National Park Service
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Natural Resource Program Center
Fort Collins, Colorado

Weather and Climate Inventory
National Park Service
Arctic Network

Natural Resource Technical Report NPS/ARCN/NRTR—2007/005

ON THE COVER
Cape Krusenstern National Monument
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Natural Resource Technical Report NPS/ARCN/NRTR—2007/005
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Acronyms

AASC	American Association of State Climatologists
ACIS	Applied Climate Information System
ARCN	Arctic Inventory and Monitoring Network
ASOS	Automated Surface Observing System
ATLAS	Arctic Transitions in the Land-Atmosphere System
AWOS	Automated Weather Observing System
BELA	Bering Land Bridge National Preserve
BLM	Bureau of Land Management
CAKR	Cape Krusenstern National Monument
CASTNet	Clean Air Status and Trends Network
COOP	Cooperative Observer Program
DFIR	Double-Fence Intercomparison Reference
DST	daylight savings time
ENSO	El Niño Southern Oscillation
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FIPS	Federal Information Processing Standards
GAAR	Gates of the Arctic National Park and Preserve
GCOS	Global Climate Observing System
GMT	Greenwich Mean Time
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning System
GTN-P	Global Terrestrial Network - Permafrost
I&M	NPS Inventory and Monitoring Program
KOVA	Kobuk Valley National Park
LST	local standard time
MDN	Mercury Deposition Network
NADP	National Atmospheric Deposition Program
NAO-AO	North Atlantic Oscillation – Arctic Oscillation
NASA	National Aeronautics and Space Administration
NCDC	National Climatic Data Center
NetCDF	Network Common Data Form
NOAA	National Oceanic and Atmospheric Administration
NOAT	Noatuk National Preserve
NPS	National Park Service
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
PDO	Pacific Decadal Oscillation
PNA	Pacific-North America Oscillation
PRISM	Parameter Regression on Independent Slopes Model
RAWS	Remote Automated Weather Station network
RCC	regional climate center
SAO	Surface Airways Observation network
SOD	Summary Of the Day

Surfrad	Surface Radiation Budget network
SNOTEL	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

Executive Summary

Climate is a dominant factor driving the physical and ecologic processes affecting the Arctic Inventory and Monitoring Network (ARCN). 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. Apparent climate changes are especially evident in high-latitude regions such as the ARCN. Temperature increases in the ARCN over the last several decades will likely have significant impacts on permafrost in the ARCN, including alterations in characteristics such as soil moisture, soil temperature, and soil respiration rates. These in turn can alter rates of nutrient inputs into the ARCN ecosystems, which could have far reaching impacts on the biological community of the ARCN. Long-term changes in climate are also associated with reductions in sea ice cover near coastal ARCN park units, and the northward and coastward migration of treeline. Drier interior areas of the ARCN are prone to fires during the late spring and early summer months, influencing vegetation structure and composition, permafrost dynamics, nutrient cycling, carbon loss/gain, primary productivity and biodiversity in these areas. Because of its influence on the ecology of ARCN park units and the surrounding areas, climate was identified as a high-priority vital sign for ARCN and is one of the 12 basic inventories to be completed for all National Park Service (NPS) Inventory and Monitoring Program (I&M) networks.

The NPS climate inventory and monitoring project was initiated to inventory past and present weather and climate monitoring efforts in NPS park units. In this report, we provide the following information:

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

The climate characteristics of the ARCN are influenced both by the Brooks Range to the north and east, and the Chukchi Sea to the west. The ARCN park units are characterized by long, cold winters and cool, wet summers. Park units near the Chukchi Sea experience a predominantly maritime climate, while interior park units have a more continental climate, with greater seasonal variations in temperatures and precipitation. Occasional wind storms impact the coastal ARCN park units, particularly in the winter months. Estimates from the Parameter Regression on Independent Slopes Model (PRISM) indicate that mean annual precipitation ranges from under 300 mm in coastal park units to almost 1000 mm in the higher elevations of the Brooks Range in Gates of the Arctic National Park and Preserve (GAAR). Summertime precipitation accounts for 30-50 percent of the total annual precipitation in the ARCN, with precipitation generally peaking in August across all ARCN park units. Temperatures in the ARCN vary largely as a function of latitude, elevation, and proximity to the coast. Mean annual temperatures in the ARCN range

from below -14°C in the higher elevations of northern GAAR to almost -6°C in Bering Land Bridge National Preserve (BELA).

Through a search of national databases, and inquiries to NPS staff and faculty at the University of Alaska Fairbanks, we have identified 10 weather and climate stations within ARCN park units. Seven of these stations are known to be active currently. This includes one station in BELA, two stations in GAAR, one station in Kobuk Valley National Park (KOVA), and three stations in Noatak National Preserve (NOAT). Five of these stations are Remote Automated Weather Station (RAWS) sites. The fact that there are only at most two or three weather/climate stations within each ARCN park unit means that coverage is currently very sparse within these parks units, which are quite large in total area, covering almost 7.7 million hectares (19 million acres). Large portions of the ARCN park units have no station coverage, including western GAAR, northern KOVA, far eastern and west-central portions of NOAT, all of Cape Krusenstern National Monument (CAKR), and northwestern (coastal) areas of BELA. There are no reliable long-term climate records available anywhere within ARCN park units.

The ARCN park units are in a unique position to monitor climate change. Adequate monitoring of all potentially affected systems should be well under way before any such changes become widespread. Plans are currently in place to install a series of new climate-monitoring stations in the ARCN park units, focusing in particular on those areas that are now completely lacking weather observations. Transition zones such as treeline and those areas with rapid permafrost thawing would be candidate locations for these new stations, providing tangible opportunities to monitor climate change and its impacts on ARCN natural systems.

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 Mid-Atlantic Inventory and Monitoring Network. Particular thanks are extended to Diane Sanzone and Scott Miller, along with Matt Nolan at the University of Alaska Fairbanks. We also thank John Gross, Margaret Beer, Grant Kelly, Greg McCurdy, and Heather Angeloff for all their help. Portions of the work were supported by the NOAA Western Regional Climate Center.

1.0. Introduction

Weather and climate are key drivers in ecosystem structure and function. Global- and regional-scale climate variations have a tremendous impact on natural systems (Chapin et al. 1996; Schlesinger 1997; Jacobson et al. 2000; Bonan 2002). Long-term patterns in temperature and precipitation provide first-order constraints on potential ecosystem structure and function. Secondary constraints are realized from the intensity and duration of individual weather events and, additionally, from seasonality and inter-annual climate variability. These constraints influence the fundamental properties of ecologic systems, such as soil–water relationships, plant–soil processes, and nutrient cycling, as well as disturbance rates and intensity. These properties, in turn, influence the life-history strategies supported by a climatic regime (Neilson 1987; Sanzone et al. 2005).

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

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

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

Table 1.1. Park units in the Arctic Network.

Acronym	Name
BELA	Bering Land Bridge National Preserve
CAKR	Cape Krusenstern National Monument
GAAR	Gates of the Arctic National Park and Preserve
KOVA	Kobuk Valley National Park
NOAT	Noatuk National Preserve

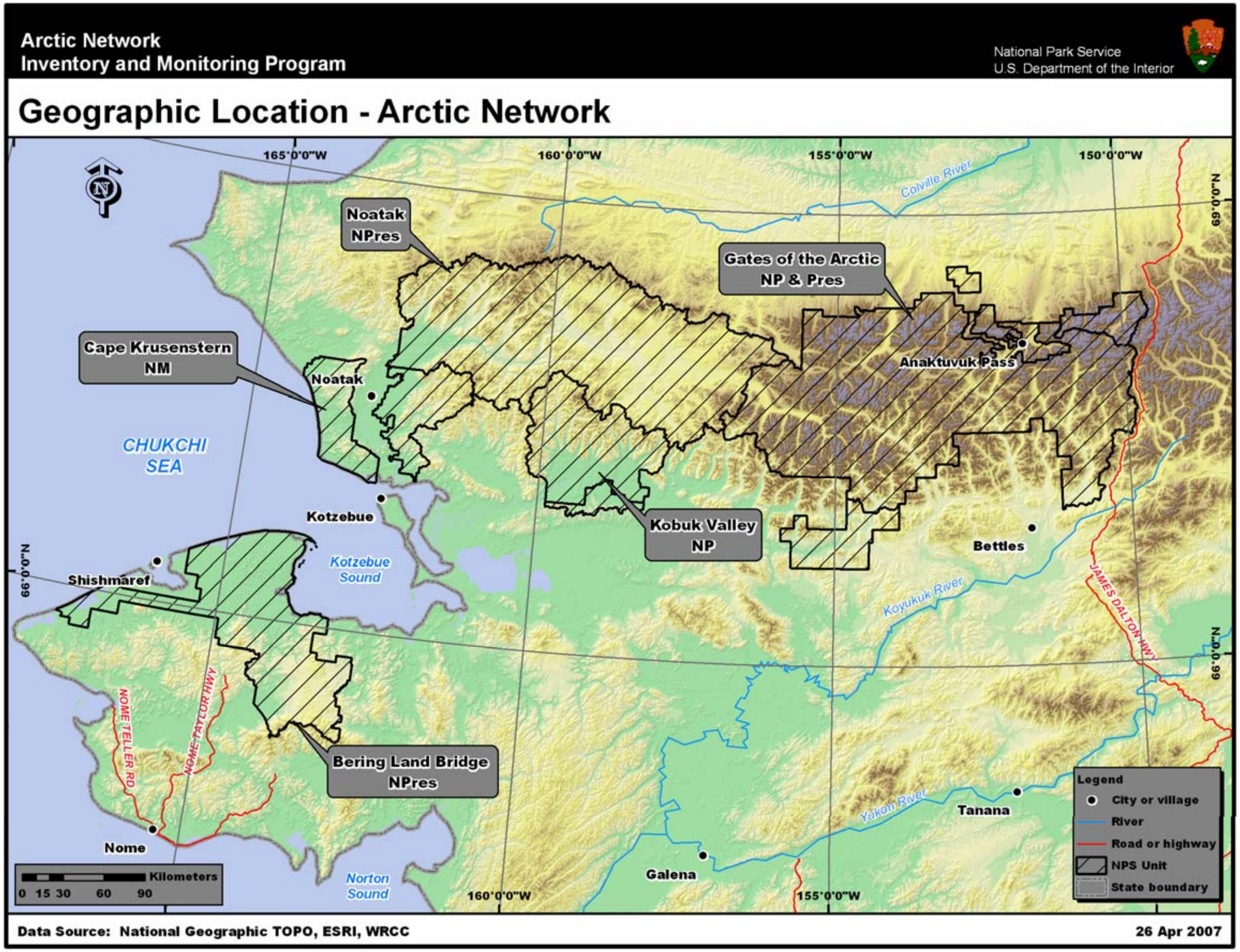


Figure 1.1. Map of the Arctic Network.

It is essential that park units within the ARCN have an effective climate-monitoring system in place to track climate changes and to aid in management decisions relating to these changes. Some of the primary objectives for climate- and weather-monitoring in ARCN are as follows (Sanzone et al. 2005):

A. Understand the natural variation in weather and climate patterns across ARCN using past and current data.
B. Analyze current trends in climate and weather patterns.
C. Predict future trends in climate and weather patterns in ARCN.
D. Understand the natural variability in depth, phenology and distribution of snow and ice in ARCN.
E. Determine how the extent, duration and timing of snow and ice cover are changing in the ARCN.

1.1. Network Terminology

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

1.1.1. Weather/Climate Station Networks

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

1.1.2. NPS I&M Networks

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

1.2. Weather versus Climate Definitions

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

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

1.3. Purpose of Measurements

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

- What is the purpose of weather and climate measurements?

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

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

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

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

1.4. Design of Climate-Monitoring Programs

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

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

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

1.4.1. Need for Consistency

A principal goal in climate monitoring is to detect and characterize slow and sudden changes in climate through time. This is of less concern for day-to-day weather changes, but it is of paramount importance for climate variability and change. There are many ways whereby changes in techniques for making measurements, changes in instruments or their exposures, or seemingly innocuous changes in site characteristics can lead to erroneous interpretations of climate change. 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 consume major amounts of time and budget but are absolutely necessary. Without such attention, data gradually become less credible and then often are misused or not used at all.

1.4.4. Automated versus Manual Stations

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

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

1.4.5. Communications

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

Automated stations are capable of functioning normally without communication and retaining many months of data. At such sites, however, alerts about station problems are not possible, large gaps can accrue when accessible stations quit, and the constituencies needed to support such stations are smaller and less vocal. Two-way communications permit full recovery from disruptions, ability to reprogram data loggers remotely, and better opportunities for diagnostics and troubleshooting. In virtually all cases, two-way communications are much preferred to all other communication methods. However, two-way communications require considerations of cost, signal access, transmission rates, interference, and methods for keeping sensor and communication power loops separate. Two-way communications are frequently impossible (no service) or impractical, expensive, or power consumptive. Two-way methods (cellular, land line, radio, Internet) require smaller up-front costs as compared to other methods of communication and have variable recurrent costs, starting at zero. Satellite links work everywhere (except when blocked by trees or cliffs) and are quite reliable but are one-way and relatively slow, allow no re-transmissions, and require high up-front costs ($3000–4000) but no recurrent costs. Communications technology is changing constantly and requires vigilant attention by maintenance personnel.

1.4.6. Quality Assurance and Quality Control

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

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

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

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

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

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

1.4.7. Standards

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

1.4.8. Who Makes the Measurements?

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

2.0. Climate Background

Ecosystem processes in the ARCN are governed by climate characteristics (Sanzone et al. 2005). Climatic stressors may be the foremost issues that ARCN park management will deal with. Global climate models indicate that subtle climate changes will have the most dramatic effect in arctic regions. These changes will be observable in many arctic system characteristics, such as permafrost dynamics, snowpack persistence, variations in timing of wildlife migrations, plant phenology, albedo, and sea ice extent and duration. Of all known arctic ecosystem drivers, climate has the greatest potential to cause pronounced, cascading effects on arctic processes and subsystems (Sanzone et al. 2005).

It is essential that the ARCN park units have an effective climate monitoring system to track climate changes and to aid in management decisions relating to these changes. These efforts are needed in order to support current vital sign monitoring activities within the park units of the ARCN. In order to do this, however, it is essential to understand the climate characteristics of the ARCN, as discussed in this chapter.

2.1. Climate and the ARCN Environment

The climate of northwest Alaska, and the ARCN parks in particular, is characterized by long, cold winters and cool wet summers (NAST 2001; Sanzone et al. 2005). While areas near the Chukchi Sea experience a predominantly maritime climate, the interior area has a more continental climate, with greater seasonal variations in temperatures and precipitation. During the summer months, conditions in interior park units are generally warmer than coastal areas, which are generally cool and moist (Sanzone et al. 2005). Precipitation is more common during the summer months, with the highest values occurring in the higher elevations of the Brooks Range, including portions of GAAR. During the winter season, the maritime influence at coastal areas is somewhat modified by the presence of pack ice, which minimizes the moderating effect of the sea during the months of October through May. Therefore, winters even in coastal areas are very cold and dry.

The climate features of the ARCN parks support a broad array of the ecosystems typical of the subarctic (boreal forest or taiga), and arctic (tundra) biomes of northwestern North America, along with coastal ecosystems (Sanzone et al. 2005). The most conspicuous feature of the vegetation in northwestern Alaska is treeline, which reaches its northwestern limit in North America in the vicinity of the eastern border of Cape Krusenstern and the western edge of the Noatak Preserve (Young 1974).

Winds are somewhat less common at the interior park units than at the coastal park units. Mean monthly winds at Kotzebue are above 10 knots from September through April and blow from the east (Sanzone et al. 2005). Mean wind speeds during the summer months are comparable in speed (average 10.5 knots) but are from the west. August and September are the windiest months, while the most extreme winds are associated with winter storms. Two types of high wind events are common along coastal park units of the ARCN (Papineau 2005a). One event brings strong easterly winds that are associated with winter high pressure areas over the Beaufort Sea and the Arctic Ocean. A second type of event brings strong southwesterly winds that are associated with strong low-pressure centers off the northwest coast of Alaska. This second type of high-wind event usually occurs during the summer months. These winds influence heavily shoreline erosion processes along the coastal ARCN park units (Papineau 2005a; Sanzone et al. 2005).

In the drier interior areas of the ARCN, fires are common during the late spring and early summer months. Fires can exert landscape-scale controls on vegetation structure and composition, permafrost dynamics, nutrient cycling, carbon loss/gain, primary productivity and biodiversity (Racine et al. 2004). The southern third of GAAR lies within the northernmost belt of Interior Alaska, and has the greatest number of fire starts within the Arctic Network. GAAR is on the periphery of interior weather patterns and is occasionally subject to large lightning storms associated with low precipitation and high temperatures in June and July (Sanzone et al. 2005).

It is generally accepted that climate change is occurring and that it is especially evident in high-latitude regions (NAST 2001); The temperature increases in the ARCN that have been observed in the last several decades (e.g., Stottlemyer 2001) will likely have significant impacts on permafrost in the ARCN (Lachenbruch and Marshall 1986; Osterkamp and Romanovsky 1999; Jorgenson et al. 2001; NAST 2001; Hinzman et al. 2005; Sanzone et al. 2005). In particular, higher temperatures may be associated with increased soil active layer depth and permafrost depth which may in turn be linked to alterations in characteristics such as soil moisture, soil temperature, and soil respiration rates. These in turn can alter rates of nutrient inputs into the ARCN ecosystems, which could have far reaching impacts on the biological community of the ARCN (Sanzone et al. 2005).

Long-term changes in climate are also associated with reductions in sea ice cover (Maslanik et al. 1996; Maslanik et al. 1999) and changes in the distributions of various organisms in the ARCN region (Serreze et al. 2000; Hinzman et al. 2005). In the North, the most conspicuous and well-studied expression of this is the location of the treeline. Changing climate and associated factors have already resulted in increased plant growth (Myneni et al. 1997) and associated advancement of treeline into the tundra biome (Sanzone et al. 2005).

2.2. Parameter Regression on Independent Slopes Model

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

2.3. Spatial Variability

The climate characteristics of the ARCN are influenced both by the Brooks Range to the north and east, and the Chukchi Sea to the west. Mean annual precipitation estimates from PRISM range from under 300 mm in portions of BELA and CAKR to almost 1000 mm in the higher elevations of the Brooks Range in western GAAR (Figure 2.1). Winter and early spring are quite dry throughout the ARCN. In March, for example, mean monthly precipitation totals range from under 10 mm along the coast to almost 50 mm in the higher elevations of GAAR (Figure 2.2). Precipitation is more prevalent during the summer months (e.g., Figure 2.3), peaking during August throughout the ARCN (Figure 2.4). Summertime precipitation generally accounts for 30-50 percent of the total annual precipitation in the ARCN (Sanzone et al. 2005). This summertime precipitation is usually due to thunderstorm activity in interior park units, and more frequent non-convective light-rain events in the coastal park units. Snowfall can generally be expected in the ARCN in all months except July and August. Snowfall totals across the ARCN range from under 100 cm at lower elevations to over 250 cm in GAAR at higher elevations of the Brooks Range (Sanzone et al. 2005).

Temperatures in the ARCN vary largely as a function of latitude and elevation, although proximity to the coast is also a factor. Mean annual temperatures in the ARCN (Figure 2.5), estimated from PRISM, range from below -14°C in the higher elevations of northern GAAR to almost -6°C in southern BELA. The maritime influence along the coast becomes more noticeable in the mean January minimum temperatures for the ARCN. Along the coast, particularly in western BELA, these minimum temperatures are as high as -20°C (Figure 2.6; Sanzone et al. 2005). Moving inland, however, lower elevations within southeastern GAAR see much colder wintertime minimum temperatures that are routinely less than -35°C (also see Sanzone et al. 2005). In fact, the record lowest minimum temperature for the state of Alaska, -62°C (-80°F), occurred on January 23, 1971 at Prospect Creek Camp, near the southeast corner of GAAR. Maritime influences are also notable during the summer months, leading to much cooler daytime temperatures for the ARCN park units along the Chukchi Sea compared to lower elevations in the interior. Mean July maximum temperatures along the coast are under 10°C in some places, while some portions of interior ARCN park units south of the Brooks Range commonly get above 20°C for this same time period (Figure 2.7). Daytime temperatures in July have been known to reach almost 30°C in CAKR (Sanzone et al. 2005) and other coastal ARCN park units, and 35°C or higher in the lower elevations of the interior ARCN park units.

2.4. Temporal Variability

Much evidence shows that temperatures are steadily increasing in polar regions (Overpeck et al. 1997; Serreze et al. 2000; NAST 2001; Hinzman et al. 2005). Ambient temperatures in northwest Alaska have increased since 1950 (Stottlemyer 2001). Precipitation has also increased significantly in northwest Alaska during the past century (NAST 2001).

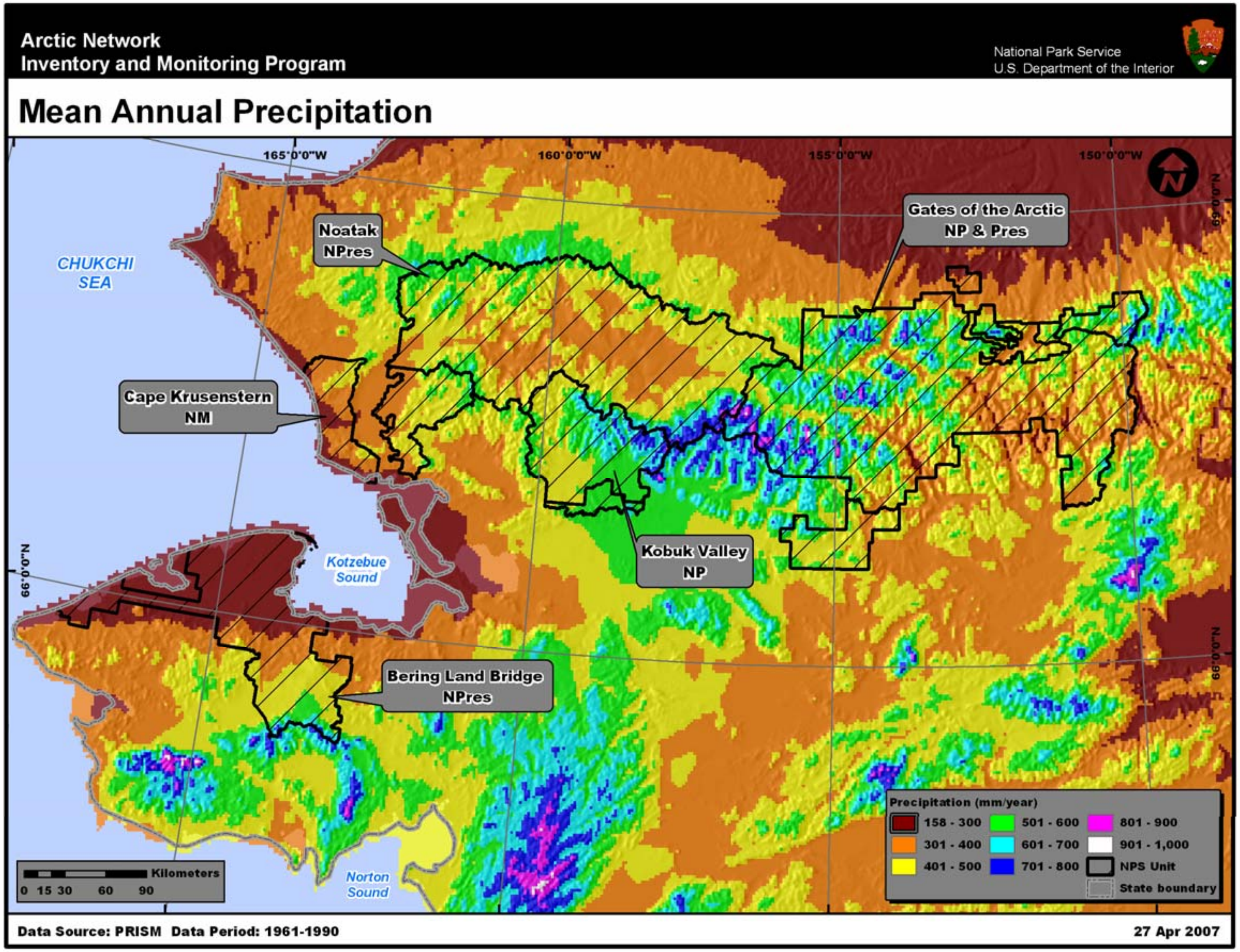


Figure 2.1. Mean annual precipitation, 1961-1990, for the ARCN.

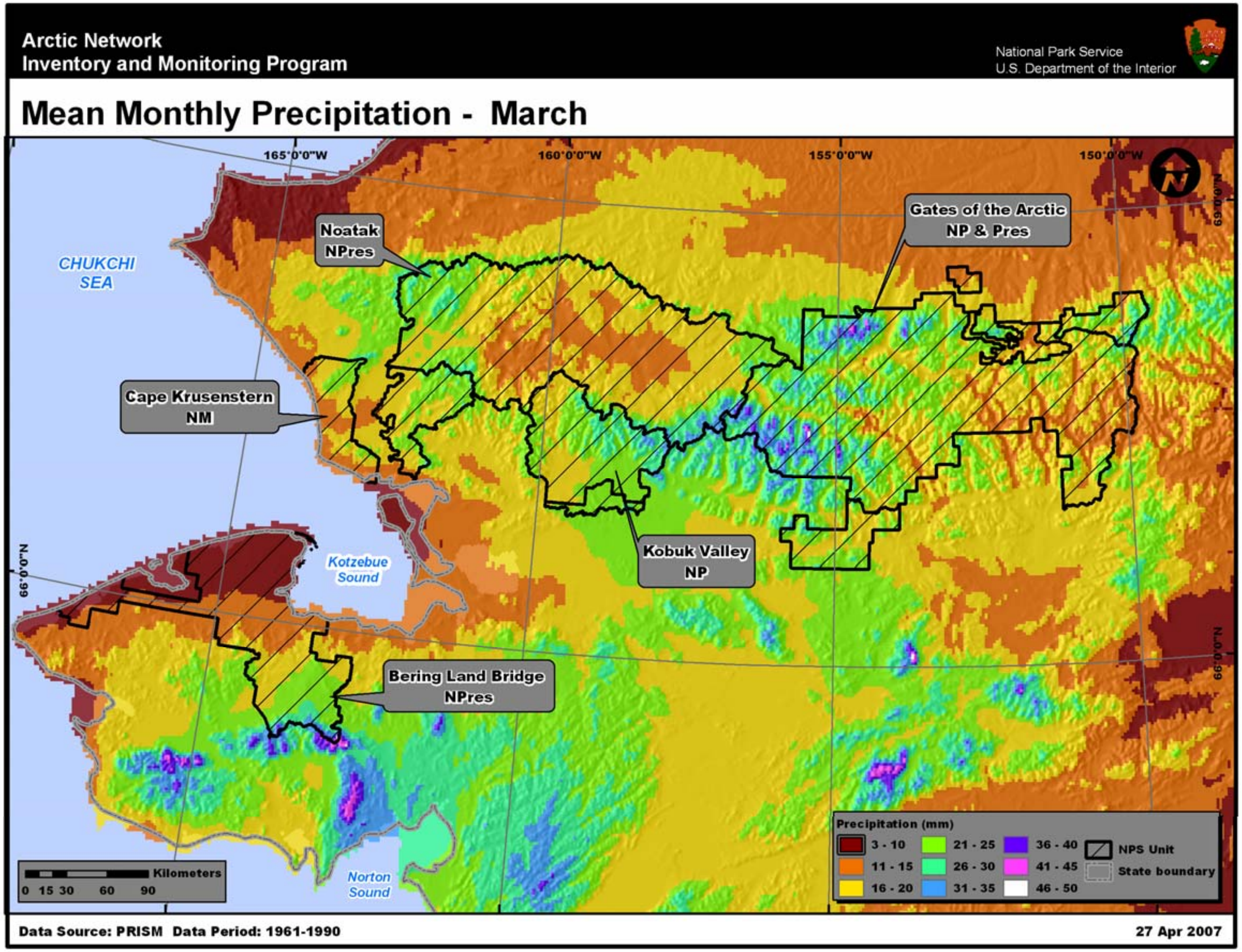


Figure 2.2. Mean March precipitation, 1961-1990, for the ARCN.

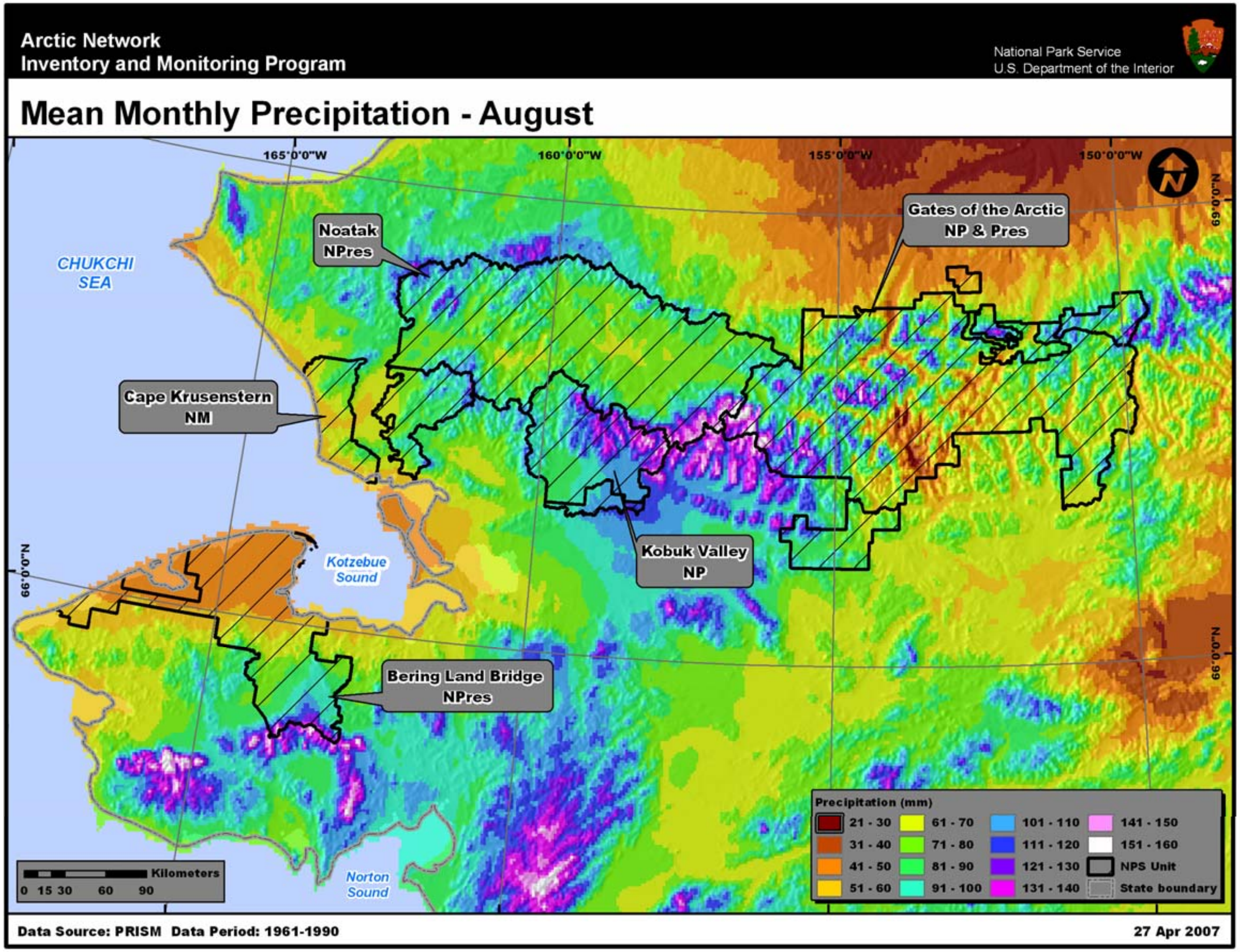
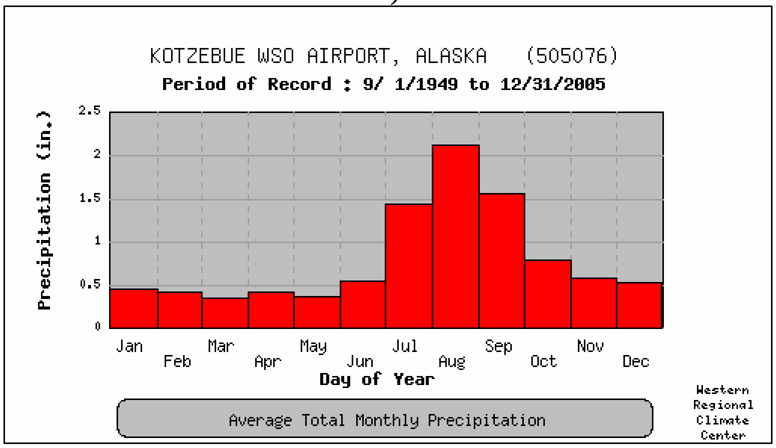


Figure 2.3. Mean August precipitation, 1961-1990, for the ARCN.

a)



b)

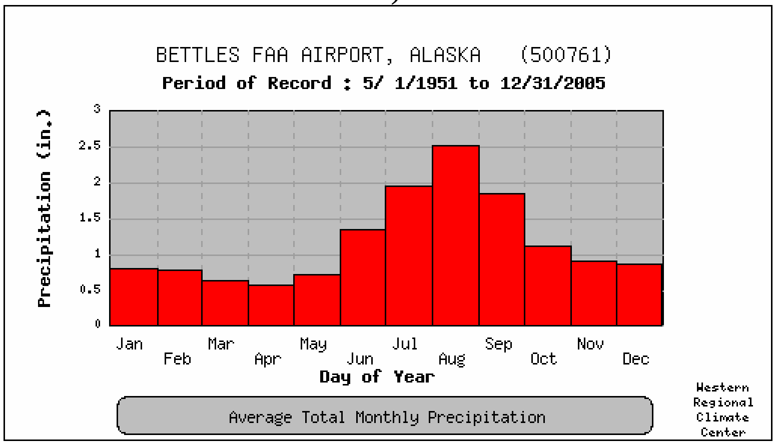


Figure 2.4. Mean monthly precipitation at selected locations in the ARCN region. Kotzebue WSO Airport (a) is near CAKR and Bettles FAA Airport (b) is near GAAR.

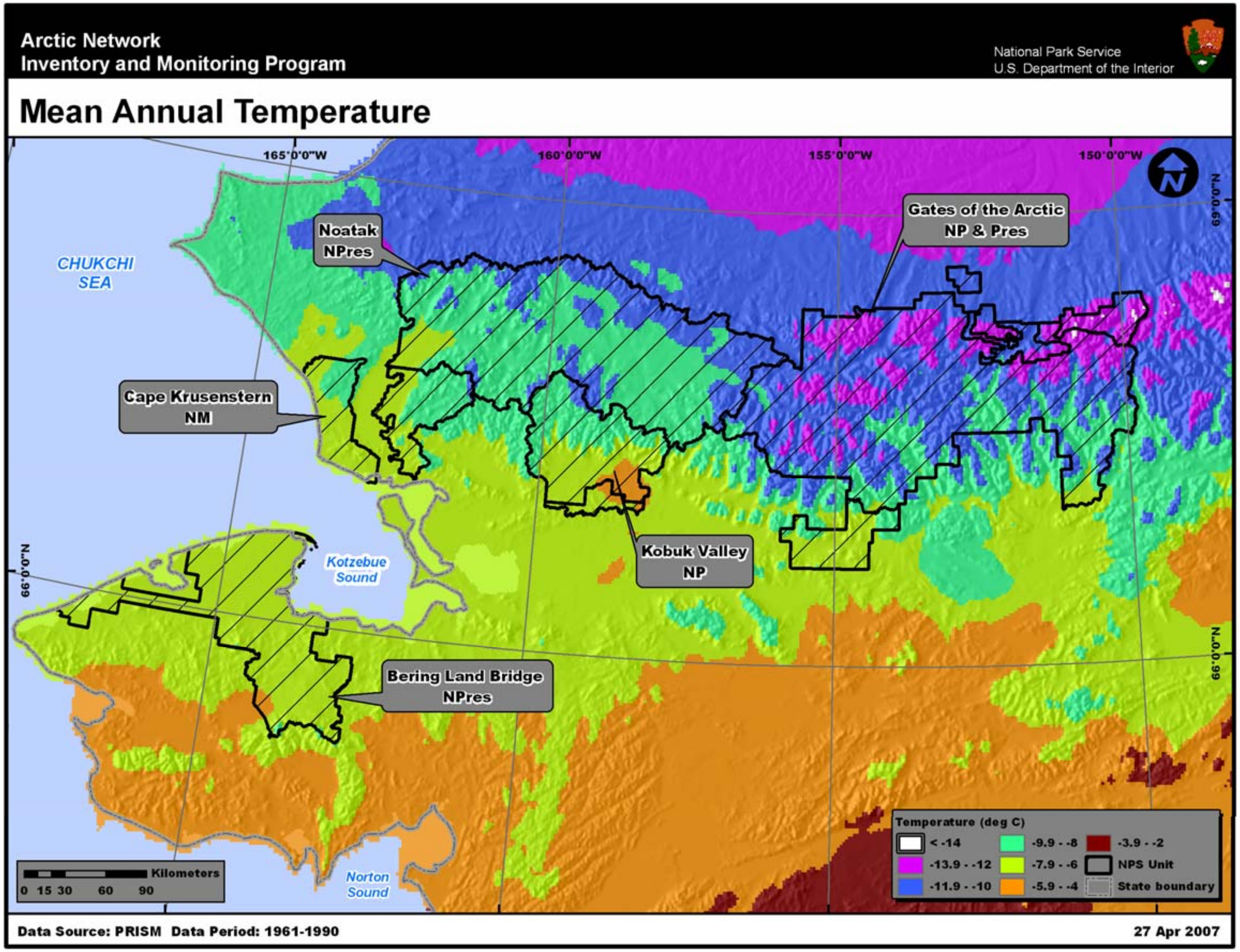


Figure 2.5. Mean annual temperature, 1961-1990, for the ARCN.

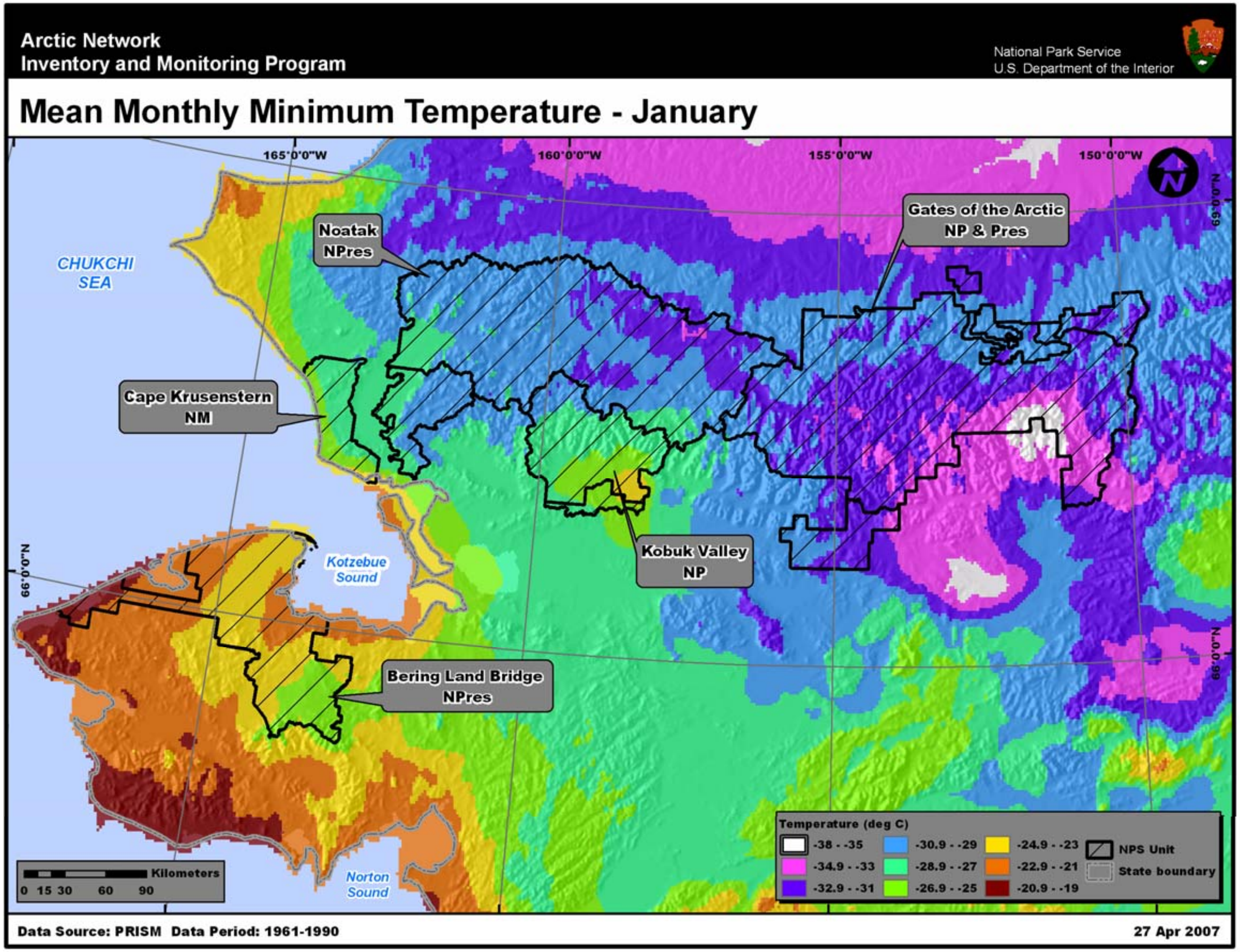


Figure 2.6. Mean January minimum temperature, 1961-1990, for the ARCN.

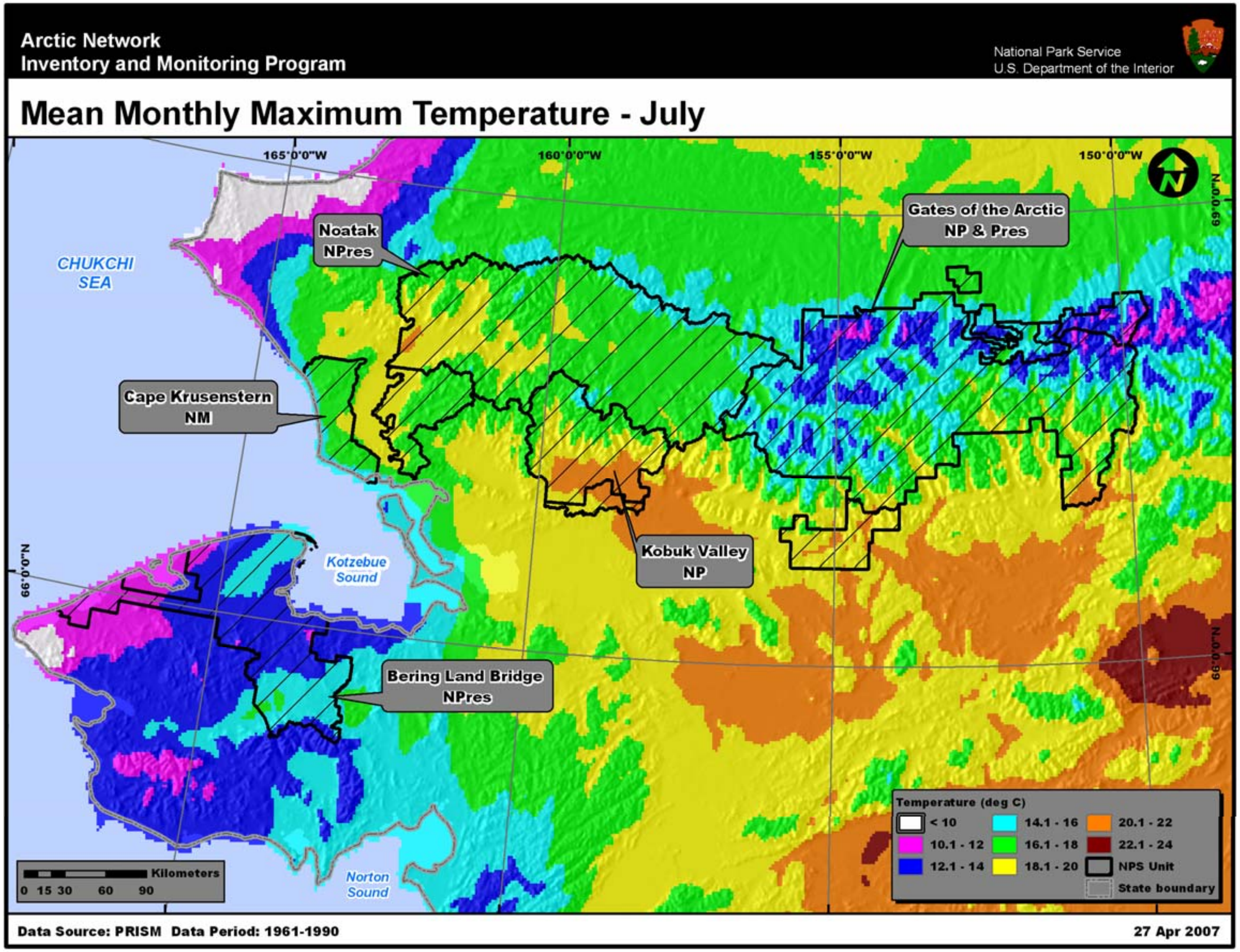


Figure 2.7. Mean July maximum temperature, 1961-1990, for the ARCN.

The Pacific-North America Oscillation (PNA; Wallace and Gutzler 1981) is an important contributor to variability of storm frequencies and tracks in the ARCN region during a given year, with variations that occur on the order of weeks. Shifts in large-scale circulation indices such as the El Nino Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the North Atlantic Oscillation – Arctic Oscillation (NAO-AO) lead to significant interannual and interdecadal variations in the climate of the ARCN (Trenberth and Hurrell 1994; Mantua et al. 1997; Thompson and Wallace 1998; Mantua 2000; Papineau 2005b).

3.0. Methods

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

3.1. Metadata Retrieval

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

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

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

Table 3.1. Primary metadata fields for ARCN weather/climate stations. Explanations are provided as appropriate.

Metadata Field	Notes
Station name	Station name associated with network listed in “Climate Network.”
Latitude	Numerical value (units: see coordinate units).
Longitude	Numerical value (units: see coordinate units).
Coordinate units	Latitude/longitude (units: decimal degrees, degree-minute-second, etc.).
Datum	Datum used as basis for coordinates: WGS 84, NAD 83, etc.
Elevation	Elevation of station above mean sea level (m).
Slope	Slope of ground surface below station (degrees).
Aspect	Azimuth that ground surface below station faces.
Climate division	NOAA climate division where station is located. Climate divisions are NOAA-specified zones sharing similar climate and hydrology characteristics.
Country	Country where station is located.
State	State where station is located.
County	County where station is located.
Weather/climate network	Primary weather/climate network the station belongs to (COOP, RAWS, etc.).
NPS unit code	Four-letter code identifying park unit where station resides.
NPS unit name	Full name of park unit.
NPS unit type	National park, national monument, etc.
UTM zone	If UTM is the only coordinate system available.
Location notes	Useful information not already included in “station narrative.”
Climate variables	Temperature, precipitation, etc.
Installation date	Date of station installation.
Removal date	Date of station removal.
Station photograph	Digital image of station.
Photograph date	Date photograph was taken.
Photographer	Name of person who took the photograph.
Station narrative	Anything related to general site description; may include site exposure, characteristics of surrounding vegetation, driving directions, etc.
Contact name	Name of the person involved with station operation.
Organization	Group or agency affiliation of contact person.
Contact type	Designation that identifies contact person as the station owner, observer, maintenance person, data manager, etc.
Position/job title	Official position/job title of contact person.
Address	Address of contact person.
E-mail address	E-mail address of contact person.
Phone	Phone number of contact person (and extension if available).
Contact notes	Other information needed to reach contact person.

Personnel from the University of Alaska Fairbanks (Table 3.2) provided additional information on stations providing weather data in the ARCN region. We have also relied on information supplied at various times in the past by the BLM, NPS, NCDC, and NWS.

Table 3.2. Additional sources of weather and climate metadata for the ARCN.

Name	Position	Phone Number	Email Address
Matt Nolan	Asst. Research Prof., Inst. Of Northern Engineering, Univ. of Alaska-Fairbanks	(907)474-7979	matt.nolan@uaf.edu
Vladimir Romanovsky	Geophysical Institute, Univ. of Alaska-Fairbanks	(907)474-7459	ffver@uaf.edu

Two types of information have been used to conduct the ARCN climate station inventory.

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

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

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

Certain types of weather and climate networks that possess any of the following attributes have not been considered for inclusion in the inventory. Previous inventory efforts at WRCC have shown that for the weather and climate networks identified in the following 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:

- 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.

3.2. Criteria for Locating Stations

To identify weather and climate stations for each park unit in the ARCN we have considered all available weather and climate stations, but highlight in this report only those stations located within 60 km of the ARCN park units. This was done in an attempt to include at least a few automated stations from major networks such as SAO.

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

4.0. Station Inventory

4.1. Climate and Weather Networks

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

Table 4.1. Weather/climate networks represented within the ARCN.

Acronym	Name
ATLAS	Arctic Transitions in the Land-Atmosphere System network
CASTNet	Clean Air Status and Trends Network
COOP	NWS Cooperative Observer Program
NADP	National Atmospheric Deposition Program
RAWS	Remote Automated Weather Station network
SAO	NWS/FAA Surface Airways Observation network
SNOTEL	USDA/NRCS Snowfall Telemetry network

4.1.1. Arctic Transitions in the Land-Atmosphere System (ATLAS) Network

The University of Alaska Fairbanks Water and Environmental Research Center operates the ATLAS network, which consists of several near-real-time weather stations located on the Seward Peninsula in western Alaska. The parameters measured at each site can include hourly observations of wind speed, wind direction, air temperature, relative humidity, net radiation, up/downward long/shortwave radiation, barometric pressure, precipitation, and snow depth. Unfortunately, these sites have no long-term funding and are not actively maintained anymore.

4.1.2. Clean Air Status and Trends Network (CASTNet)

CASTNet is primarily an air-quality monitoring network managed by the EPA. Standard hourly meteorological 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 monitoring 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. National Atmospheric Deposition Program (NADP)

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

4.1.5. Remote Automated Weather Station Network (RAWS)

The RAWS network of near-real-time weather stations is administered through many land management agencies, particularly the BLM and the Forest Service. Hourly observations 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 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. Weather Bureau Army Navy (WBAN)

This is a station identification system rather than a true weather or climate network. Stations identified with WBAN are largely historical stations that reported meteorological observations on the WBAN weather observation forms that were common during the early and middle parts of the 20th Century. The use of WBAN numbers to identify stations was one of the first attempts in the U.S. to use a coordinated station numbering scheme between several weather station networks, such as the SAO and COOP networks.

4.1.9. Other Networks

In addition to the major networks mentioned above, we are aware of at least two other networks that have stations situated in the ARCN region; these networks are the Global Terrestrial Network-Permafrost (GTN-P) and NRCS aerial markers. The GTN-P is a subset of the Global Climate Observing System (GCOS), established in 1992 to identify a network of reliable, long-term climate stations around the globe. Most of the GTN-P sites in Alaska are located north of the ARCN park units and measure air temperature, wind, and precipitation. There are also some GTN-P sites in the discontinuous permafrost zones south of the ARCN park units; these sites only measure air temperature. Aerial markers are sites where snow depth is measured by aircraft one or two times per month during the months of January to June. However, station metadata for these two networks were not able to be obtained in a timely manner for this report and hence these stations are not included in the report.

There are also various networks that are operated for specific purposes by specific organizations or governmental agencies or scientific research projects, which could be present within ARCN but have not been identified in this report. Some of the commonly used networks include the following:

- NOAA upper-air stations
- Federal and state departments of transportation
- U.S. Department of Energy Surface Radiation Budget Network (Surfrad)
- 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 and climate networks in the ARCN (discussed in Section 4.1) have at most a few stations that are inside each park unit (Table 4.2). Gates of the Arctic National Park and Preserve (GAAR) and NOAT have the greatest number of stations inside park boundaries (three).

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

Network	BELA	CAKR	GAAR	KOVA	NOAT
ATLAS	**6**(0)	**0**(0)	**1**(0)	**0**(0)	**1**(0)
CASTNet	**0**(0)	**0**(0)	**1**(0)	**1**(0)	**1**(0)
COOP	**13**(0)	**5**(0)	**22**(1)	**8**(0)	**12**(0)
NADP	**0**(0)	**0**(0)	**1**(0)	**1**(0)	**1**(0)
RAWS	**2**(1)	**1**(0)	**3**(0)	**5**(2)	**5**(2)
SAO	**8**(0)	**5**(0)	**7**(1)	**5**(0)	**9**(0)
SNOTEL	**2**(0)	**2**(0)	**6**(0)	**0**(0)	**2**(1)
Other	**5**(1)	**0**(0)	**7**(1)	**0**(0)	**0**(0)
Total	**36**(2)	**13**(0)	**48**(3)	**20**(2)	**31**(3)

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

Two stations have been identified within BELA (Table 4.3; Figure 4.1). Both of these stations are located in the southeastern corner of BELA (Figure 4.1). "Imuruk Lake AAF," is a historical station that only operated for a very short time towards the end of World War II. The other station, the RAWS site "Hoodoo Hill" is a near-real-time weather station that has been taking observations since 1992. "Hoodoo Hill" had numerous data gaps up until April 2000 but its data record has been complete since. No weather or climate stations were identified along the coastal portions of BELA, although historical COOP and SAO sites at Shishmaref were identified, operating between 1919 and 1973.

The ATLAS network operates eight weather stations that provide near-real-time data on the southwestern Seward Peninsula (Figure 4.1). Six of these stations are located within 60 km southwest of BELA. The closest ATLAS station to BELA is "Kougarok," which is situated about 25 km west of the southwestern boundary of BELA.

Five active COOP stations are located within 60 km of BELA (Table 4.3). Three of these climate stations have data records dating back to the 1920s or earlier. "Kotzebue Ralph Wein Mem. Arpt.," located 50 km northeast of BELA (Figure 4.1), has the longest data record of these three stations, beginning operations in 1897. This station has a very complete data record. The COOP station "Deering" started operating in 1917 but the completeness of its data record is questionable. The COOP station "Wales" is about 30 km west of the westernmost tip of BELA, at the western tip of Seward Peninsula. "Wales" started operating in 1925. However, there was a significant data gap from January 1978 through July 1979 at this site and data have not been available reliably since 1995. Fortunately, a SAO station is co-located with the COOP station at Wales.

In addition to the SAO weather station "Wales," three other SAO stations are currently active within 60 km of BELA (Table 4.3). Like Wales, the Kotzebue Airport has a SAO station co-located with a COOP station. Other active SAO stations include "Deering Airport," which has operated since 1998, and "Tin City," located 30 km southwest of BELA (Figure 4.1).

Several stations with the RAWS and SNOTEL networks have been identified that provide near-real-time weather data within 60 km of BELA. Only one active RAWS site was identified within 60 km of the boundary of BELA (Table 4.3). This weather station (Quartz Creek) has been active since 1988, although observations were not made consistently until June 1990. This site has also had data gaps between February and May for several years (1991, 1993, 1995, 1999, 2000, and 2005). Four active SNOTEL sites were identified within 60 km of BELA.

Table 4.3. Weather/climate stations for the ARCN. Stations inside park units and within 60 km of the park unit boundaries are included. Missing entries are indicated by "M".

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Bering Land Bridge National Preserve – BELA							
Hoodoo Hill	65.586	-163.408	472	RAWS	6/1/1992	Present	Yes
Imuruk Lake AAF	65.583	-163.833	170	WBAN	12/1/1944	11/30/1945	Yes
Blueberry Hill	64.891	-163.644	M	ATLAS	M	M	No
Council Grid Site	64.843	-163.722	46	ATLAS	M	M	No
Guy Rowe	64.746	-163.894	M	ATLAS	M	M	No
Kigluavik Mountains	65.014	-164.809	754	ATLAS	M	M	No
Kougarok	65.440	-164.579	M	ATLAS	M	M	No
Skookum Pass	64.708	-164.048	396	ATLAS	M	M	No
Buckland	65.978	-161.112	9	COOP	8/30/1996	Present	No
Candle	65.933	-161.917	7	COOP	10/13/1903	4/30/1951	No
Council	64.883	-163.683	29	COOP	5/1/1936	12/31/1942	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Deering	66.069	-162.767	5	COOP	7/1/1917	Present	No
Elim	64.618	-162.272	15	COOP	3/15/1997	Present	No
Igloo	65.150	-165.067	1	COOP	11/1/1919	12/31/1937	No
Kotzebue 25 N	67.250	-162.800	9	COOP	10/26/1982	6/30/1995	No
Kotzebue Ralph Wein Mem. Arpt.	66.885	-162.597	3	COOP	9/12/1897	Present	No
Koyuk	64.933	-161.150	18	COOP	10/1/1988	2/1/1990	No
Port Clarence	65.250	-166.867	4	COOP	7/21/1895	1/1/1996	No
Shishmaref	66.250	-166.067	3	COOP	10/1/1919	11/30/1973	No
Tin City	65.567	-167.917	82	COOP	10/1/1937	12/1/1984	No
Wales	65.624	-168.099	8	COOP	10/10/1925	Present	No
Quartz Creek	65.400	-164.650	130	RAWS	5/1/1988	Present	No
Candle	65.933	-161.917	7	SAO	10/13/1903	4/30/1951	No
Deering Airport	66.069	-162.764	5	SAO	7/27/1998	Present	No
Kotzebue Ralph Wein Mem. Arpt.	66.885	-162.597	3	SAO	9/12/1897	Present	No
Port Clarence	65.250	-166.867	4	SAO	7/21/1895	1/1/1996	No
Shishmaref	66.250	-166.067	3	SAO	10/1/1919	11/30/1973	No
Tin City	65.567	-167.917	82	SAO	10/1/1937	12/1/1984	No
Tin City AFS	65.567	-167.917	253	SAO	M	M	No
Wales	65.624	-168.099	8	SAO	10/10/1925	Present	No
Cottonwood Camp	65.117	-164.717	30	SNOTEL	M	Present	No
Pargon Creek	64.983	-163.100	91	SNOTEL	M	Present	No
American River AAF	65.450	-165.767	36	WBAN	4/1/1944	8/31/1945	No
Noxapage AAF	65.533	-164.200	76	WBAN	9/1/1943	10/31/1943	No
Teller AAF	65.300	-166.917	3	WBAN	8/1/1943	12/31/1945	No
Wales AAF	65.617	-168.050	5	WBAN	7/1/1943	12/31/1946	No
	Cape Krusenstern National Monument – CAKR						
Kivalina	67.733	-164.533	3	COOP	9/1/1973	12/31/1975	No
Kotzebue 25 N	67.250	-162.800	9	COOP	10/26/1982	6/30/1995	No
Kotzebue Ralph Wein Mem. Arpt.	66.885	-162.597	3	COOP	9/12/1897	Present	No
Noatak	67.576	-162.970	18	COOP	10/1/1917	Present	No
Noorvik	66.833	-161.048	18	COOP	1/1/1919	11/10/1997	No
Kelly	67.933	-162.300	126	RAWS	4/1/1990	Present	No
Kivalina	67.733	-164.567	M	SAO	M	M	No
Kivalina Airport	67.732	-164.548	3	SAO	7/7/1998	Present	No
Kotzebue Ralph Wein Mem. Arpt.	66.885	-162.597	3	SAO	9/12/1897	Present	No
Noatak Arpt.	67.566	-162.975	27	SAO	5/25/2005	Present	No
Red Dog	68.033	-162.900	399	SAO	M	M	No
Ikalukrok Creek	68.033	-163.017	198	SNOTEL	M	Present	No
Kelly Station	67.933	-162.283	94	SNOTEL	M	Present	No
	Gates of the Arctic National Park and Preserve – GAAR						
Anaktuvuk Auto	68.167	-151.767	640	COOP	7/1/1953	Present	Yes
Anaktuvuk Pass	68.133	-151.733	2003	SAO	M	M	Yes

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Old Man	67.450	-150.583	11	WBAN	M	Present	Yes
Ivotuk	68.480	-155.743	M	ATLAS	M	M	No
Ambler	67.093	-157.869	88	CASTNet	7/1/2004	9/15/2005	No
Ambler	67.083	-157.850	37	COOP	7/30/1969	10/31/1995	No
Ambler West	67.083	-157.867	37	COOP	11/18/1981	Present	No
Bettles	66.933	-151.500	183	COOP	10/1/1969	Present	No
Bettles Airport	66.916	-151.509	196	COOP	4/1/1951	Present	No
Bettles CAA	66.900	-151.717	261	COOP	4/1/1944	4/30/1951	No
Chandalar Shelf Dot	68.078	-149.565	991	COOP	3/1/2000	Present	No
Coldfoot	67.254	-150.188	320	COOP	8/1/1993	Present	No
Coldfoot Camp	67.267	-150.233	336	COOP	7/1/1970	7/31/1977	No
Dahl Creek	66.933	-156.867	82	COOP	8/1/1909	7/29/1968	No
Dietrich	67.683	-149.733	454	COOP	7/1/1970	Present	No
Galbraith	68.483	-149.483	813	COOP	6/1/1970	9/23/1980	No
Killik	68.450	-154.300	803	COOP	5/1/1981	1/1/1982	No
Kobuk	66.900	-156.867	43	COOP	8/1/1953	Present	No
Prospect Creek	66.824	-150.669	291	COOP	7/1/1970	Present	No
Sag River D O T	68.761	-148.873	497	COOP	3/14/1997	Present	No
Shungnak	66.879	-157.151	61	COOP	7/1/1914	2/24/1997	No
Shungnak CAA	66.900	-157.033	42	COOP	8/1/1941	4/30/1951	No
Toolik	68.633	-149.567	747	COOP	7/1/1970	Present	No
Wild Lake	67.483	-151.600	366	COOP	1/1/1955	9/30/1960	No
Wild Lake 2	67.550	-151.550	363	COOP	11/1/1963	12/31/1976	No
Wiseman	67.419	-150.107	350	COOP	11/1/1918	Present	No
Ambler	67.093	-157.869	88	NADP	5/12/2004	8/9/2005	No
Hogatza River	66.217	-155.667	209	RAWS	5/1/1988	Present	No
Norutak Lake	66.833	-154.333	244	RAWS	5/1/1990	Present	No
Onion Portage	67.113	-158.266	61	RAWS	9/1/1995	1/31/1996	No
Ambler Airport	67.100	-157.850	88	SAO	6/9/1992	Present	No
Ambler West	67.083	-157.867	37	SAO	11/18/1981	Present	No
Bettles Airport	66.916	-151.509	196	SAO	4/1/1951	Present	No
Kobuk	66.900	-156.867	43	SAO	8/1/1953	Present	No
Shungnak CAA	66.900	-157.033	42	SAO	8/1/1941	4/30/1951	No
Wiseman	67.419	-150.107	350	SAO	11/1/1918	Present	No
Atigun Cirque	68.117	-149.300	1448	SNOTEL	M	12/12/9999	No
Atigun Pass	68.133	-149.467	1463	SNOTEL	M	12/12/9999	No
Bettles Field	66.917	-151.533	195	SNOTEL	M	Present	No
Coldfoot	67.250	-150.183	12	SNOTEL	M	Present	No
Gobblers Knob	66.733	-150.667	9	SNOTEL	M	Present	No
Imnaviat Creek	68.633	-149.300	930	SNOTEL	M	Present	No
Atigun	68.183	-149.417	1017	WBAN	11/1/1974	Present	No
Chandalar Shelf	68.067	-149.583	606	WBAN	M	Present	No
Cold Foot	67.067	-149.583	948	WBAN	M	Present	No
Cold Foot	67.050	-149.567	324	WBAN	3/1/1974	Present	No
Galbraith Lake	68.483	-149.483	435	WBAN	M	Present	No
Prospect Creek	66.800	-150.633	337	WBAN	2/1/1974	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Kobuk Valley National Park – KOVA							
Kavet Creek	67.139	-159.044	72	RAWS	6/1/1992	Present	Yes
Onion Portage	67.113	-158.266	61	RAWS	9/1/1995	1/31/1996	Yes
Ambler	67.093	-157.869	88	CASTNet	7/1/2004	9/15/2005	No
Ambler	67.083	-157.850	37	COOP	7/30/1969	10/31/1995	No
Ambler West	67.083	-157.867	37	COOP	11/18/1981	Present	No
Dahl Creek	66.933	-156.867	82	COOP	8/1/1909	7/29/1968	No
Kobuk	66.900	-156.867	43	COOP	8/1/1953	Present	No
Noorvik	66.833	-161.048	18	COOP	1/1/1919	11/10/1997	No
Selawik	66.600	-160.033	6	COOP	1/1/1953	4/30/1955	No
Shungnak	66.879	-157.151	61	COOP	7/1/1914	2/24/1997	No
Shungnak CAA	66.900	-157.033	42	COOP	8/1/1941	4/30/1951	No
Ambler	67.093	-157.869	88	NADP	5/12/2004	8/9/2005	No
Kiana	66.977	-160.438	46	RAWS	4/1/1988	Present	No
Noatak	68.071	-158.704	300	RAWS	4/1/1990	Present	No
Selawik	66.603	-159.113	32	RAWS	6/1/1991	Present	No
Ambler Airport	67.100	-157.850	88	SAO	6/9/1992	Present	No
Ambler West	67.083	-157.867	37	SAO	11/18/1981	Present	No
Kobuk	66.900	-156.867	43	SAO	8/1/1953	Present	No
Selawik Arpt.	66.600	-159.986	8	SAO	5/25/2005	Present	No
Shungnak CAA	66.900	-157.033	42	SAO	8/1/1941	4/30/1951	No
Noatak National Preserve – NOAT							
Kelly	67.933	-162.300	126	RAWS	4/1/1990	Present	Yes
Noatak	68.071	-158.704	300	RAWS	4/1/1990	Present	Yes
Kelly Station	67.933	-162.283	94	SNOTEL	M	Present	Yes
Ivotuk	68.480	-155.743	M	ATLAS	M	M	No
Ambler	67.093	-157.869	88	CASTNet	7/1/2004	9/15/2005	No
Ambler	67.083	-157.850	37	COOP	7/30/1969	10/31/1995	No
Ambler West	67.083	-157.867	37	COOP	11/18/1981	Present	No
Dahl Creek	66.933	-156.867	82	COOP	8/1/1909	7/29/1968	No
Killik	68.450	-154.300	803	COOP	5/1/1981	1/1/1982	No
Kivalina	67.733	-164.533	3	COOP	9/1/1973	12/31/1975	No
Kobuk	66.900	-156.867	43	COOP	8/1/1953	Present	No
Kotzebue 25 N	67.250	-162.800	9	COOP	10/26/1982	6/30/1995	No
Kotzebue Ralph Wein Mem. Arpt.	66.885	-162.597	3	COOP	9/12/1897	Present	No
Noatak	67.576	-162.970	18	COOP	10/1/1917	Present	No
Noorvik	66.833	-161.048	18	COOP	1/1/1919	11/10/1997	No
Shungnak	66.879	-157.151	61	COOP	7/1/1914	2/24/1997	No
Shungnak CAA	66.900	-157.033	42	COOP	8/1/1941	4/30/1951	No
Ambler	67.093	-157.869	88	NADP	5/12/2004	8/9/2005	No
Kavet Creek	67.139	-159.044	72	RAWS	6/1/1992	Present	No
Kiana	66.977	-160.438	46	RAWS	4/1/1988	Present	No
Onion Portage	67.113	-158.266	61	RAWS	9/1/1995	1/31/1996	No
Ambler Airport	67.100	-157.850	88	SAO	6/9/1992	Present	No
Ambler West	67.083	-157.867	37	SAO	11/18/1981	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Kivalina	67.733	-164.567	M	SAO	M	M	No
Kivalina Airport	67.732	-164.548	3	SAO	7/7/1998	Present	No
Kobuk	66.900	-156.867	43	SAO	8/1/1953	Present	No
Kotzebue Ralph Wein Mem. Arpt.	66.885	-162.597	3	SAO	9/12/1897	Present	No
Noatak Arpt.	67.566	-162.975	27	SAO	5/25/2005	Present	No
Red Dog	68.033	-162.900	399	SAO	M	M	No
Shungnak CAA	66.900	-157.033	42	SAO	8/1/1941	4/30/1951	No
Ikalukrok Creek	68.033	-163.017	198	SNOTEL	M	Present	No

No weather or climate stations are currently in operation within CAKR (Table 4.3; Figure 4.1). Only two COOP stations are currently active within 60 km of the park unit. One of these stations is the previously-discussed COOP climate station at Kotzebue's airport, located about 30 km southeast of CAKR. "Noatak" is located about 15 km east of CAKR and is a climate station that has been active since 1917. However, it is uncertain how complete its data record is. There are currently five active SAO weather stations within 60 km of CAKR. The SAO station with the longest data record is at Kotzebue's airport. The other SAO sites identified in this report are found at Noatak Airport, 15 km east of CAKR, at Kivalina Airport, 20 km up the coast from the northwest tip of CAKR, and at Red Dog, 40 km northeast of CAKR. Unlike most SAO stations, the SAO station at the Red Dog airport is a manual station, with manual observations generally taken by airport staff when aircraft are arriving or departing. One RAWS station (Kelly) and two SNOTEL stations (Ikalukrok Creek and Kelly Station) also provide near-real-time weather observations within 60 km of CAKR. Two of these stations, "Kelly" (RAWS) and "Kelly Station" (SNOTEL), are located in westernmost NOAT, 50 km northeast of CAKR. The RAWS station "Kelly" has a data record that has been complete since June 1997. Numerous data gaps occurred before this date, particularly in the winter and spring months. The SNOTEL station "Ikalukrok Creek" is located within a few kilometers of the Red Dog Airport.

We have identified three stations inside the boundaries of GAAR (Table 4.3). At least two of these sites are known to be active. The COOP climate station "Anaktuvuk Auto," located at Anaktuvuk Pass in northeastern GAAR (Figure 4.1), has been operating since 1953 but it has a data record that is largely incomplete, with many gaps. A SAO weather station (Anaktuvuk Pass) is located nearby but its operating status is currently unknown. "Old Man" is identified as a WBAN station in this report and is located in southeastern GAAR, about 30 km west of the James Dalton Highway.

Many of the stations we have identified that are outside of GAAR but within 60 km of the park unit are located along the east boundary of GAAR, along the James Dalton Highway (Figure 4.1). The remaining stations are generally located at small towns and/or landing strips to the south and west of GAAR. There are currently 11 active COOP stations outside of GAAR but within 60 km of the park unit (Table 4.3). The longest data record from these 11 stations is found at "Wiseman," which is 11 km south of GAAR (about 90 km north of Bettles) and has been active since 1918. Unfortunately, the data from this station have only been reliably complete from September 1948 to August 1952 and from August 1996 to present. The COOP station

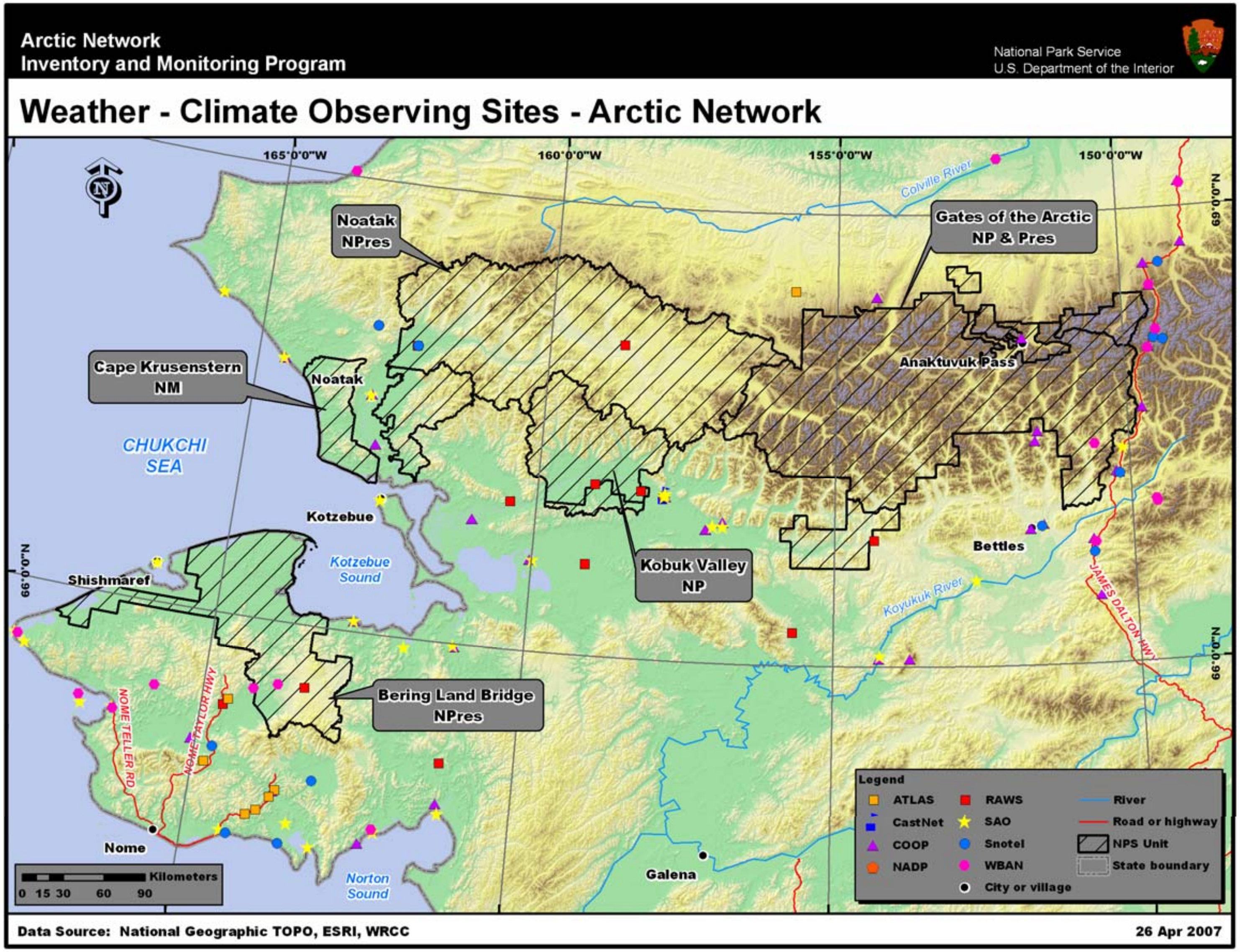


Figure 4.1. Station locations for the ARCN.

“Kobuk”, 50 km west of southwestern GAAR, has been active since 1953 but also has a very incomplete data record. There are more reliable long-term climate records that are available for GAAR. Observations have been available from COOP stations at Bettles Airport since the 1940s. “Bettles CAA” was active from 1944 to 1951 and the current COOP station, Bettles Airport, has been operating since 1951. These stations have provided a very complete data record with very few data gaps for the past 60 years.

Outside of GAAR, we have identified 19 weather stations within 60 km of the park unit boundaries that are currently providing near-real-time data (Table 4.3). One of these is an ATLAS station (Ivotuk) is located about 20 km from the northwest corner of GAAR (Figure 4.1). Two of these automated stations are RAWS stations, both of which are south of GAAR and have data records of 15-20 years in length. “Hogatza River” is located 50 km south of the southwestern tip of GAAR. Observations from this site are usually available during the months of May-August each year. Gaps in observations are common during the winter and early spring months. “Norutak Lake” is located just outside of GAAR, about 80 km northeast of the “Hogatza River” RAWS site. Its data record has been quite reliable, with no significant large gaps, since May 1998.

Twelve of the 19 automated weather stations identified within 60 km of the GAAR boundary are airport stations, either SAO or WBAN stations (Table 4.3). Most of these stations are south or east of GAAR (Figure 4.1). The longest available record from these sites is at the SAO station “Wiseman,” which has been active since 1918. The most complete records (i.e., fewest data gaps) are found at the SAO station “Bettles Airport,” which has been active since 1951. Most of the remaining SAO and WBAN stations identified here have data records starting in the 1970s or later.

In addition to the automated weather stations identified above, four SNOTEL sites are active within 60 km of the boundary of GAAR. With the exception of “Bettles Field,” these SNOTEL sites are all located along or within 10 km of the James Dalton Highway, on the east side of GAAR. Stations with the CASTNet and NADP networks took observations for a brief time in 2004-2005 at Ambler, about 60 km southwest of GAAR.

Two stations have been identified inside KOVA (Table 4.3), in the southeastern portions of the park unit. These are both RAWS stations, which provide near-real-time weather observations, but only one (Kavet Creek) is currently active. “Kavet Creek” is in the south-central part of KOVA (Figure 4.1) and its data record has had occasional large data gaps. The most recent gap in observations occurred from March through July of 2006. No long-term climate stations have been identified inside KOVA. Only two active climate stations, the COOP stations “Ambler West” and “Kobuk,” have been identified within 60 km of KOVA; both are located southeast of the park unit. The data records at each of these COOP sites are unreliable, with very little usable data.

Various networks provide automated weather observations around KOVA. Stations with the CASTNet and NADP networks took observations for a brief time in 2004-2005 at Ambler, about 20 km east of KOVA (Table 4.3; Figure 4.1). In addition to the RAWS station “Kavet Creek,” three RAWS stations provide automated data within 60 km of KOVA. “Noatak” is located 50 km north of KOVA, in NOAT. This site has had occasional gaps in data, particularly during the spring months. The most recent gaps occurred in April and May of 2003, and in January 2005. “Selawik” is 40 km south of KOVA. The data record at this station has been quite complete since 1993, with the exception of a gap in observations from January through April of 2000. “Kiana” is 30 km southwest of KOVA. This RAWS site only took summer observations (usually June-August) up until May 1991. Since May 1991, the data record at “Kiana” has been more complete throughout the year. Occasional data gaps are present, however. The most recent significant gap occurred between February and July of 2006.

Five SAO sites have been identified within 60 km of KOVA (Table 4.3). Four of these weather stations are currently active. Most of the SAO sites are located south and east of KOVA, with the exception of “Selawik Arpt.,” which is 40 km southwest of KOVA. Besides “Kobuk,” most of these SAO sites began operating in the 1970s or later.

We have identified three weather stations inside the boundaries of NOAT (Table 4.3). Two of these (Noatak and Kelly) are RAWS stations, both discussed previously, while the remaining station (Kelly Station) is associated with the SNOTEL network. The RAWS station “Noatak” is in east-central NOAT, while the other two stations are in westernmost NOAT (Figure 4.1).

Four COOP stations are currently active within 60 km of NOAT (Table 4.3). The longest and most reliable data record from these four climate stations is found at the Kotzebue airport, 40 km from the southwestern tip of NOAT. “Noatak,” is another COOP station with a long data record (1917-present) but the data at this station are of uncertain quality.

Automated data within 60 km of NOAT are currently provided by twelve weather stations affiliated with the ATLAS, RAWS, SAO, or SNOTEL networks (Table 4.3). These stations are all generally located south and west of NOAT (Figure 4.1). The most reliable weather data are obtained at the airport in Kotzebue.

5.0. Conclusions and Recommendations

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

5.1. Arctic Inventory and Monitoring Network

Weather station coverage is currently very sparse within the parks units of the ARCN, with only seven active weather stations being identified across the 7.7 million hectares (19 million acres) of ARCN park lands. Large tracts within ARCN park units have no station coverage whatsoever, including western GAAR, northern KOVA, far eastern and west-central portions of NOAT, all of CAKR, and northwestern (coastal) areas of BELA. No reliable long-term climate records are available within the ARCN park units. The only climate record longer than five decades within ARCN park units is “Anaktuvuk Auto,” but its data record is full of large gaps and is therefore largely useless for monitoring long-term climate changes in the ARCN. This lack of long-term climate information in the ARCN park units makes it virtually impossible, at the present time, to quantify with any certainty what climate changes are occurring in the ARCN and the impact these changes may have on other ARCN vital signs.

Fortunately, the ARCN network currently has plans to put in a series of new climate stations in the park units, focusing in particular on those areas that are now completely lacking weather observations. These climate stations are intended to monitor climate changes within ARCN park units and their impacts on ARCN ecosystems.

5.2. Spatial Variations in Mean Climate

Topography and coastal-interior gradients are major controlling factors on the park units within ARCN, 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 D 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 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, particularly inversions.

The desirability of credible and accurate long-term complete climate records, from any location, cannot be overstressed. This consideration should thus always have a high priority. However, because of spatial and elevation diversity in climate, monitoring that fills knowledge gaps, and in the bargain provides information on long-term temporal variability in short-distance relationships, will also likely prove of inestimable value. We cannot be sure that climate variability and climate change will affect all parts of a given park unit equally; it is in fact a safe bet that this is not the case, and that the spatial variations in temporal variability extend to small spatial scales (a few km or less in some cases), a consequence of extreme elevation diversity.

5.3. Climate Change Detection

The high latitudes are likely to be some of the first regions to experience the effects of climate change, most obviously through effects of temperature on boreal ecosystems (including release of carbon and methane), large masses of ice near critical temperatures, significant areas of permafrost now just below freezing, and behavior of fish and wildlife (Arctic Climate Impact Assessment 2004; Hinzman et al. 2005). Though there is not as much agreement about potential precipitation changes as about temperature changes, there is a general consensus among models that higher latitudes will probably become wetter. The ARCN park units are therefore in a unique position, and adequate monitoring of all potentially affected systems should be well under way before any such changes become widespread.

The position of treeline and the extent of permafrost in the ARCN would both be affected by changes in temperature. Permafrost changes in particular are a major concern, from ecological and practical standpoints, for the ARCN. Indeed, some changes in permafrost have already been noted in Alaska (e.g., Jorgenson et al. 2001; Hinzman et al. 2005). For these reasons, sites that are currently located near treeline and sites that either are experiencing or will likely soon experience rapid reductions in permafrost extent would constitute particularly attractive candidate locations to monitor climate changes. Such locations might be expected to show significant shifts in ecosystem characteristics over time in response to small changes in temperature. It is quite likely that the ranges of a number of plant and animal species are controlled by (species-specific) particular threshold temperatures. Thus, in anticipation of any of these changing, a broad sampling of climate regimes constitutes the best initial strategy.

Based on climate change considerations alone, a recommended strategy would entail station placement in the pure coastal zone, in the pure interior zone, and in transition zones such as treeline and areas currently experiencing rapid reduction in permafrost extent. The idea of transects spanning these transitions also has great merit.

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. Additional Factors

Appendix D discusses a number of factors that should be considered in making decisions about monitoring strategies. All are important, but just a few will be highlighted as they pertain to the ARCN.

The climate of northern Alaska is notoriously unkind to instrumentation. Cold is more tolerable (for instruments) than is precipitation, and liquid precipitation is much more instrument-friendly than frozen precipitation. The lack of AC power at many locations in the ARCN precludes heating for precipitation and anemometers. In this harsh region, without experienced and skilled technical personnel to oversee stations and communications, the odds of failure (missing, intermittent, or low quality data) are high. The cautions in Appendix D are even more applicable here than in the contiguous 48 states. Sites are remote, communications are difficult to maintain, human access is expensive and often affected by weather events, and visits to sites can seldom be impromptu. Animals of all sizes and inclinations can interact with stations in myriad ways. Sites can be buried in snow, automated equipment and electronics can be subjected to severe conditions at or beyond design criteria for wind, cold, snow, or precipitation. Station communications are often only one-way, preventing reprogramming or backfilling interrupted transmissions. In the end, it is almost always logistics, maintenance and other practical factors that determine the success of weather and climate monitoring activities.

At these higher latitudes, the sun is found at low angles even in the summer, so a good portion of the horizon needs to be free of terrain and vegetation blockage. Only a pyranometer in a fairly flat location without nearby obstructions will record the direct beam contribution of solar radiation through the year. Solar panels often fail to provide sufficient battery recharge at these latitudes, especially when cloudy and/or when covered with snow.

5.6. 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 ARCN 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 ARCN park units but also to climate-monitoring efforts for ARCN. 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

- Near-real-time weather station coverage in the ARCN is quite sparse. Only seven active stations have been identified in an area covering 7.7 million hectares (19 million acres).
- No useful long-term climate records exist currently within ARCN park units.
- ARCN plans to install a series of climate stations in ARCN park units, to monitor climate changes and their impacts on ARCN ecosystems.
- Transition zones (treeline, areas with rapid permafrost thaw, etc.) would be excellent candidate sites for installing new weather stations. Transects across these transitions zones could also be considered.

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Appendix A. Glossary

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Appendix B. Climate-monitoring principles

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

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

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

B.1.1. Effects on climate records of instrument changes, observing practices, observation locations, sampling rates, etc., must be known before such changes are implemented. This can be ascertained through a period where overlapping measurements from old and new observing systems are collected or sometimes by comparing the old and new observing systems with a reference standard. Site stability for in situ measurements, both in terms of physical location and changes in the nearby environment, also should be a key criterion in site selection. Thus, many synoptic network stations, which are primarily used in weather forecasting but also provide valuable climate data, and dedicated climate stations intended to be operational for extended periods must be subject to this policy.

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

B.1.3. Knowledge of instrument, station, and/or platform history is essential for interpreting and using the data. Changes in instrument sampling time, local environmental conditions for in situ measurements, and other factors pertinent to interpreting the observations and measurements should be recorded as a mandatory part in the observing routine and be archived with the original data.

B.1.4. In situ and other observations with a long, uninterrupted record should be maintained. Every effort should be applied to protect the data sets that have provided long-term, homogeneous observations. "Long-term" for space-based measurements is measured in decades, but for more conventional measurements, "long-term" may be a century or more. Each element in the observational system should develop a list of prioritized sites or observations based on their contribution to long-term climate monitoring.

B.1.5. Calibration, validation, and maintenance facilities are critical requirements for long-term climatic data sets. Homogeneity in the climate record must be assessed routinely, and corrective action must become part of the archived record.

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

B.1.7. Regions having insufficient data, variables and regions sensitive to change, and key measurements lacking adequate spatial and temporal resolution should be given the highest priority in designing and implementing new climate-observing systems.

B.1.8. Network designers and instrument engineers must receive long-term climate requirements at the outset of the network design process. This is particularly important because most observing systems have been designed for purposes other than long-term climate monitoring. Instruments must possess adequate accuracy with biases small enough to document climate variations and changes.

B.1.9. Much of the development of new observational capabilities and the evidence supporting the value of these observations stem from research-oriented needs or programs. A lack of stable, long-term commitment to these observations and lack of a clear transition plan from research to operations are two frequent limitations in the development of adequate, long-term monitoring capabilities. Difficulties in securing a long-term commitment must be overcome in order to improve the climate-observing system in a timely manner with minimal interruptions.

B.1.10. Data management systems that facilitate access, use, and interpretation are essential. Freedom of access, low cost, mechanisms that facilitate use (directories, catalogs, browse capabilities, availability of metadata on station histories, algorithm accessibility and documentation, etc.) and quality control should guide data management. International cooperation is critical for successful management of data used to monitor long-term climate change and variability.

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

B.2.1. Assess the impact of new climate-observing systems or changes to existing systems before they are implemented.

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

B.2.2. Require a suitable period where measurement from new and old climate-observing systems will overlap.

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

B.2.3. Treat calibration, validation, algorithm-change, and data-homogeneity assessments with the same care as the data.

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

B.2.4. Verify capability for routinely assessing the quality and homogeneity of the data including high-resolution data for extreme events.

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

B.2.5. Integrate assessments like those conducted by the International Panel on Climate Change into global climate-observing priorities.

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

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

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

B.2.7. Place high priority on increasing observations in regions lacking sufficient data and in regions sensitive to change and variability.

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

B.2.8. Provide network operators, designers, and instrument engineers with long-term requirements at the outset of the design and implementation phases for new systems.

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

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

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

B.2.10. Focus on data-management systems that facilitate access, use, and interpretation of weather data and metadata.

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

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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. General design considerations for weather/ climate-monitoring programs

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

D.1. Introduction

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

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

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

D.1.1. Network Purpose

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

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

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

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

D.1.2. Robustness

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

D.1.3. Weather versus Climate

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

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

D.1.4. Physical Setting

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

D.1.5. Measurement Intervals

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

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

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

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

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

D.1.6. Mixed Time Scales

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

D.1.7. Elements

For manual measurements, the typical elements recorded included temperature extremes, precipitation, and snowfall/snow depth. Automated measurements typically include temperature, precipitation, humidity, wind speed and direction, and solar radiation. An exception to this exists in very windy locations where precipitation is difficult to measure accurately. Automated measurements of snow are improving, but manual measurements are still preferable, as long as shielding is present. Automated measurement of frozen precipitation presents numerous challenges that have not been resolved fully, and the best gauges are quite expensive ($3–8K).

Soil temperatures also are included sometimes. Soil moisture is extremely useful, but measurements are not made at many sites. In addition, care must be taken in the installation and maintenance of instruments used in measuring soil moisture. Soil properties vary tremendously in short distances as well, and it is often very difficult ("impossible") to accurately document these variations (without digging up all the soil!). In cooler climates, ultrasonic sensors that detect snow depth are becoming commonplace.

D.1.8. Wind Standards

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

D.1.9. Wind Nomenclature

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

D.1.10. Frozen Precipitation

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

In climates that receive frozen precipitation, a decision must be made whether or not to try to record such events accurately. This usually means that the precipitation must be turned into liquid either by falling into an antifreeze fluid solution that is then weighed or by heating the precipitation enough to melt and fall through a measuring mechanism such as a nearly-balanced tipping bucket. Accurate measurements from the first approach require expensive gauges; tipping buckets can achieve this resolution readily but are more apt to lose some or all precipitation. Improvements have been made to the heating mechanism on the NWS tipping-bucket gauge used for the ASOS to correct its numerous deficiencies making it less problematic; however, this gauge is not inexpensive. A heat supply needed to melt frozen precipitation usually requires more energy than renewable energy (solar panels or wind recharging) can provide thus AC power is needed. 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.

D.1.11. Save or Lose

A second consideration with precipitation is determining if the measurement should be saved (as in weighing systems) or lost (as in tipping-bucket systems). With tipping buckets, after the water has passed through the tipping mechanism, it usually just drops to the ground. Thus, there is no checksum to ensure that the sum of all the tips adds up to what has been saved in a reservoir at some location. By contrast, the weighing gauges continually accumulate until the reservoir is emptied, the reported value is the total reservoir content (for example, the height of the liquid column in a tube), and the incremental precipitation is the difference in depth between two known times. These weighing gauges do not always have the same fine resolution. Some gauges only record to the nearest centimeter, which is usually acceptable for hydrology but not necessarily for other needs. (For reference, a millimeter of precipitation can get a person in street clothes quite wet.) 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.

D.1.12. Time

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

D.1.13. Automated versus Manual

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

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

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

D.1.14. Manual Conventions

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

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

D.2. Representativeness

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

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

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

Thus, the representativeness of a site can refer either to the basic climatic averages for a given duration (or time window within the annual cycle) or to the extent that the site co-varies in time with respect to all surrounding locations. One site can be representative of another in the first sense but not the second, or vice versa, or neither, or both—all combinations are possible. If two sites are perfectly correlated then, in a sense, they are “redundant.” However, redundancy has value because all sites will experience missing data especially with automated equipment in rugged environments and harsh climates where outages and other problems nearly can be guaranteed. In many cases, those outages are caused by the weather, particularly by unusual weather and the very conditions we most wish to know about. Methods for filling in those values will require proxy information from this or other nearby networks. Thus, redundancy is a virtue rather than a vice.

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

D.2.1. Temporal Behavior

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

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

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

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

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

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

D.2.2. Spatial Behavior

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

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

D.2.3. Climate-Change Detection

Although general purpose climate stations should be situated to address all aspects of climate variability, it is desirable that they also be in locations that are more sensitive to climate change from natural or anthropogenic influences should it begin to occur. The question here is how well we know such sensitivities. The 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 gasses.

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

D.2.4. Element-Specific Differences

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

D.2.5. Logistics and Practical Factors

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

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

D.2.6. Personnel Factors

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

D.3. Site Selection

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

D.3.1. Equipment and Exposure Factors

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

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

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

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

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

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

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

D.3.2. Element-Specific Factors

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

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

D.3.2.3. Precipitation (frozen): Calm locations or shielding are a must. Undercatch for rain is only about 5 percent, but with winds of only 2–4 m/s, gauges may catch only 30–70 percent of the actual snow falling depending on density of the flakes. To catch 100 percent of the snow, the standard configuration for shielding is employed by the CRN (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 coast, much snow is heavy and falls more vertically. In colder locations or storms, light flakes frequently will fly in and then out of the gauge. Clearings in forests are usually excellent sites. Snow blowing from trees that are too close can augment actual precipitation totals. Artificial shielding (vanes, etc.) placed around gauges in snowy locales always should be used if accurate totals are desired. Moving parts tend to freeze up. Capping of gauges during heavy snowfall events is a common occurrence. When the cap becomes pointed, snow falls off to the ground and is not recorded. Caps and plugs often will not fall into the tube until hours, days, or even weeks have passed, typically during an extended period of freezing temperature or above or when sunlight finally occurs. Liquid-based measurements (e.g., SNOTEL “rocket” gauges) do not have the resolution (usually 0.3 cm [0.1 in.] rather than 0.03 cm [0.01 in.]) that tipping bucket and other gauges have but are known to be reasonably accurate in very snowy climates. Light snowfall events might not be recorded until enough of them add up to the next reporting increment. More expensive gauges like Geonors can be considered and could do quite well in snowy settings; however, they need to be emptied every 40 cm (15 in.) or so (capacity of 51 cm [20 in.]) until the new 91-cm (36-in.) capacity gauge is offered for sale. Recently, the NWS has been trying out the new (and very expensive) Ott all-weather gauge. Riming can be an issue in windy foggy environments below freezing. Rime, dew, and other forms of atmospheric condensation are not real precipitation, since they are caused by the gauge.

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

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

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

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

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

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

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

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

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

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

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

D.3.3. Long-Term Comparability and Consistency

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

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

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

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

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

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

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Appendix E. Master metadata field list

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

Field Name	Field Type	Field Description
updated_by	char(8)	Person who last updated a record.
var_major_id	int2	Defines major climate variable.
var_minor_id	int2	Defines data source within a var_major_id.
zipcode	char(5)	Zipcode where a latitude/longitude point resides.
nps_netcode	char(4)	Network four-character identifier.
nps_netname	varchar(128)	Displayed English name for a network.
parkcode	char(4)	Park four-character identifier.
parkname	varchar(128)	Displayed English name for a park/
im_network	char(4)	NPS I&M network where park belongs (a net code)/
station_id	varchar(16)	Station identifier.
station_id_type	varchar(16)	Type of station identifier.
network.subnetwork.id	varchar(16)	Identifier of a sub-network in associated network.
subnetwork_key	int2	Foreign key defining sub-network for a station.
subnetwork_name	varchar(30)	English name for a sub-network.
slope	integer	Terrain slope at the location.
aspect	integer	Terrain aspect at the station.
gps	char(1)	Indicator of latitude/longitude recorded via GPS (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 F. Electronic supplements

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

Appendix G. Descriptions of weather/climate monitoring networks

G.1. Arctic Transitions in the Land-Atmosphere System (ATLAS) Network

- Purpose of network: provide meteorological measurements in arctic environments, particularly transition areas.
- Primary management agency: University of Alaska Fairbanks Water and Environmental Research Center.
- Data website: http://www.uaf.edu/water/projects/atlas/metdata/atlasmetsitemap.htm.
- Measured weather/climate elements:
  - Air temperature.
  - Precipitation.
  - Relative humidity.
  - Wind speed.
  - Wind direction.
  - Solar radiation.
  - Barometric pressure.
  - Snow depth.
- Sampling frequency: hourly.
- Reporting frequency: hourly.
- Estimated station cost: unknown.
- Network strengths:
  - Automated data.
- Network weaknesses:
  - Station coverage is limited.
  - Poor maintenance.
  - Uncertain funding.

The University of Alaska Fairbanks Water and Environmental Research Center has operated the ATLAS network, which consists of several meteorological stations located on the Seward Peninsula in western Alaska. The parameters measured at each site can include hourly observations of wind speed, wind direction, air temperature, relative humidity, net radiation, up/downward long/shortwave radiation, barometric pressure, precipitation, and snow depth. Unfortunately, funding is no longer available for this network and these stations are not actively maintained anymore.

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

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.

G.3. NWS Cooperative Observer Program (COOP)

- Purpose of network:
    - Provide observational, meteorological data required to define U.S. climate and help measure long-term climate changes.
    - Provide observational, meteorological data in near real-time to support forecasting and warning mechanisms and other public service programs of the NWS.
- Primary management agency: NOAA (NWS).
- Data website: data are available from the NCDC (http://www.ncdc.noaa.gov), RCCs (e.g., WRCC, http://www.wrcc.dri.edu), and state climate offices.
- Measured weather/climate elements:
    - Maximum, minimum, and observation-time temperature.
    - Precipitation, snowfall, snow depth.
    - Pan evaporation (some stations).
- Sampling frequency: daily.
- Reporting frequency: daily or monthly (station-dependent).
- Estimated station cost: $2000 with maintenance costs of $500–900/year.
- Network strengths:
    - Decade–century records at most sites.
    - Widespread national coverage (thousands of stations).
    - Excellent data quality when well maintained.
    - Relatively inexpensive; highly cost effective.
    - Manual measurements; not automated.
- Network weaknesses:
    - Uneven exposures; many are not well-maintained.

- Dependence on schedules for volunteer observers.
- Slow entry of data from many stations into national archives.
- Data subject to observational methodology; not always documented.
- Manual measurements; not automated and not hourly.

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

G.4. National Atmospheric Deposition Program (NADP)

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

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

G.5. Remote Automated Weather Station (RAWS) Network

- Purpose of network: provide near-real-time (hourly or near hourly) measurements of meteorological variables for use in fire weather forecasts and climatology. Data from RAWS also are used for natural resource management, flood forecasting, natural hazard management, and air-quality monitoring.
- Primary management agency: WRCC, National Interagency Fire Center.
- Data website: http://www.raws.dri.edu/index.html.
- Measured weather/climate elements:
  - Air temperature.

    - Precipitation.
    - Relative humidity.
    - Wind speed.
    - Wind direction.
    - Wind gust.
    - Gust direction.
    - Solar radiation.
    - Soil moisture and temperature.
- Sampling frequency: 1 or 10 minutes, element-dependent.
- Reporting frequency: generally hourly. Some stations report every 15 or 30 minutes.
- Estimated station cost: $12000 with satellite telemetry ($8000 without satellite telemetry); maintenance costs are around $2000/year.
- Network strengths:
    - Metadata records are usually complete.
    - Sites are located in remote areas.
    - Sites are generally well-maintained.
    - Entire period of record available on-line.
- Network weaknesses:
    - RAWS network is focused largely on fire management needs (formerly focused only on fire needs).
    - Frozen precipitation is not measured reliably.
    - Station operation is not always continuous.
    - Data transmission is completed via one-way telemetry. Data are therefore recoverable either in real-time or not at all.

The RAWS network is used by many land-management agencies, such as the BLM, NPS, Fish and Wildlife Service, Bureau of Indian Affairs, Forest Service, and other agencies. The RAWS network was one of the first automated weather station networks to be installed in the U.S. Most gauges do not have heaters, so hydrologic measurements are of little value when temperatures dip below freezing or reach freezing after frozen precipitation events. There are approximately 1100 real-time sites in this network and about 1800 historic sites (some are decommissioned or moved). The sites can transmit data all winter but may be in deep snow in some locations. The WRCC is the archive for this network and receives station data and metadata through a special connection to the National Interagency Fire Center in Boise, Idaho.

G.6. NWS/FAA Surface Airways Observation (SAO) Network

- Purpose of network: provide near-real-time (hourly or near hourly) measurements of meteorological variables and are used both for airport operations and weather forecasting.
- Primary management agency: NOAA, FAA.
- Data website: data are available from state climate offices, RCCs (e.g., WRCC, http://www.wrcc.dri.edu), and NCDC (http://www.ncdc.noaa.gov).
- Measured weather/climate elements:
    - Air temperature.
    - Dewpoint and/or relative humidity.
    - Wind speed.

  - Wind direction.
  - Wind gust.
  - Gust direction.
  - Barometric pressure.
  - Precipitation (not at many FAA sites).
  - Sky cover.
  - Ceiling (cloud height).
  - Visibility.
- Sampling frequency: element-dependent.
- Reporting frequency: element-dependent.
- Estimated station cost: $100000–$200000, with maintenance costs approximately $10000/year.
- Network strengths:
  - Records generally extend over several decades.
  - Consistent maintenance and station operations.
  - Data record is reasonably complete and usually high quality.
  - Hourly or sub-hourly data.
- Network weaknesses:
  - Nearly all sites are located at airports.
  - Data quality can be related to size of airport—smaller airports tend to have poorer datasets.
  - Influences from urbanization and other land-use changes.

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

G.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 U.S.
- Primary management agency: NRCS.
- Data website: http://www.wcc.nrcs.usda.gov/snow/.
- Measured weather/climate elements:
  - Air temperature.
  - Precipitation.
  - Snow water content.
  - Snow depth.
  - Relative humidity (enhanced sites only).
  - Wind speed (enhanced sites only).
  - Wind direction (enhanced sites only).
  - Solar radiation (enhanced sites only).
  - Soil moisture and temperature (enhanced sites only).
- Sampling frequency: 1-minute temperature; 1-hour precipitation, snow water content, and

snow depth. Less than one minute for relative humidity, wind speed and direction, solar radiation, and soil moisture and temperature (all at enhanced site configurations only).

- Reporting frequency: reporting intervals are user-selectable. Commonly used intervals are every one, two, three, or six hours.
- Estimated station cost: $20000 with maintenance costs approximately $2000/year.
- Network strengths:
  - Sites are located in high-altitude areas that typically do not have other weather or climate stations.
  - Data are of high quality and are largely complete.
  - Very reliable automated system.
- Network weaknesses:
  - Historically limited number of elements.
  - Remote so data gaps can be long.
  - Metadata sparse and not high quality; site histories are lacking.
  - Measurement and reporting frequencies vary.
  - Many hundreds of mountain ranges still not sampled.
  - Earliest stations were installed in the late 1970s; temperatures have only been recorded since the 1980s.

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

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

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