NO
Wolverine	44.80	-109.65	2332	SNOTEL	07/29/1980	Present	NO
Younts Peak	43.93	-109.82	2545	SNOTEL	08/28/1980	Present	NO

The COOP stations are the primary source of long-term observational records of weather and climate in YELL. Several of the COOP stations in YELL have records of a hundred years or more (Table 4.3). Some of these COOP stations have produced high-quality data. These stations include, for example, the Tower Falls and Lake Yellowstone COOP sites. There are other COOP sites where observational records span several decades but have significant time gaps. The Lamar Ranger Station COOP, for example, has an observational record extending from 1881 to 2006 (Table 4.3), yet it has been an unofficial site and hence regular observations have not been reported since the 1970s. Another station having a long data record is the SAO site at Mammoth Hot Springs. This record extends back to 1903 and shows the data from the site to be of high quality.

Besides Mammoth Hot Springs, SAO sites in and near YELL include airport sites at Yellowstone Lake and West Yellowstone. The site at Yellowstone Lake has been in operation since 1978 but has only produced reliable data during the last five years. The SAO site at West Yellowstone has been in operation since 1939. The West Yellowstone SAO site operates only during the summer months. In addition, this site has experienced routine data gaps throughout its observational record, and its sensor calibration standards have not been applied consistently, resulting in varying base values over time for many weather/climate elements. As a result, the data have been consistently unsatisfactory for climate-monitoring purposes.

Weather/climate stations are largely absent in the mountain ranges occupying the eastern portions of YELL. Stations are especially absent in the northeast quadrant of the park and along the southeast shore of Yellowstone Lake. Other YELL areas that are missing weather and climate stations include much of the southwest portion of the park (e.g., Pitchstone Plateau, Central Plateau, and Washburn Range).

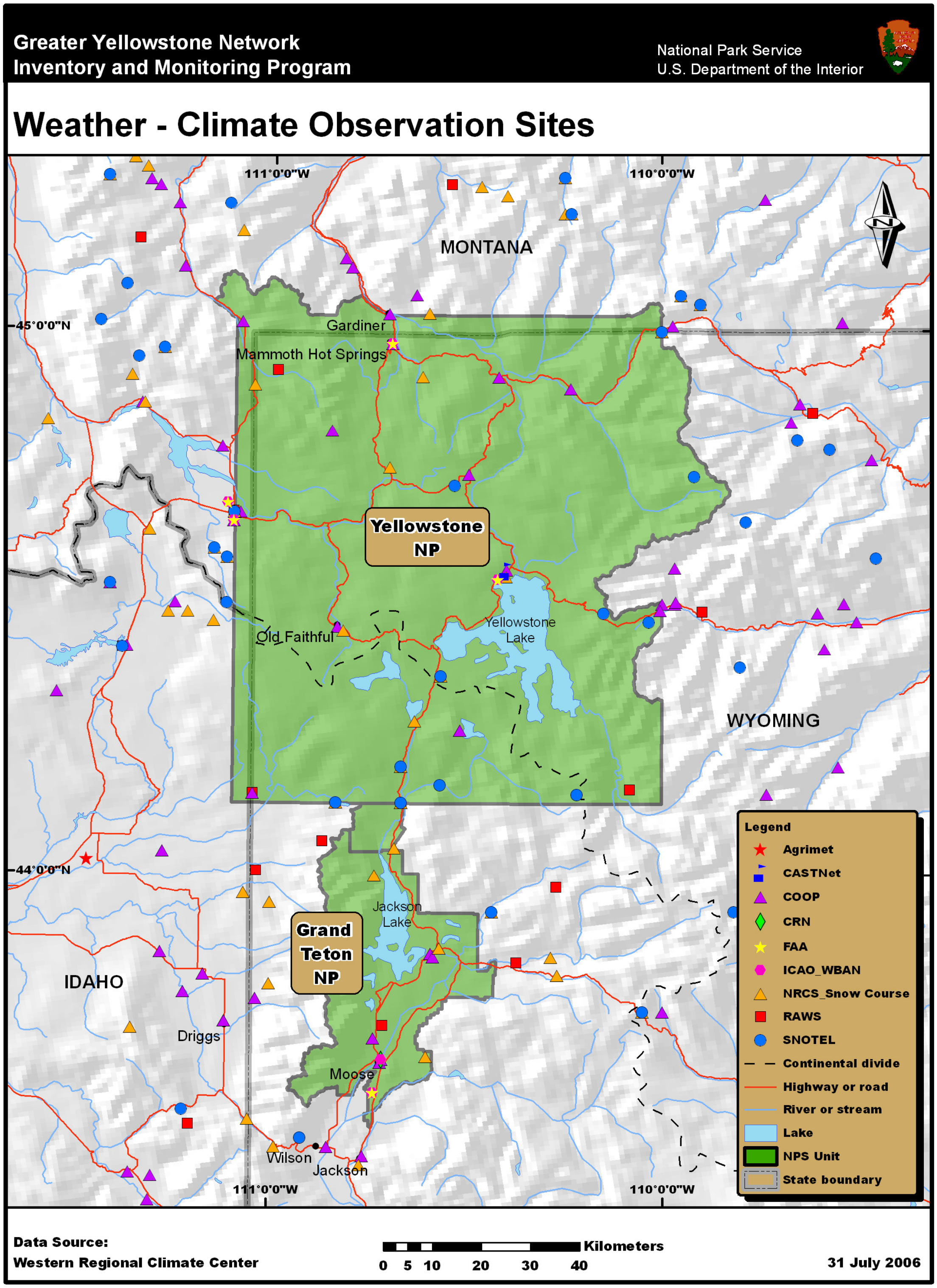

Figure 4.1. Station locations for the YELL, GRTE, and JODR units. The SAO sites are labeled as FAA.

4.2.2. Grant Teton National Park (GRTE) and John D. Rockefeller, Jr., Memorial Parkway (JODR)

Most weather and climate stations within GRTE and JODR (Table 4.4) are located along primary roadways and near important road junctions and/or visitor centers (Figure 4.1). The only stations that are distant from roads are two NRCS-SC sites in GRTE. One site is on the northwest side of Jackson Lake. The other NRCS-SC site is about 5–10 km east of Moose Village. The automated stations within GRTE are located in the southern part of GRTE. These stations include the SAO sites at Jackson Hole Airport, a CRN site at Moose Village, and a RAWS site south of Jenny Lake.

The longest climate records within GRTE have been provided by the COOP sites in and near Moose and Moran Junction. Some of these sites have been in operation since the early 1900s (Table 4.4) with very few data gaps. Data quality is questionable at the COOP site "Moose 1 NNE" between August 2004 and October 2005. A CRN site was also installed at this location during the summer of 2004 to provide long-term climate monitoring, but the observational record from this site is not long enough to be used for climate analyses.

The portions of the Teton Range that lie within the GRTE and JODR park units have almost no weather or climate station coverage—the NRCS-SC site near Jackson Lake is the only exception. There are weather stations at Jackson Hole Mountain Resort just south of GRTE, but to our knowledge the data from these stations are not publicly available and hence are not listed here. There are no automated sites within JODR or the northern portions of GRTE. There are, however, SNOTEL and RAWS sites just outside the park boundaries in northern GRTE.

Table 4.4. Weather/climate stations for GRTE and JODR. Stations inside GRTE and JODR and within 40 km of the boundaries are included. Listing includes station name, location, and elevation; weather/climate network associated with station; start/end dates for station; and flag to indicate if station is inside park boundaries. Missing entries are indicated by "M".

Grand Teton National Park (GRTE) and John D. Rockefeller Memorial Parkway (JODR)							
Name	**Lat.**	**Lon.**	**Elev. (m)**	**Network**	**Start**	**End**	**In Park?**
Jackson Lake (River)	43.85	-110.58	2065	COOP	M	06/28/1989	YES
Moose	43.66	-110.72	1972	COOP	12/01/1958	Present	YES
Moose 1 NNE	43.66	-110.71	1974	COOP	07/01/2004	Present	YES
Moose 3 NW	43.70	-110.73	2022	COOP	09/24/1935	12/13/1958	YES
Moran 5 WNW	43.86	-110.59	2072	COOP	03/11/1911	Present	YES
Signal Mountain Lookout	43.87	-110.57	2358	COOP	07/01/1953	Present	YES
Moose 1 NNE Wyoming	43.66	-110.71	1971	CRN	06/30/2004	Present	YES
Elbo Ranch	43.67	-110.60	2164	NRCS-SC	01/011976	Present	YES
Moran	43.87	-110.57	2057	NRCS-SC	01/011919	Present	YES
Grand Teton	43.72	-110.71	1981	RAWS	09/7/1989	Present	YES
Jackson Hole (AWOS) Wyoming	43.61	-110.74	1966	SAO	11/01/2003	Present	YES
Jackson Hole Airport	43.60	-110.73	1957	SAO	07/01/1946	Present	YES
Ashton Idaho	44.03	-111.47	1615	AgriMet	06/02/1987	Present	NO
Alta 1 NNW	43.77	-111.03	1962	COOP	07/18/1909	Present	NO

Grand Teton National Park (GRTE) and John D. Rockefeller Memorial Parkway (JODR)							
Name	**Lat.**	**Lon.**	**Elev. (m)**	**Network**	**Start**	**End**	**In Park?**
Ashton	44.04	-111.27	1589	COOP	02/01/1897	Present	NO
Diamond G	43.75	-110.00	2593	COOP	09/01/1949	08/31/1976	NO
Driggs	43.73	-111.11	1865	COOP	08/01/1904	Present	NO
Driggs 1 N	43.73	-111.11	1916	COOP	09/01/2001	Present	NO
Driggs Teton River	43.78	-111.22	1815	COOP	04/10/1978	11/06/1985	NO
Irwin 2 SE	43.40	-111.30	1617	COOP	06/01/1909	07/31/1960	NO
Jackson	43.48	-110.76	1899	COOP	01/03/1905	Present	NO
Palisades	43.35	-111.22	1641	COOP	07/08/1947	08/31/1993	NO
Swan Valley 2 E	43.44	-111.29	1634	COOP	07/01/1960	Present	NO
Swan Valley Ranger S	43.45	-111.35	1604	COOP	07/01/1955	Present	NO
Tetonia	43.82	-111.17	1842	COOP	07/01/1932	05/31/1952	NO
Tetonia Experiment S	43.86	-111.28	1881	COOP	08/01/1948	Present	NO
Triangle F Ranch	43.30	-110.50	1922	COOP	10/01/1938	12/31/1945	NO
Wilson 2 E	43.50	-110.85	1876	COOP	03/01/1951	09/30/1966	NO
Base Camp	43.93	-110.43	2143	NRCS-SC	01/01/1930	Present	NO
Darby Canyon	43.80	-111.00	2515	NRCS-SC	01/01/1964	Present	NO
Four Mile Meadow	43.82	-110.27	2396	NRCS-SC	01/01/1936	Present	NO
Jackpine Creek	43.95	-111.00	2240	NRCS-SC	01/01/1974	Present	NO
McRenolds Reservoir	43.97	-111.07	2048	NRCS-SC	01/01/1974	Present	NO
Packsaddle Spring	43.72	-111.35	2499	NRCS-SC	01/01/1981	Present	NO
Snow King Mountain	43.47	-110.77	2335	NRCS-SC	01/01/1959	Present	NO
State Line	43.55	-111.05	2030	NRCS-SC	01/01/1936	Present	NO
Teton Pass WS	43.50	-110.98	2359	NRCS-SC	01/01/1973	Present	NO
Togwotee Pass	43.75	-110.05	2920	NRCS-SC	01/01/1936	Present	NO
Turpin Meadows	43.85	-110.28	2103	NRCS-SC	01/01/1936	Present	NO
Burro Hill	43.84	-110.37	2512	RAWS	07/01/1988	Present	NO
Coyote Meadows	44.01	-111.04	2003	RAWS	01/01/2004	Present	NO
Enos Lake	43.98	-110.27	2512	RAWS	07/14/1988	Present	NO
Pine Creek Pass	43.54	-111.20	2207	RAWS	09/01/2002	Present	NO
Base Camp	43.93	-110.43	2143	SNOTEL	10/01/1980	Present	NO
Granite Creek	43.35	-110.43	2064	SNOTEL	10/01/1987	Present	NO
Phillips Bench	43.52	-110.92	2499	SNOTEL	10/01/1980	Present	NO
Pine Creek Pass	43.57	-111.22	2048	SNOTEL	10/01/1988	Present	NO
Togwotee Pass	43.75	-110.05	2920	SNOTEL	10/01/1980	Present	NO

4.2.3. Bighorn Canyon National Recreation Area (BICA)

Five COOP stations are located within the boundary of BICA (Figure 4.2, Table 4.5). These stations are located primarily at visitor centers, such as Yellowtail Dam and/or along major highway routes within Bighorn Canyon. In general, there are few stations along much of Bighorn Lake and few stations outside BICA near the Montana/Wyoming border. There are no automated weather/climate stations within BICA. The nearest automated sites are RAWS sites located in the open spaces near BICA. These RAWS sites have produced observational records beginning in the 1980s or later. The primary source of long-term climate information on precipitation and temperature within BICA is the COOP station at Yellowtail Dam. The observational record of Yellowtail Dam extends to the late 1940s. A significant gap in the data occurred at this site during the 1950s and early 1960s. However, since then this site has produced reliable data.

There are sites outside of BICA that have produced long data records and can be used for climate-monitoring purposes. These include the COOP sites in Deaver and Lovell and SAO sites at the airports near Greybull and Powell, all in Wyoming.

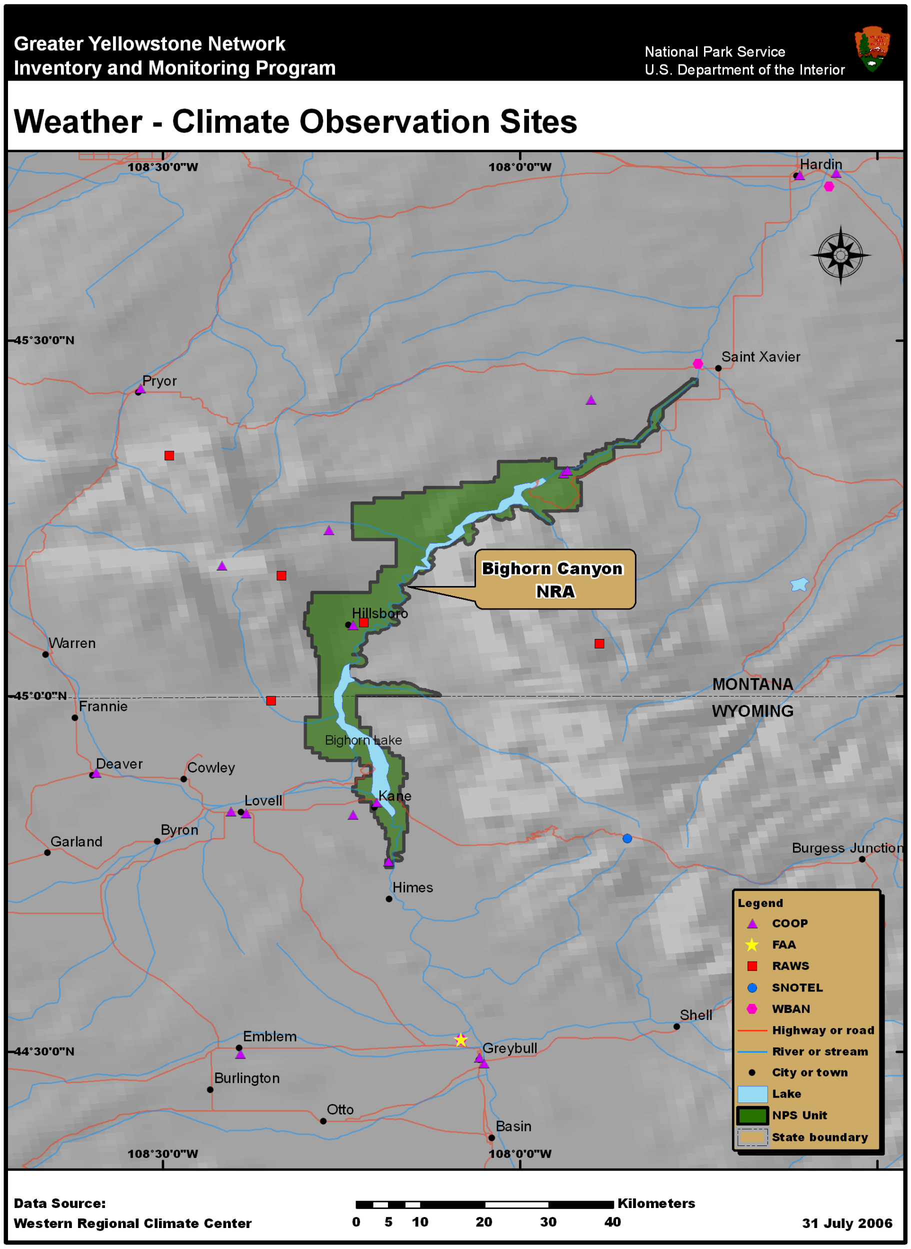

Figure 4.2. Station locations for BICA. The SAO sites are labeled as either WBAN (Weather Bureau Army Navy) or FAA.

Table 4.5. Weather/climate stations for BICA. Stations within 40 km of BICA are included. Listing includes station name, location, and elevation; weather/climate network; start/end dates for station; and flag to indicate if station is inside BICA. Missing entries are indicated by "M".

Bighorn Canyon National Recreation Area (BICA)							
Name	**Lat.**	**Lon.**	**Elev. (m)**	**Network**	**Start**	**End**	**In Park?**
Kane	44.85	-108.20	1110	COOP	07/29/1949	07/01/1958	YES
Lovell 10 SE (DCP)	44.77	-108.18	1116	COOP	07/01/1972	02/18/2005	YES
Pryor 27 SE Hillsboro	45.10	-108.23	1220	COOP	09/01/1951	09/30/1954	YES
St. Xavier 15 SW	45.32	-107.93	946	COOP	01/01/1956	09/30/1975	YES
Yellowtail Dam	45.31	-107.94	1007	COOP	07/01/1948	Present	YES
Hillsboro	45.10	-108.22	1215	RAWS	04/01/2003	Present	YES
Burlington	44.45	-108.42	1351	COOP	07/01/1949	11/30/1957	NO
Campbell Farm Camp 4	45.42	-107.90	1113	COOP	02/17/1882	11/30/1962	NO
Crow Agency	45.60	-107.45	924	COOP	04/01/1898	08/01/1991	NO
Deaver	44.89	-108.59	1251	COOP	01/01/1916	Present	NO
Edgar 9 SE	45.38	-108.72	1220	COOP	10/01/1950	10/03/1974	NO
Emblem	44.50	-108.39	1356	COOP	07/01/1949	Present	NO
Garland	44.78	-108.67	1296	COOP	08/01/1948	08/31/1966	NO
Greybull	44.49	-108.06	1155	COOP	03/01/1951	Present	NO
Greybull River	44.48	-108.05	1161	COOP	07/01/1972	06/27/1995	NO
Hardin	45.73	-107.61	885	COOP	07/01/1948	Present	NO
Hardin 3 E	45.74	-107.56	850	COOP	05/01/1971	04/18/2002	NO
Kane 2 SW	44.83	-108.23	1150	COOP	11/06/1951	03/25/1958	NO
Lodge Grass	45.32	-107.36	1024	COOP	02/01/1935	Present	NO
Lovell	44.84	-108.40	1170	COOP	04/01/1897	Present	NO
Lovell Hwy. Dept.	44.84	-108.38	1163	COOP	01/25/1984	12/30/2002	NO
Powell Field Station	44.78	-108.76	1332	COOP	01/01/1964	Present	NO
Pryor	45.43	-108.53	1240	COOP	06/01/1950	Present	NO
Pryor 18 SE Dryhead	45.23	-108.27	1159	COOP	06/01/1949	09/30/1951	NO
Sage Creek River Stn.	45.18	-108.42	2333	COOP	10/01/1964	08/31/1976	NO
Shell	44.54	-107.78	1279	COOP	08/17/1953	Present	NO
Shell 5 N	44.60	-107.77	1284	COOP	08/01/1949	08/31/1953	NO
Bighorn Mountain	45.07	-107.89	2219	RAWS	08/01/1991	Present	NO
Boyd Ridge	44.94	-107.71	2359	RAWS	01/01/1999	Present	NO
Britton Springs	44.99	-108.35	872	RAWS	06/01/1995	Present	NO
Little Bighorn	45.57	-107.44	1036	RAWS	07/01/1997	Present	NO
Pryor Mountain	45.34	-108.49	1885	RAWS	08/01/1991	Present	NO
South Bridger	45.20	-108.79	1440	RAWS	11/01/1987	Present	NO
Wild Horse	45.17	-108.33	2675	RAWS	10/01/1991	Present	NO
Greybull Airport	44.52	-108.08	M	SAO	10/01/2003	Present	NO
Greybull South Big Horn County Airport	44.52	-108.08	1199	SAO	06/01/1947	Present	NO
Hardin A	45.72	-107.57	885	SAO	09/01/1934	11/30/1939	NO
Powell	44.87	-108.78	1552	SAO	06/01/1947	Present	NO
St. Xavier	45.47	-107.75	976	SAO	04/01/1940	03/31/1942	NO
Bald Mountain	44.80	-107.85	2859	SNOTEL	10/01/1978	Present	NO

5.0. Conclusions and Recommendations

We have based our findings on an examination of the available records and the topography and climate within GRYN 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 GRYN. Much preliminary work has been accomplished to identify weather/climate stations within the park units (Selkowitz 2003; Gray 2005). This report builds on these previous station inventories and suggestions for investigative climate protocols.

5.1. Greater Yellowstone Inventory and Monitoring Network

Metadata are complete sufficiently for most of the weather/climate stations within GRYN. The only metadata fields listed in Table 3.1 consistently lacking current information were those fields pertaining to contact information for site owners and operators.

There are at least two sites in GRYN where poor data quality is a concern. One station of concern in recent years has been the Moose COOP site in GRTE (see Table 4.4). This site is a particularly illustrative example of a host of intersecting modern issues. The Moose COOP station has been situated near its present location since December 1958 and, until recently, produced a high-quality and apparently homogenous climate record, suitable for climate studies. A CRN station was installed in June 2004, about 1 km away from the COOP station. The automated CRN station has recorded high-quality temperature readings and should have recorded high-quality precipitation readings as well. A validation of this assumption was needed in this cold and snowy climate. The CRN site was therefore deliberately sited near the Moose COOP station, so that (among other reasons) its record could be cross-checked with the continuing, long-term historic COOP record. During CRN reconnaissance discussions, it was strongly emphasized that it would be necessary to keep the records from the two stations distinct. Otherwise, data comparisons between the two stations would be compromised (see Appendix A, Climate Monitoring Principles, Item 2).

From August 2004 through October 2005, added duties for the observer of the Moose COOP station made it increasingly difficult to make observations at the agreed morning hour, so observations in the afternoon and at other times of the day were substituted. It is well known within the climate research community that this practice leads to artificial "climate change" and is strongly discouraged. In addition, many maximum/minimum temperatures from the COOP site were identical to those from the CRN site (which summarizes at midnight and thus its observation day differs by either 8 or 16 hours from the observation day of the COOP station). After further investigation of these identical maximum/minimum temperatures, it was determined that the CRN values were taken off the Internet and applied to the COOP form, severely compromising the COOP record. The CRN does not measure snow, and precipitation is measured differently between the CRN and COOP networks. This inappropriate substitution of data has rendered ongoing comparisons worthless, and in conjunction with recent numerous data gaps, the usable climate record at this important location appears to have come to an end, after a 45-year record. This has occurred just when a need exists to evaluate whether the winter climate has changed over this time period. Fortunately, beginning in November, 2005, these data substitutions have stopped. The observers at the Moose COOP station do recognize the importance of this station and are committed to maintaining the quality of data collected with no further compromises to the data record. The Wyoming State Climate Office is currently investigating the observational record of the Moose COOP station to determine if and how the station's data record can be corrected.

A second weather station where poor data availability and quality is of concern is the SAO station at West Yellowstone. Near-real-time weather observations on the western edge of YELL are important because this area is usually the entry point into YELL for most weather events, which generally come from the west. Monitoring such events is very important for weather-dependent park management decisions that must be made at shorter time scales. There are RAWS sites and several SNOTEL sites that provide near-real-time hourly weather observations around West Yellowstone. The SAO station at West Yellowstone is located in a larger clearing than where the nearby RAWS and SNOTEL sites are located, which is more suitable for weather observations. In addition, SAO sites are advantageous because they are often the only sources of real-time observations on visibility parameters such as cloudiness and sky cover. The NWS office in Great Falls, Montana, administers the West Yellowstone SAO station. The NPS may benefit by partnering with the Great Falls NWS office to encourage efforts to expand operations of the West Yellowstone SAO site from a summer-only to year-round schedule.

The GRYN park units host a large selection of alpine environments and there is much interest in the characteristics of the GRYN alpine ecosystem. Therefore, climate monitoring in these high-elevation zones is useful despite higher maintenance costs due to remoteness and frequently inclement conditions. Climate monitoring has applications in hydrologic studies, as well as in high-altitude ecosystem studies where responses to climate change are investigated. Currently, there are few weather/climate stations operating at high elevations within GRYN. The highest-elevation sites are the COOP stations near the summits of Mount Holmes (3142 m) and Mount Sheridan (3126 m). These are manual sites. The highest-automated station within GRYN is the Parker Peak SNOTEL site in eastern YELL (2865 m). To better sample climate characteristics in alpine environments, an advisable starting point would be to augment one of the two high-elevation COOP sites with an enhanced SNOTEL station. Enhanced SNOTEL stations are automated sites that provide not only snowfall data but also wind and solar radiation data. These are important weather/climate elements for monitoring alpine environments. If either the Mount Holmes or Mount Sheridan sites are not feasible for an enhanced SNOTEL site, a third option is the summit of Mount Washburn.

Precipitation estimates obtained with PRISM for the higher elevations in southwestern YELL and the Teton Range (Figure 2.2) indicate that this is one of the wettest regions within GRYN. This GRYN climate zone possesses characteristics (and associated ecosystem properties) that are truly unique from other regions in GRYN. There are, however, very few stations in this area capable of verifying PRISM estimates. One of the primary themes of GRTE is its alpine terrain. However, as previously discussed, weather/climate conditions associated with high-elevation ecosystems within GRYN, including the Teton Range, are not being measured adequately (Figure 4.1). We therefore recommend that the NPS partner with the USDA/NRCS to install a regular (not enhanced) SNOTEL station in the higher elevations of the Teton Range. A suitable location would be the head of the Cascade Creek Basin. This high-elevation site would provide maximum accessibility from the NPS facilities near Jenny Lake. Opportunities to obtain data from the existing weather stations at Jackson Hole Mountain Resort also could be pursued.

For BICA, it is important that the existing manual COOP site at Yellowtail Dam be retained for the purpose of long-term climate monitoring within BICA. If resources allow, this site could be enhanced by adding an automated RAWS site, which would allow NPS to better sample climate gradients along the length of the canyon.

5.2. Spatial Variations in Mean Climate

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

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

5.3. Climate Change Detection

There is much interest in the characteristics of GRYN alpine ecosystems. Despite the higher maintenance costs of these sites due to remoteness and frequently inclement conditions, climate monitoring in the high-elevation zones is quite useful. Applications for climate monitoring include hydrologic studies and responses of high-altitude ecosystems to climate change.

The desire for credible, accurate, complete, and long-term climate records—from any location—cannot be overemphasized. Thus, this consideration always should have a high priority. However, because of spatial diversity in climate, monitoring that fills knowledge gaps and provides information on long-term temporal variability in short-distance relationships also will be valuable. We cannot be sure that climate variability and climate change will affect all parts of a given park unit equally. In fact, it is appropriate to speculate that this is not the case, and spatial variations in temporal variability extend to small spatial scales (a few kilometers or less in some cases), a consequence of extreme topographic diversity within GRYN.

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 GRYN 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 GRYN park units but also to climate-monitoring efforts for GRYN. These pages can be found through http://www.wrcc.dri.edu/nps.

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

5.6. Summarized Conclusions and Recommendations

- Much work already has been done by the GRYN office to locate weather/climate stations (e.g., Selkowitz 2003; Gray 2005).
- Climate within GRYN is highly variable spatially due to regional topography and influences from two dominant climate regimes, one with winter precipitation and the other with spring and summer precipitation.
- Long-term records are most available for YELL (e.g., Mammoth Hot Springs) and are least available for BICA.
- Data records at various COOP sites in GRYN and the Moose COOP in particular have been compromised by changing duties of NPS personnel and by not facilitating consistent observation schedules.
- Supporting efforts from the NWS in Great Falls, Montana, to expand operation of the West Yellowstone SAO station from summer-only to year-round will benefit NPS .
- High-altitude biomes are an important component of GRYN park units. These areas are important for hydrology and for monitoring climate change within GRYN. Unfortunately, these areas are underrepresented in current weather/climate-monitoring efforts. We suggest upgrading current summit sites in YELL and/or installing an automated site in the Teton Range.
- Automated measurements are currently available at one location in BICA. We suggest retaining the existing COOP site at Yellowtail Dam and augmenting it with an automated RAWS station.

6.0. Literature Cited

American Association of State Climatologists. 1985. Heights and exposure standards for sensors on automated weather stations. The State Climatologist **9**.

Bartlein, P. J., C. Whitlock, and S. L. Shafer. 1997. Future climate in the Yellowstone National Park region and its potential impact on vegetation. Conservation Biology **11**:782-792.

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.

Cayan, D. R., M. D. Dettinger, H. F. Diaz, and N. E. Graham. 1998. Decadal variability of precipitation over western North America. Journal of Climate **11**:3148-3166.

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.

Despain, D. G. 1987. The two climates of Yellowstone National Park. Proc. Mont. Acad. Sci. **47**:11-19.

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.

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, NC.

Elder, K., S. Fullerton, and K. Tonnessen. 1994. Winter mass balance measurements on Teton Glacier begin to build basis for predicting seasonal melt and runoff. Park Science **14**:11-13.

Farnes, P. E. 1995. Estimating monthly distribution of average annual precipitation in mountainous areas of Montana. 63rd Annual Western Snow Conference. Sparks, NV, April 1995:78-87.

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.

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.

Graumlich, L. J., M. F. J. Pisaric, L. A. Waggoner, J. S. Littell, and J. C. King. 2003. Upper Yellowstone River flow and teleconnections with Pacific basin climate variability during the past three centuries. Climatic Change **59**:245-262.

Gray, S. T., C. Fastie, S. T. Jackson, and J. L. Betancourt. 2004. Tree-ring based reconstructions of precipitation in the Bighorn Basin, Wyoming since A.D. 1260. Journal of Climate **17**:3855-3865.

Gray, S. T. 2005. Climate Monitoring Protocols for the Greater Yellowstone Network: Bighorn Canyon National Recreation Area, Grand Teton National Park (including J.D. Rockefeller, Jr. Memorial Parkway), and Yellowstone National Park. Greater Yellowstone Network, National Park Service Inventory and Monitoring Program, Bozeman, Montana.

Hessl, A. E., D. McKenzie, and R. Schellhaas. 2004. Drought and Pacific Decadal Oscillation linked to fire occurrence in the inland Pacific Northwest. Ecological Applications **14**:425-442.

Heyerdahl, E. K., L. B. Brubaker, and J. K. Agee. 2002. Annual and decadal climate forcing of historical fire regimes in the interior Pacific Northwest, USA. The Holocene **12**:597-604.

Higgins, R. W., K. C. Mo, and Y. Yao. 1998. Interannual variability of the U.S. summer precipitation regime with emphasis on the southwestern monsoon. Journal of Climate **11**:2582-2606.

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.

Jean, C., A. M. Schrag, R. E. Bennetts, R. Daley, E. A. Crowe, and S. O'Ney. 2005. Vital signs monitoring plan for the Greater Yellowstone Network. National Park Service, Greater Yellowstone Network, National Park Service Inventory and Monitoring Program, Bozeman, Montana.

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.

Koteen, L. 2001. Climate change, whitebark pine, and grizzly bears in the Greater Yellowstone ecosystem. Pages 343-414 *in* H. Schneider and T. L. Root, editors. Wildlife Responses to Climate Change. Island Press, Washington, D.C.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society **78**:1069-1079.

Mantua, N. J. 2000. The Pacific Decadal Oscillation and climate forecasting for North America. Online. (http://www.atmos.washington.edu/~mantua/REPORTS/PDO/PDO_cs.htm). Accessed 27 April 2004.

Mock, C. J. 1996. Climatic controls and spatial variations of precipitation in the western United States. Journal of Climate **9**:1111-1125.

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.

Redmond, K. T., and R. W. Koch. 1991. Surface climate and streamflow variability in the western United States and their relationship to large-scale circulation indices. Water Resources Research **27**:2381-2399.

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.

Romme, W. H., and D. G. Despain. 1989. Historical perspective on the Yellowstone fires of 1988. BioScience **39**:695-699.

Romme, W. H., and M. G. Turner. 1991. Implications of global climate change for biogeographic patterns in the Greater Yellowstone ecosystem. Conservation Biology **5**:373-386.

Schlesinger, W. H. 1997. Biogeochemistry: An Analysis of Global Change. Academic Press, San Diego.

Selkowitz, D. 2003. Compilation and analysis of climate data in the Greater Yellowstone ecosystem/Bighorn Canyon area: completed products, problems encountered, and recommendations for the future. National Park Service, Greater Yellowstone Network, National Park Service Inventory and Monitoring Program, Bozeman, Montana..

Tanner, B. D. 1990. Automated weather stations. Remote Sensing Reviews **5**:73-98.

Whitlock, C. 1993. Postglacial vegetation and climate of Grand Teton and southern Yellowstone National Parks. Ecological Monographs **63**:173-198.

Whitlock, C., and P. J. Bartlein. 1993. Spatial variations of Holocene climatic change in the Yellowstone region. Quaternary Research **39**:231-238.

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.

Appendix A. Climate-monitoring principles.

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

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

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

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

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

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

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

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

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

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

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

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

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

A.2. Abbreviated version, "Ten Commandments of Climate Monitoring"

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

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

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

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

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

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

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

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

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

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

F. Maintain long-term weather and climate stations.

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

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

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

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

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

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

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

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

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

A.3. Literature Cited

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

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

Appendix B. Glossary.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Appendix C. Factors in operating a climate network.

C.1. Climate versus Weather

- Climate measurements require *consistency through time.*

C.2. Network Purpose

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

C.3. Site Identification and Selection

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

C.4. Station Hardware

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

C.5. Communications

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

C.6. Maintenance

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

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

C.7. Maintaining Programmatic Continuity and Corporate Knowledge

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

C.8. Data Flow

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

C.9. Products

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

C.10. Funding

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

C.11. Final Comments

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

Source: Western Regional Climate Center (WRCC)

Appendix D. Master metadata field list.

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

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

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

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

E.1. Introduction

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

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

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

E.1.1. Network Purpose

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

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

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

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

E.1.2. Robustness

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

E.1.3. Weather versus Climate

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

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

E.1.4. Physical Setting

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

E.1.5. Measurement Intervals

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

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

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

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

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

E.1.6. Mixed Time Scales

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

E.1.7. Elements

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

E.1.8. Wind Standards

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

E.1.9. Wind Nomenclature

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

E.1.10. Frozen Precipitation

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

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

E.1.11. Save or Lose

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

E.1.12. Time

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

E.1.13. Automated versus Manual

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

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

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

E.1.14. Manual Conventions

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

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

E.2. Representativeness

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

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

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

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

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

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

E.2.1. Temporal Behavior

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

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

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

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

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

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

E.2.2. Spatial Behavior

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

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

E.2.3. Climate-Change Detection

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

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

E.2.4. Element-Specific Differences

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

E.2.5. Logistics and Practical Factors

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

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

E.2.6. Personnel Factors

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

E.3. Site Selection

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

E.3.1. Equipment and Exposure Factors

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

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

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

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

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

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

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

E.3.2. Element-Specific Factors

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

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

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

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

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

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

E.3.2.6. Wind: Open exposures are needed for wind measurements. Small prominences or benches without blockage from certain sectors are preferred. A typical rule for trees is to site stations back 10 tree-heights from all tree obstructions. Sites in long, narrow valleys can obviously only exhibit two main wind directions. Gently-rounded eminences are more favored. Any kind of topographic steering should be avoided to the extent possible. Avoiding major mountain chains or single isolated mountains or ridges is usually a favorable approach, if there is a choice. Sustained wind speed and the highest gusts (1-second) should be recorded. Averaging methodologies for both sustained winds and gusts can affect climate trends and should be recorded as metadata with all changes noted. Vegetation growth affects the vertical wind profile, and growth over a few years can lead to changes in mean wind speed even if the "real" wind does not change, so vegetation near the site (perhaps out to 50 m) should be maintained in a quasi-permanent status (same height and spatial distribution). Wind devices can rime up and freeze or spin out of balance. In severely rimed or windy climates, rugged anemometers, such as those made by Taylor, are worth considering. These anemometers are expensive but durable and can withstand substantial abuse. In exposed locations, personnel should plan for winds to be at least 50 m/s and be able to measure these wind speeds. At a minimum, anemometers should be rated to 75 m/s.

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

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

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

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

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

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

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

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

E.3.3. Long-Term Comparability and Consistency

E.3.3.1. Consistency: The emphasis here is to hold biases constant. Every site has biases, problems, and idiosyncrasies of one sort or another. The best rule to follow is simply to try to keep biases constant through time. Since the goal is to track climate through time, keeping sensors, methodologies, and exposure constant will ensure that only true climate change is being measured. This means leaving the site in its original state or performing maintenance to keep it that way. Once a site is installed, the goal should be to never move the site even by a few meters or to allow significant changes to occur within 100 m for the next several decades.

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

E.3.3.2. Metadata: Since the climate of every site is affected by features in the immediate vicinity, it is vital to record this information over time and to update the record repeatedly at each service visit. Distances, angles, heights of vegetation, fine-scale topography, condition of instruments, shielding discoloration, and other factors from within a meter to several kilometers should be noted. Systematic photography should be undertaken and updated at least once every one–two years.

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

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

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

E.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, Washington, American Meteorological Society, Boston, Massachusetts, 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, Oregon, American Meteorological Society, Boston, Massachusetts, 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 (PACLIM) Workshop. Pacific Grove, California, 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., G. L. Hufford, 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 F. Descriptions of weather/climate monitoring networks.

F.1. Pacific Northwest Cooperative Agricultural Network (AgriMet)

- Purpose of network: provide weather/climate data for regional crop-water-use modeling, frost monitoring, and various agricultural research projects in the Pacific Northwest.
- Primary management agency: BLM.
- Data website: http://www.usbr.gov/pn/agrimet/wxdata.html.
- Measured weather/climate elements:
  - Air temperature.
  - Relative humidity and dewpoint temperature.
  - Precipitation.
  - Wind speed.
  - Solar radiation.
- Sampling frequency: hourly.
- Reporting frequency: hourly; some stations report every 10 minutes if real-time communications are available.
- Estimated station cost: $12K with maintenance costs around $2K/year.
- Network strengths:
  - AgriMet has near-real-time data.
  - Period of record is relatively long.
  - Sites are well maintained.
- Network weaknesses:
  - Only agricultural sites are sampled.
  - AgriMet has a limited geographic extent (Pacific Northwest).

AgriMet is a satellite-based network of automated weather stations operated by the BLM. Stations in AgriMet are located primarily in irrigated agricultural areas throughout the Pacific Northwest.

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

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

- Soil moisture and temperature.
- Sampling frequency: hourly.
- Reporting frequency: hourly.
- Estimated station cost: $13K.
- Network strengths:
  - High-quality data.
  - Sites are well-maintained.
- Network weaknesses:
  - Density of station coverage is low.
  - Shorter periods of record for western United States.

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

F.3. NWS Cooperative Observer Program (COOP)

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

The COOP network has long served as the main climate observation network in the 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.

F.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: $30K with maintenance costs around $2K/year.
- Network strengths:
  - Station siting is excellent (appropriate for long-term climate monitoring).
  - Data quality is excellent.
  - Site maintenance is excellent.
- Network weaknesses:
  - CRN network is still developing.
  - Period of record is short compared to other automated networks. Earliest sites date from 2004.
  - Station coverage is limited.
  - Not intended for snowy climates.

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

F.5. Remote Automated Weather Station (RAWS)

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

The RAWS network is used by many land-management agencies, such as the BLM, NPS, Fish and Wildlife Service, Bureau of Indian Affairs, Forest Service, and other agencies. The RAWS network was one of the first automated weather station networks to be installed in the 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.

F.6. NWS Surface Airways Observation Program (SAO)

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

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

F.7. USDA/NRCS Snowfall Telemetry (SNOTEL) network

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

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

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

F.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 United States.
- Primary management agency: NRCS.
- Data website: http://www.wcc.nrcs.usda.gov/snowcourse/.
- Measured weather/climate elements:
  - Snow depth.
  - Snow water equivalent.
- Measurement, reporting frequency: monthly or seasonally.
- Estimated station cost: cost of man-hours needed to set up snowcourse and make measurements.

- Network strengths
  - Periods of record are generally long.
  - Large number of high-altitude sites.
- Network weaknesses
  - Measurement and reporting only occurs on monthly to seasonal basis.
  - Few weather/climate elements are measured.

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

Appendix G. Electronic supplements.

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

G.2. GRYN metadata files for weather and climate stations associated with the GRYN: http://www.wrcc.dri.edu/nps/pub/gryn/metadata/GRYN_cli_sta.tar.gz.

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