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Weather and Climate Inventory
National Park Service
Great Lakes Network

Natural Resource Technical Report NPS/GLKN/NRTR—2007/038

ON THE COVER
Pictured Rocks National Lakeshore

Weather and Climate Inventory
National Park Service
Great Lakes Network

Natural Resource Technical Report NPS/GLKN/NRTR—2007/038
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Acronyms

AASC	American Association of State Climatologists
ACIS	Applied Climate Information System
APIS	Apostle Islands National Lakeshore
ASOS	Automated Surface Observing System
AWOS	Automated Weather Observing System
BLM	Bureau of Land Management
CANADA	Canadian weather/climate stations
CASTNet	Clean Air Status and Trends Network
COOP	Cooperative Observer Program
CRN	Climate Reference Network
CWOP	Citizen Weather Observer Program
DFIR	Double-Fence Intercomparison Reference
DST	daylight savings time
ENSO	El Niño Southern Oscillation
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FIPS	Federal Information Processing Standards
GLERL	Great Lakes Environmental Research Laboratory
GLKN	Great Lakes Inventory and Monitoring Network
GMT	Greenwich Mean Time
GOES	Geostationary Operational Environmental Satellite
GPMP	NPS Gaseous Pollutant Monitoring Program
GPS	Global Positioning System
GPS-MET	NOAA ground-based GPS meteorology
GRPO	Grand Portage National Monument
IADN	Integrated Atmospheric Deposition Network
I&M	NPS Inventory and Monitoring Program
INDU	Indiana Dunes National Lakeshore
ISRO	Isle Royale National Park
LEO	Low Earth Orbit
LST	local standard time
MDN	Mercury Deposition Network
MISS	Mississippi National River and Recreation Area
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
NPS	National Park Service
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
PIRO	Pictured Rocks National Lakeshore
POMS	Portable Ozone Monitoring System

PRISM	Parameter Regression on Independent Slopes Model
RAWS	Remote Automated Weather Station network
RCC	regional climate center
SACN	Saint Croix National Scenic Riverway
SAO	Surface Airways Observation network
SLBE	Sleeping Bear Dunes National Lakeshore
SNOTEL	Snowfall Telemetry network
SOD	Summary Of the Day
Surfrad	Surface Radiation Budget network
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
UTC	Coordinated Universal Time
WBAN	Weather Bureau Army Navy
WIDOT	Wisconsin Department of Transportation
VOYA	Voyageurs National Park
WMO	World Meteorological Organization
WRCC	Western Regional Climate Center
WX4U	Weather For You network

Executive Summary

Climate is a dominant factor driving the physical and ecologic processes in the Great Lakes Inventory and Monitoring Network (GLKN). The Great Lakes moderate temperatures, enhance precipitation, and induce slight seasonal shifts on islands and immediate lakeshore areas. Cloudiness and precipitation are more common to the lee (south and east sides) of the Great Lakes. Lake-effect snow events are an important source of precipitation around the GLKN, especially on the leeward sides of the Great Lakes. Recent increases in such events may be connected to larger-scale climate changes. If predictions of further changes hold true, GLKN habitats could change dramatically, shifting the distributions of many plants and animals. Studies of past climate changes in the region provide clues to the nature of future responses.

This project was initiated to inventory past and present climate monitoring efforts in the GLKN. Climate is one of the 12 basic inventories to be completed for all National Park Service (NPS) Inventory and Monitoring Program (I&M) networks. In this report, we provide the following information:

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

Despite the moderating influence of the Great Lakes, seasonal climate variations in the GLKN region can be great, especially away from the Great Lakes. Mean annual precipitation ranges from under 700 mm in western portions of Voyageurs National Park (VOYA) to almost 1000 mm at Indiana Dunes National Lakeshore (INDU). Annual snowfall ranges from 70 cm in southernmost GLKN park units to over 400 cm in Isle Royale National Park (ISRO). Precipitation generally peaks in summer or early fall. Mean annual temperatures range from under 2°C in VOYA, up to 9°C in INDU. January minimum temperatures regularly get below -20°C in VOYA and Grand Portage National Monument (GRPO). Winter temperatures can occasionally get below -40°C at VOYA. July maximum temperatures commonly approach 30°C in the southern GLKN park units. The El Niño-Southern Oscillation (ENSO) and the North Atlantic Oscillation – Arctic Oscillation (NAO-AO) both contribute to interannual climate variations in the GLKN. El Niño conditions (warm ENSO phases) are associated with warmer and drier than normal conditions. Warmer winter temperatures also tend to occur when the NAO-AO index is positive.

Through a search of national databases and inquiries to NPS staff, we have identified 43 weather and climate stations within GLKN park units. The most stations within park boundaries are in ISRO (13). Most of the weather and climate stations identified for GLKN park units had metadata and data records that are satisfactory in quality.

Pictured Rocks National Lakeshore (PIRO) had no weather or climate stations inside their boundaries. Additional precipitation stations within PIRO would greatly benefit climate monitoring efforts. PIRO is located in an area with high spatial precipitation variability associated with lake-effect events and sharp lake-interior climate gradients. Weather and climate station coverage is present but severely deficient (particularly for sampling precipitation patterns) in a few other GLKN park units. There are some known gaps in the existing spatial coverage of weather stations at ISRO and the Network has funded upgrades to two RAWS (Remote Automated Weather Station) sites at ISRO. Any important climate records for these park units should also be continued.

Long-term climate stations have recently ceased operating near some GLKN park units, which unfortunately hurts climate monitoring efforts across the GLKN. These losses are particularly noticeable for Apostle Islands National Lakeshore (APIS) and INDU. Some long-term records we identified may actually come from multiple stations. For example, near Sleeping Bear Dunes National Lakeshore (SLBE), two Cooperative Observer Program (COOP) stations in Traverse City, Michigan, may actually be the same station. The National Climatic Data Center (NCDC) can be contacted to verify the status of these two station records. In the meantime, caution must be exercised when utilizing these records.

The GLKN park units in central Minnesota and Wisconsin have much denser weather and climate station coverage compared to their northern counterparts. The Minneapolis-St. Paul metropolitan area provides many sources of weather and climate data along the Mississippi National River and Recreation Area (MISS) and southern SACN (Saint Croix National Scenic Riverway). Station coverage is less dense around northern SACN. Consideration could be given to the idea of installing new RAWS stations in this area, since the RAWS network already has a substantial presence in northern Wisconsin. Both MISS and SACN protect riverways; therefore, NPS may want to consider using existing stations and any new stations to monitor temperature and precipitation gradients along the riverways.

Water plays a key role in maintaining the ecosystems of the GLKN. Precipitation influences strongly the availability of water for GKLN ecosystems and has a high degree of spatial variability across the GLKN. However, due to limited weather station coverage in many park units, local precipitation patterns are often severely undersampled. It is therefore critical that NPS and the GLKN consider ways in which to increase the coverage of precipitation measurements throughout GLKN units along the Great Lakes. Partnerships could be formed with the Great Lakes Environmental Research Laboratory (GLERL) and perhaps even the Natural Resources Conservation Service (NRCS) Snowfall Telemetry (SNOTEL) network to install near-real-time weather stations that can better sample precipitation characteristics in the region. Another reason that winter precipitation is severely undersampled in the GLKN park units is that many of the weather and climate stations we identified only take observations in the summer. We identified both COOP and RAWS stations that fall in this category. This is particularly common in northernmost Minnesota (e.g., VOYA) and in upper Michigan (e.g., ISRO). It has been encouraging to see that some stations, particularly RAWS stations, have recently shifted to year-round observations. Hopefully other COOP and RAWS stations will follow this example and also become year-round stations.

Acknowledgements

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1.0. Introduction

Weather and climate are key drivers in ecosystem structure and function. Global- and regional-scale climate variations will have a tremendous impact on natural systems (Chapin et al. 1996; Schlesinger 1997; Jacobson et al. 2000; Bonan 2002). Long-term patterns in temperature and precipitation provide first-order constraints on potential ecosystem structure and function. Secondary constraints are realized from the intensity and duration of individual weather events and, additionally, from seasonality and inter-annual climate variability. These constraints influence the fundamental properties of ecologic systems, such as soil–water relationships, plant–soil processes, and nutrient cycling, as well as disturbance rates and intensity. These properties, in turn, influence the life-history strategies supported by a climatic regime (Neilson 1987; Rodriguez-Iturbe 2000; Route and Elias 2007).

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). Climate was ranked as the eleventh highest priority Vital Sign in the Great Lakes Network, or GLKN (Route and Elias 2007). As primary environmental drivers for the other vital signs, weather and climate patterns present various practical and management consequences and implications for the NPS (Oakley et al. 2003). Most park units observe weather and climate elements as part of their overall mission. The lands under NPS stewardship provide many excellent locations for monitoring climatic conditions.

It is essential that park units within the GLKN have an effective climate-monitoring system in place to track climate changes and to aid in management decisions relating to these changes. The purpose of this report is to determine the current status of weather and climate monitoring within the GLKN (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 GLKN park units.
- Inventory of locations for all weather stations in and near GLKN park units that are relevant to the NPS I&M networks.
- Results of metadata inventory for each station, including weather-monitoring network affiliations, types of recorded measurements, and information about actual measurements (length of record, etc.).
- Initial evaluation of the adequacy of coverage for existing weather stations and recommendations for improvements in monitoring weather and climate.

The primary objectives for climate- and weather-monitoring activities in GLKN are (Route and Elias 2007):

A. Measure precipitation and air temperature in all GLKN parks and surrounding areas.
B. Measure secondary climatic elements including wind speed/direction, relative humidity, snow depth, soil temperatures and incoming solar radiation in the GLKN parks.

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

Table 1.1. Park units in the Great Lakes Network.

Acronym	Name
APIS	Apostle Islands National Lakeshore
GRPO	Grand Portage National Monument
INDU	Indiana Dunes National Lakeshore
ISRO	Isle Royale National Park
MISS	Mississippi National River and Recreation Area
PIRO	Pictured Rocks National Lakeshore
SACN	Saint Croix National Scenic Riverway
SLBE	Sleeping Bear Dunes National Lakeshore
VOYA	Voyageurs National Park

1.1.1. Weather/Climate Station Networks

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

1.1.2. NPS I&M Networks

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

1.2. Weather versus Climate Definitions

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

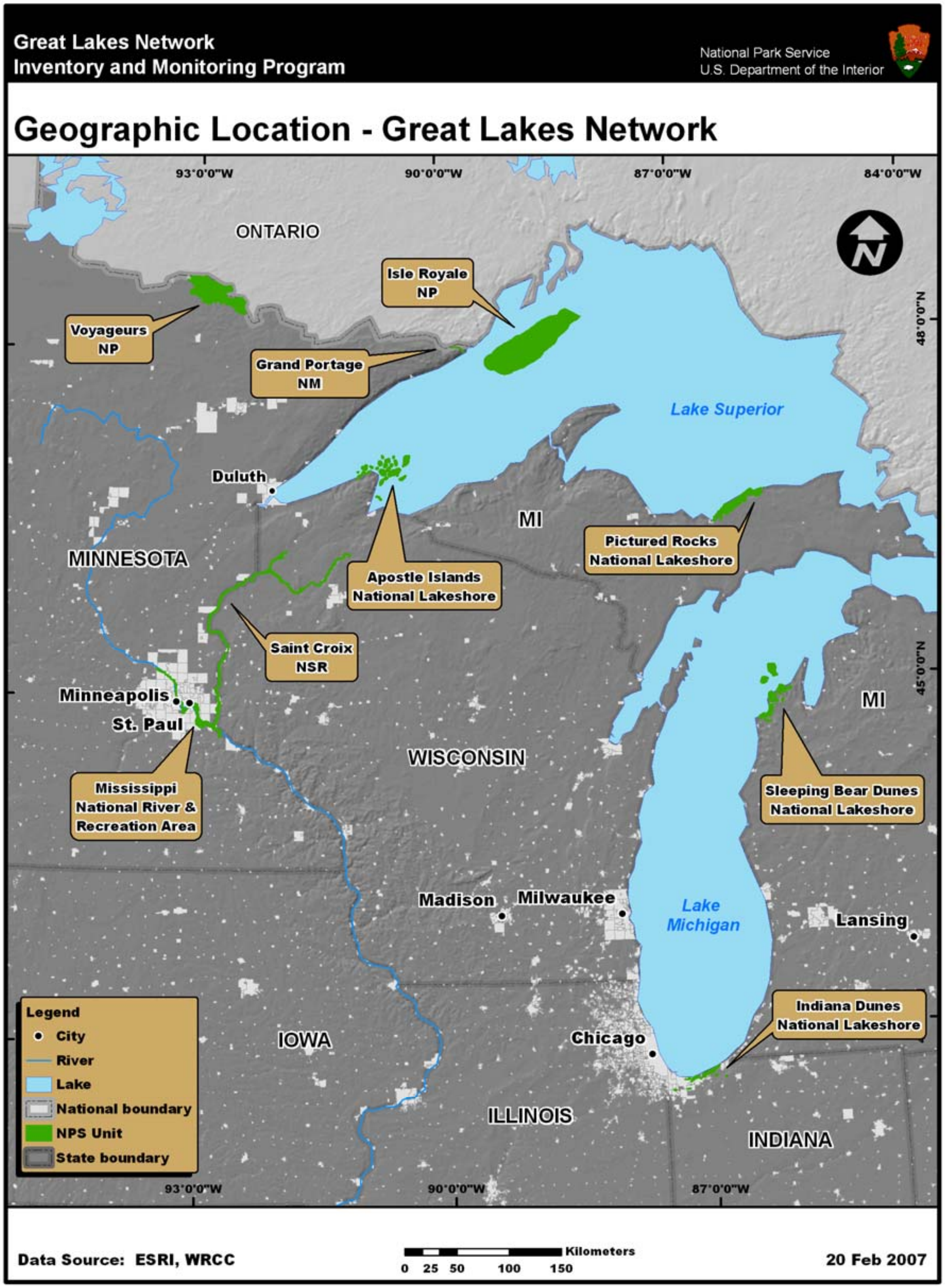


Figure 1.1. Map of the Great Lakes Network.

Some climate networks can be considered hybrids of weather and climate networks. These hybrid climate networks can supply information on a short-term "weather" time scale and a longer-term "climate" time scale.

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

1.3. Purpose of Measurements

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

- What is the purpose of weather and climate measurements?

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

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

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

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

1.4. Design of Climate-Monitoring Programs

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

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

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

1.4.1. Need for Consistency

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

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

1.4.2. Metadata

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

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

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

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

1.4.3. Maintenance

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

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

1.4.4. Automated versus Manual Stations

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

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

1.4.5. Communications

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

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

1.4.6. Quality Assurance and Quality Control

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

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

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

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

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

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

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

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

2.0. Climate Background

Climate is a primary driver of almost all physical and ecological processes in the GLKN, and its effects are especially pronounced near large waterbodies such as the Great Lakes (Moran and Hopkins 2002). Conceptual ecosystem models for the GLKN have also emphasized the influence of climate on other Vital Signs in the region (Gucciardo et al. 2004). An understanding of both current climate patterns and climate history in the GLKN is important to understanding and interpreting change and patterns in ecosystem attributes (Route and Elias 2007). It is essential that the GLKN park units have an effective climate monitoring system to track climate changes and to aid in management decisions relating to these changes. In order to do this, it is essential to understand the climate characteristics of the GLKN, as discussed in this chapter.

2.1. Climate and the GLKN Environment

The GLKN region has a primarily mid-continental climate with seasonal temperatures that can vary widely between summer highs and winter lows, especially away from the Great Lakes. These large bodies of water moderate temperatures (cooler summers, warmer winters), produce greater precipitation, and induce longer spring and autumn seasons on islands and immediate lakeshore areas compared to locations further removed from the Great Lakes (Eichenlaub 1979; Hjelmfelt 1990; Norton and Bolsenga 1993; Scott and Huff 1996; Kristovich and Spinar 2005; Route and Elias 2007). Areas along and to the lee of the Great Lakes typically experience much more cloudiness compared to upwind locations, which are much drier (Kristovich and Laird 1998).

Lake-effect snowfall near the Great Lakes causes wide variation in snowfall within and among parks in the GLKN (Norton and Bolsenga 1993; Ellis and Johnson 2004; Route and Elias 2007). The highest snowfall totals are found at park units on the south and east shores of the Great Lakes. In lake-effect snow belts, the ground becomes insulated enough with snow cover during the winter months so that the soils rarely freeze (Isard and Schaetzl 1995). At adjacent areas with less snow cover, soils are more likely to freeze during the winter months. This spatial variation in snow coverage (and resulting soil temperatures) influences strongly the distribution of plant communities in GLKN park units. In addition to driving lake-effect snow events, the Great Lakes can also provide sufficient moisture to enhance precipitation totals (rain in summer, snow in winter) associated with larger-scale mid-latitude storm systems (Hjelmfelt 1990).

Some studies indicate that the snowfall associated with lake-effect events has increased substantially in the past several decades (Kunkel et al. 2002; Burnett et al 2003; Ellis and Johnson 2004). These snowfall increases may be in response to other trends associated with long-term climate changes (Davis et al. 2000). For instance, studies of ice cover in the region (e.g., Gao and Stefan 2004) have found that ice cover duration and extent have both decreased in the region’s lakes. This includes the Great Lakes, resulting in a longer period during the winter months where energy and moisture exchange needed for lake-effect events can take place. Decreased ice cover will also likely increase precipitation, especially on the leeward sides of the Great Lakes, and cause lake levels to drop due to more evaporation. Increased evaporation has been noted for both Lake Superior and Lake Michigan in recent years. Only a portion of evaporated lake water is returned to the system via lake effect events.

Global climate changes will likely have long-term ecological consequences for the region (Post and Stenseth 1999; Davis et al. 2000; Route and Elias 2007). Evidence from ecological indicators of climate, such as glacial ice, lake sediments, tree rings, and fossil corals, shows that the earth's climate has varied significantly over timescales from months to millennia. Most studies of global climate patterns conclude that the global climate changed rapidly during the twentieth century and that the speed of these changes exceeds that of most previous fluctuations (Mann et al. 1999; NAST 2001; USGCRP 2003). Climate models suggest that by the end of the 21st century, temperatures around the Great Lakes could warm by 3 to 7°C in winter and by 3 to 11°C in summer (NAST 2001; Kling et al. 2003). Kling et al. (2003) offer evidence that in the Great Lakes region, winters are already becoming shorter, average annual temperatures are getting warmer, duration of lake ice cover is decreasing, and heavy rain events are becoming more common. If temperatures warm greatly as a result of future climate changes, lake-effect snow events could even be replaced largely by lake-effect rain events (Kunkel et al. 2002). If predictions of further changes hold true, groundwater, surface water, wetlands, and other habitats could change dramatically and cause shifts in the distributions of many plants and animals (Post and Stenseth 1999; Sousanis and Bisanz 2000). Paleoclimatic evidence in the GLKN region shows similar shifts in response to past climate changes (Davis et al. 2000), hinting at what the characteristics of future shifts in plant and animal distributions in response to climate change will look like. Plant and animal communities dependent on current spatiotemporal moisture patterns, especially caused by lake-effect snowfall, may be drastically altered (Davis et al. 2000). The many different potential impacts of climate change have significant management implications for GLKN park units. It is imperative that the GLKN has climate monitoring systems in place to detect and characterize regional climate change. This would then allow the GLKN to test for associations between climate data and other Vital Signs (Route and Elias 2007).

2.2. Parameter Regression on Independent Slopes Model (PRISM)

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

2.3. Spatial Variability

Precipitation characteristics of the GLKN region are influenced strongly by the Great Lakes themselves. Mean annual precipitation in the GLKN (Figure 2.1) generally increases to the south

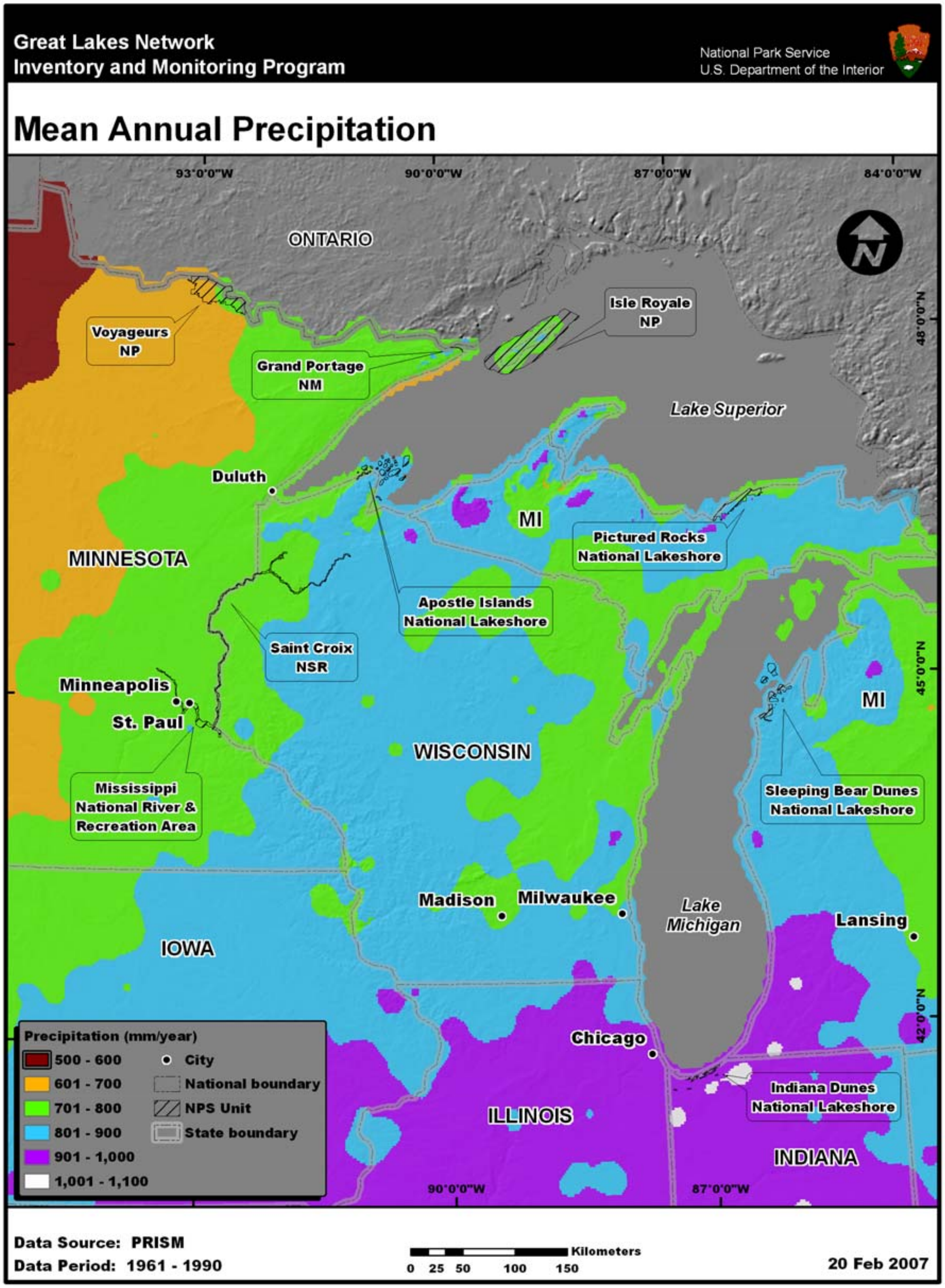


Figure 2.1. Mean annual precipitation, 1961-1990, for the GLKN.

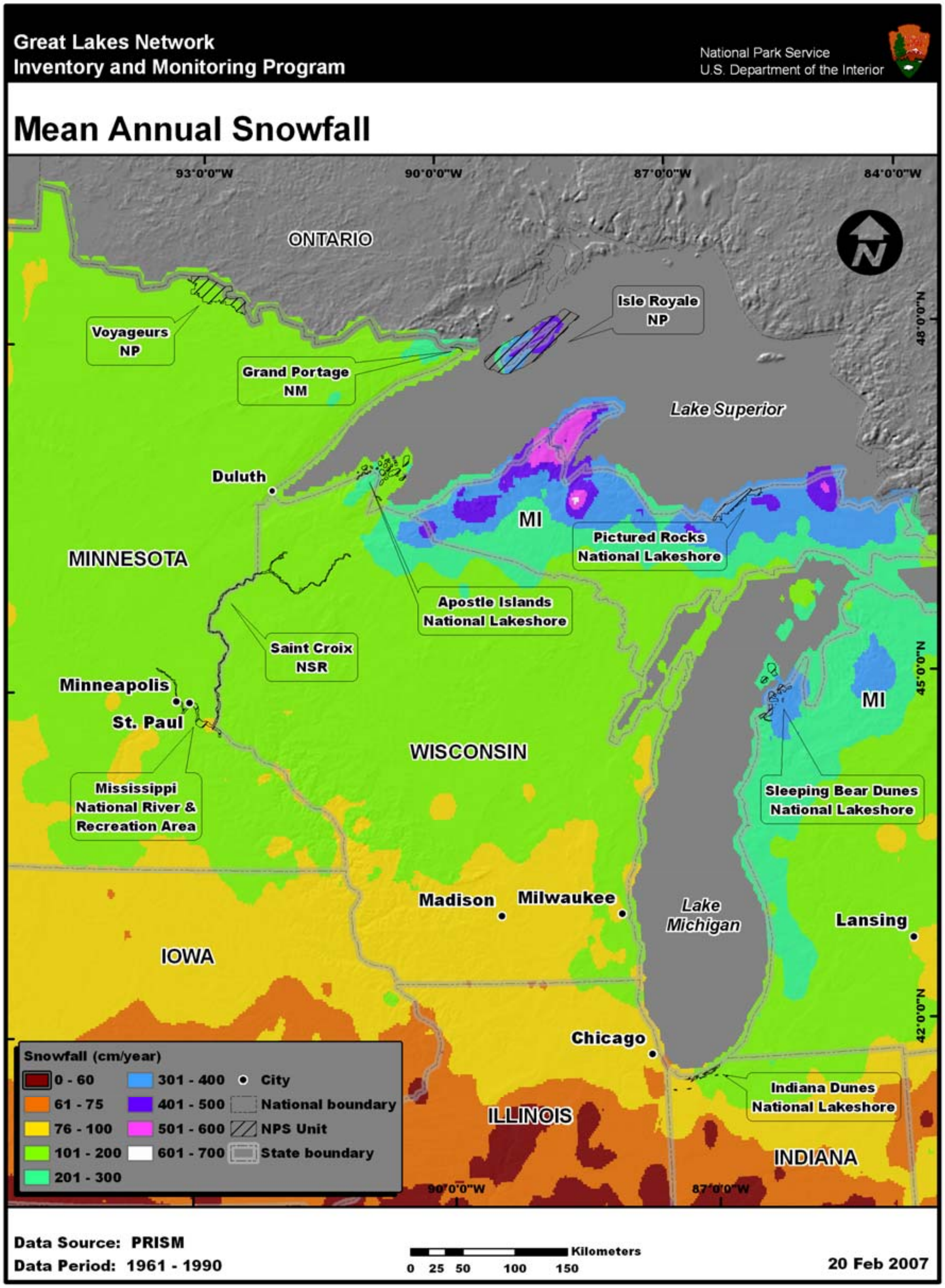
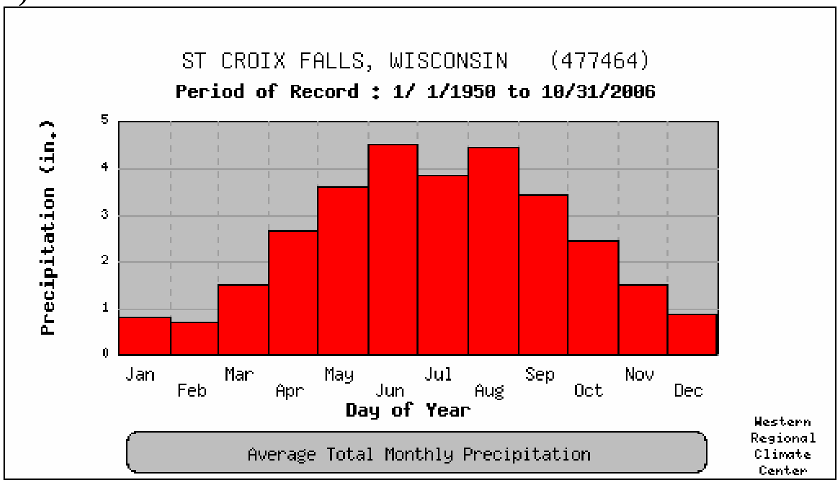
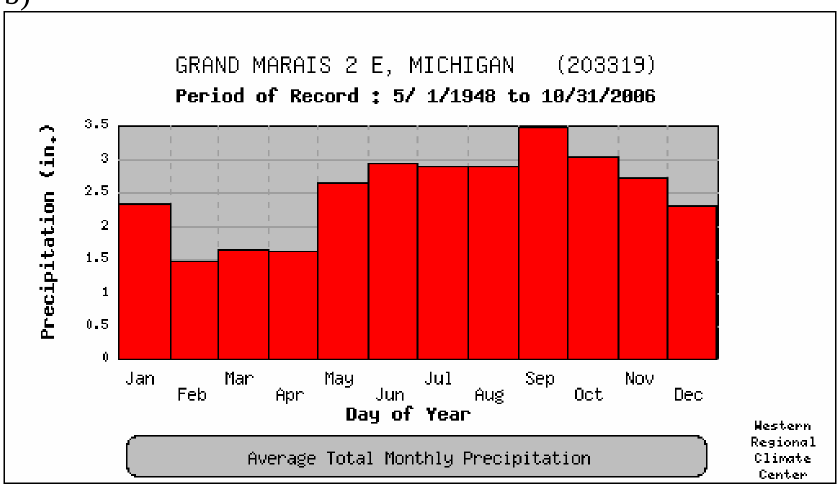


Figure 2.2. Mean annual snowfall, 1961-1990, for the GLKN.

a)



b)



c)

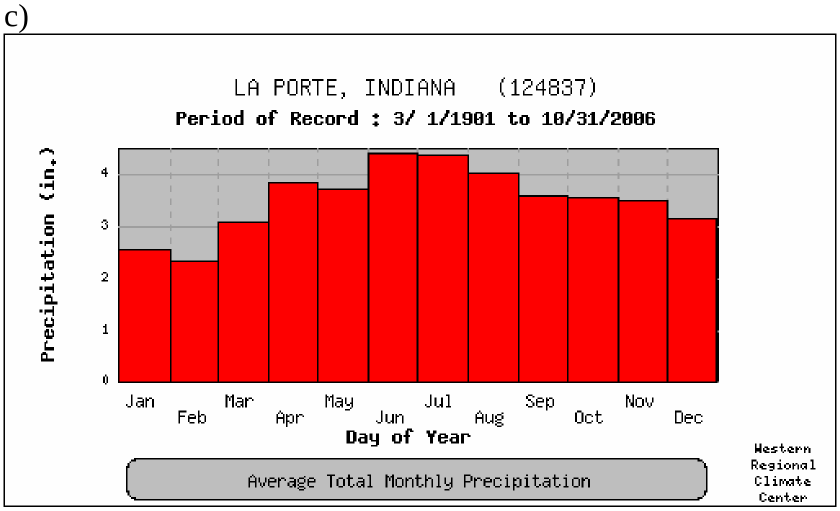


Figure 2.3. Mean monthly precipitation at selected locations in the GLKN. Locations include St. Croix Falls, in SACN (a), Grand Marais 2 E, near PIRO (b), and La Porte, near INDU (c).

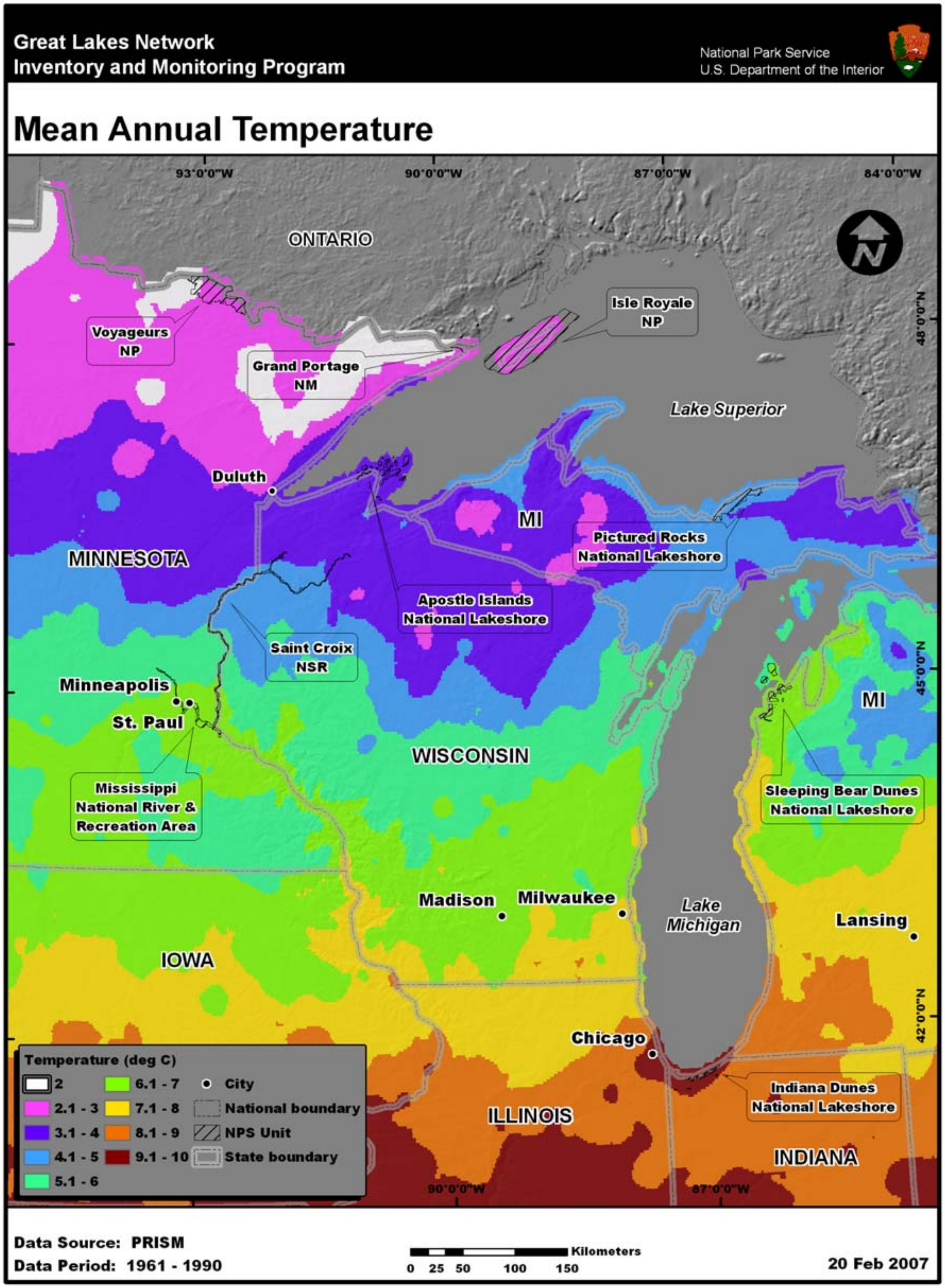


Figure 2.4. Mean annual temperature, 1961-1990, for the GLKN.

and east, with local precipitation maxima also present along the south and east shores of Lake Superior and Lake Michigan. Mean annual precipitation estimates from PRISM range from 650 to 900 mm in GLKN park units (Route and Elias 2007). The wettest park unit in the GLKN is INDU, on the south shore of Lake Michigan, where mean annual precipitation totals approach 1000 mm. On the dry end of the spectrum is VOYA, with mean annual precipitation totals under 700 mm in the western portions of the park unit. PRISM estimates of annual snowfall in the GLKN park units range from 71 to 343 cm (Route and Elias 2007). Snowfall in the GLKN park units generally increases from south to north, with the lake effect snowfall patterns superimposed on this latitudinal gradient. The highest precipitation maxima are concentrated primarily along the south shore of Lake Superior and the west shore of Lake Michigan (Figure 2.2). The GLKN park unit with the most mean annual snowfall is ISRO, where eastern portions of the park unit are estimated to receive over 400 cm of snow each year. The southernmost GLKN park units, on the other hand, generally receive 100 cm or less of snow each year. Precipitation in all GLKN park units generally peaks in summer or early fall (Figure 2.3).

Temperatures in the GLKN can vary from -40°C in winter to over 32°C in summer (Route and Elias 2007). Mean annual temperatures across the GLKN generally follow a north-south gradient (Figure 2.4), with some moderating effects from the Great Lakes superimposed on that gradient. The coldest conditions are found in northern Minnesota, including VOYA and GRPO, where mean annual temperatures are at or below 2°C. In contrast, mean annual temperatures at INDU are generally over 9°C. The moderating effect of the Great Lakes becomes readily apparent when looking at winter minimum and summer maximum temperatures. In the winter, heat from the Great Lakes keeps temperatures relatively mild nearer to the lakes. The warmest January minimum temperatures are generally found at the park units on the east shore of Lake Michigan (Figure 2.5). Portions of SLBE and INDU both have mean January minimum temperatures that are above -7°C. This compares to mean January minimum temperatures that regularly get below -22°C in VOYA. During the summer months, the moderating effects of the Great Lakes are also readily apparent (e.g., Figure 2.6). The warmest conditions are found in the southernmost GLKN park units. For instance, mean July maximum temperatures for INDU and portions of MISS and SACN exceed 27°C. In contrast, many locations along the Great Lakes see much cooler daytime temperatures. For instance, locations along the northern shore of Lake Superior see mean July maximum temperatures down around 21°C.

2.4. Temporal Variability

The El Niño Southern Oscillation (ENSO) causes interannual climate variations in the GLKN (Herche and Assel 2000). El Niño conditions (warm ENSO phases) are associated with warmer and drier than normal conditions while La Niña conditions (cool ENSO phases) are associated with cooler and wetter than normal conditions.

The North Atlantic Oscillation – Arctic Oscillation (NAO-AO) is a major source of low-frequency climate variability in eastern North America (Hurrell 1995; Hurrell and van Loon 1997; Thompson and Wallace 1998; Wettstein and Mearns 2002), with NAO-AO variations occurring on the order of a couple decades. The influence of the NAO-AO is especially pronounced in eastern GLKN. Warmer winter temperatures occur when the NAO-AO index is positive.

An initial look at daily precipitation amounts around the GLKN region over the last century (Figure 2.7) reveals little in the way of an overall trend. In western GLKN, a drier period is apparent during the late 1920s through the 1930s. This shows up particularly well in northeastern Minnesota (Figure 2.7a). Long-term trends in ambient temperature (Figure 2.8) indicate little if any trend. A cooler period is evident across the GLKN during the 1960s and 1970s, while warming is apparent since the 1970s in portions of Michigan (Figures 2.8b,c).

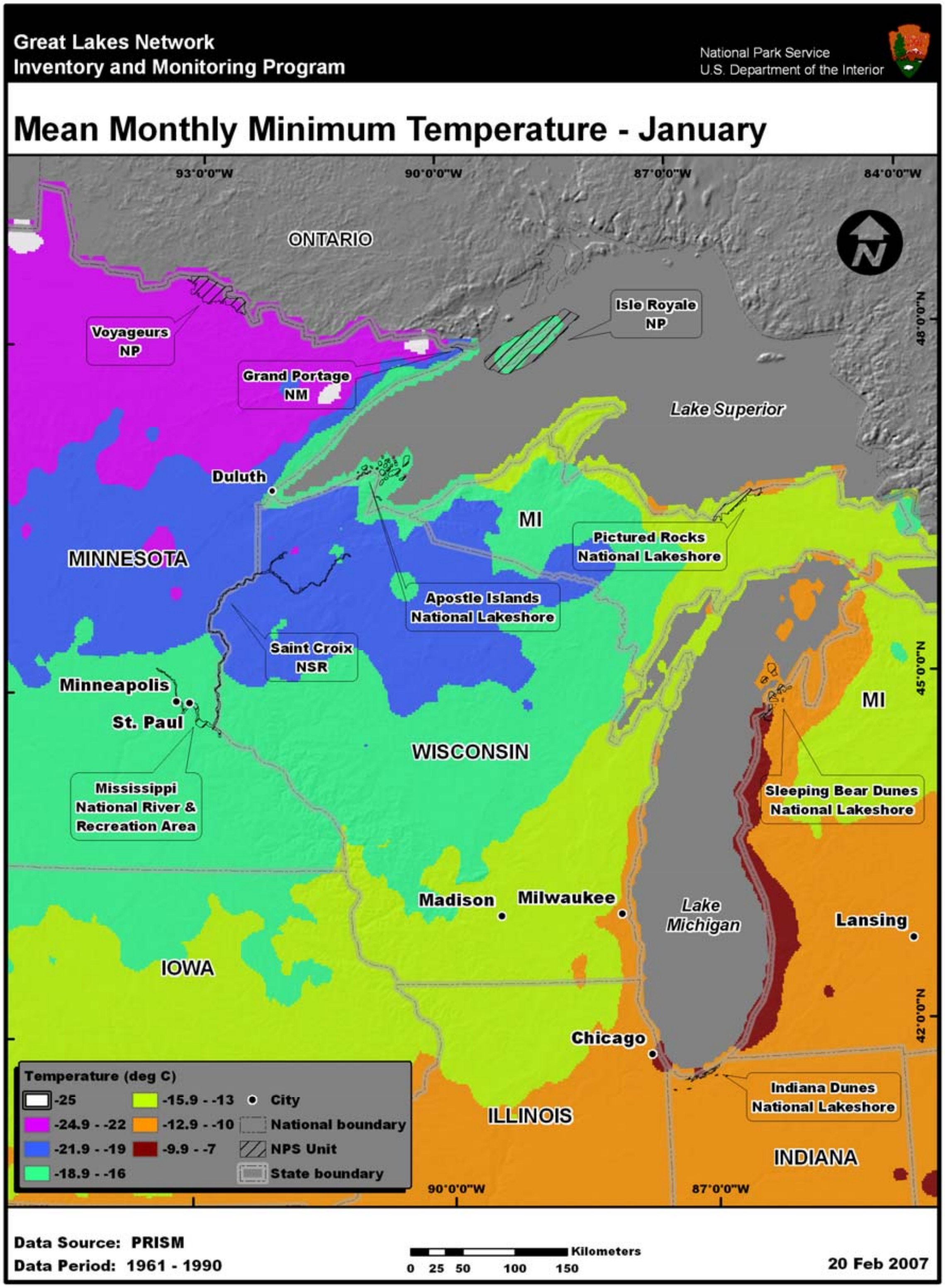


Figure 2.5. Mean January minimum temperature, 1961-1990, for the GLKN.

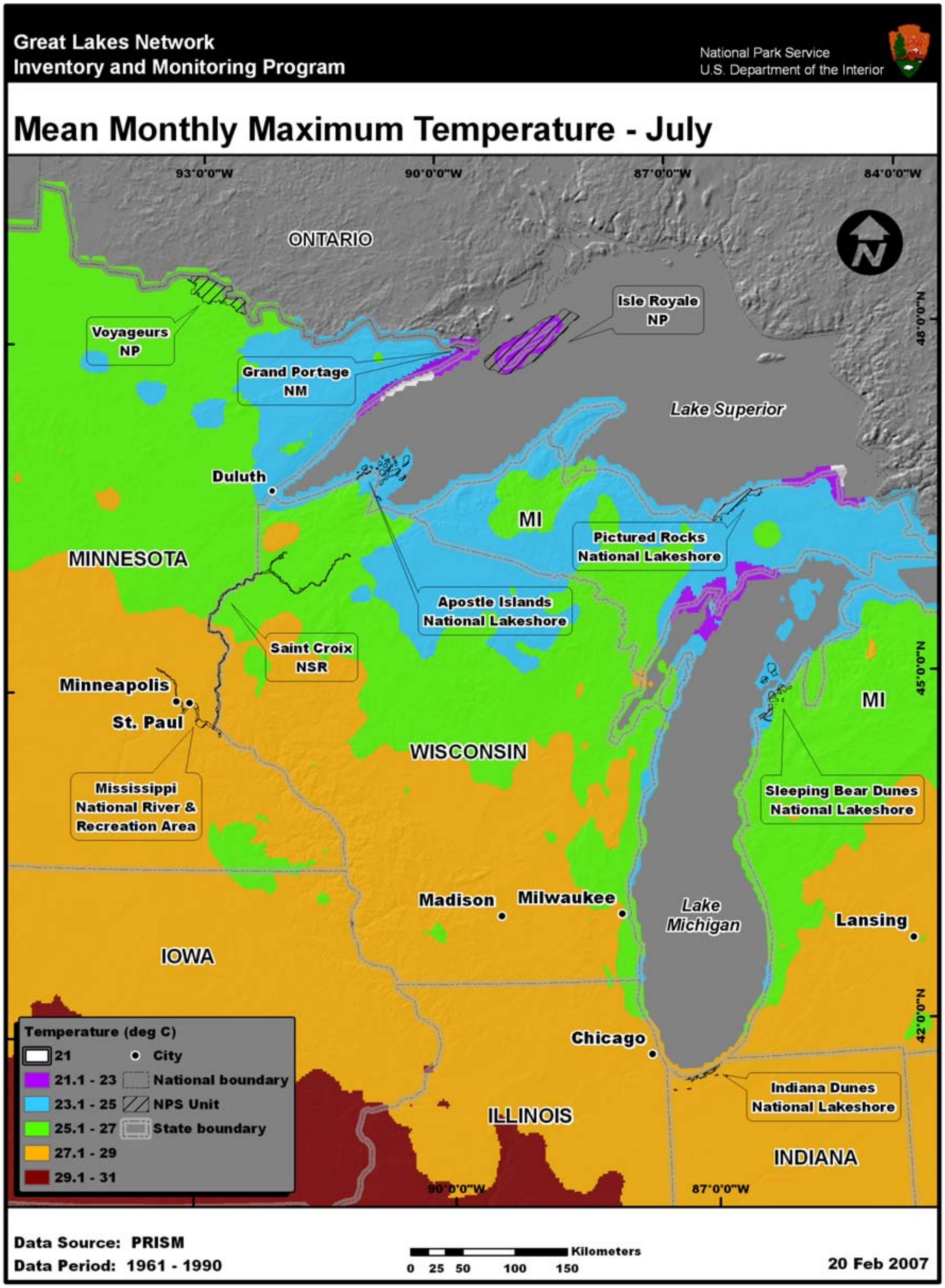
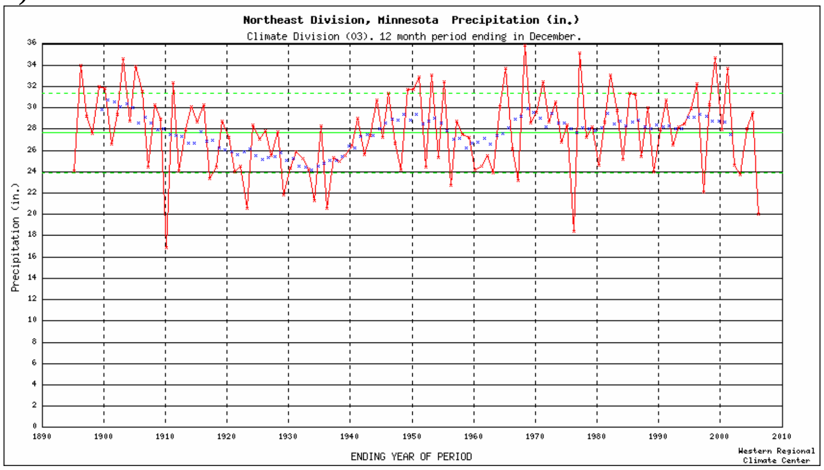


Figure 2.6. Mean July maximum temperature, 1961-1990, for the GLKN.

a)



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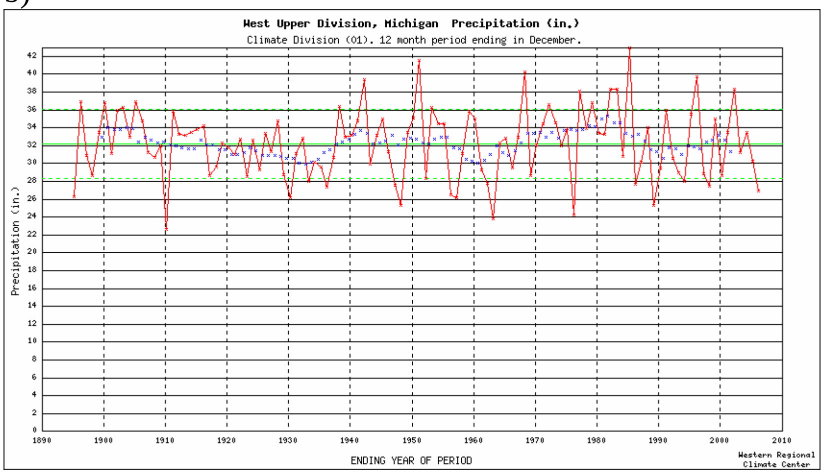


c)

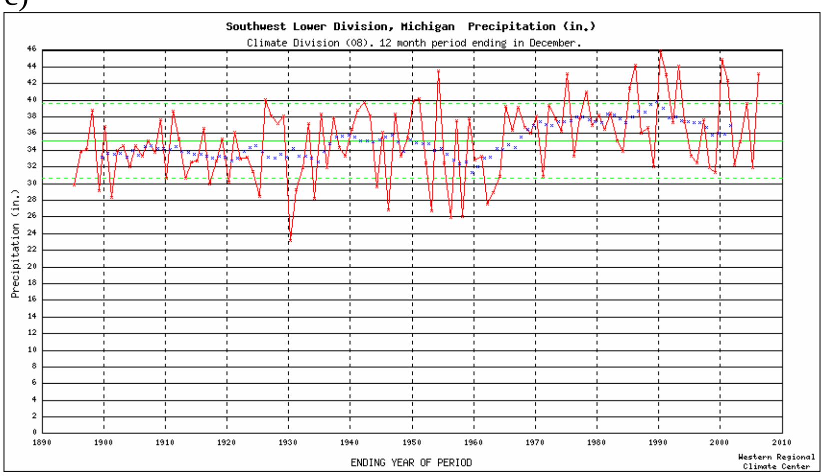
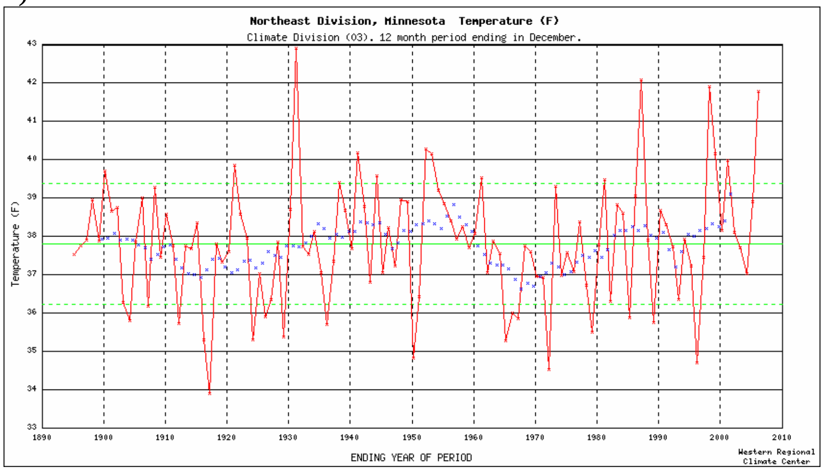
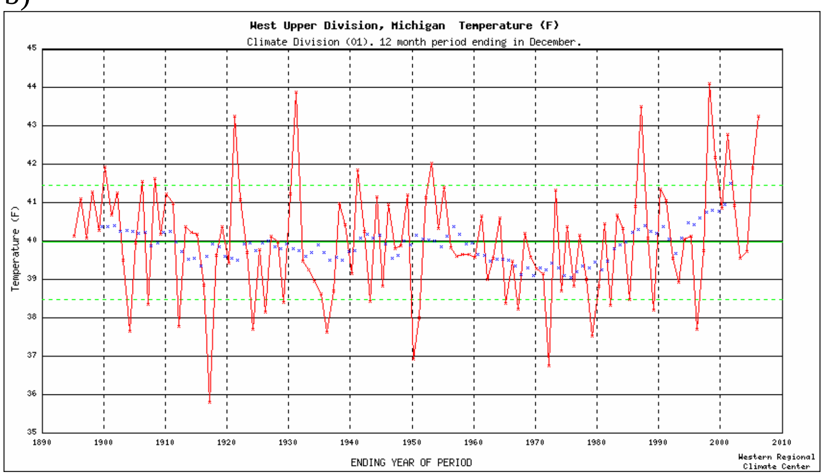


Figure 2.7. Precipitation time series, 1895-2005, for selected regions in the GLKN. These include twelve-month precipitation (ending in December) (red), 10-year running mean (blue), mean (green), and plus/minus one standard deviation (green dotted). Locations include northeastern Minnesota (a), upper Michigan (b), and southwestern Michigan (c).

a)



b)



c)

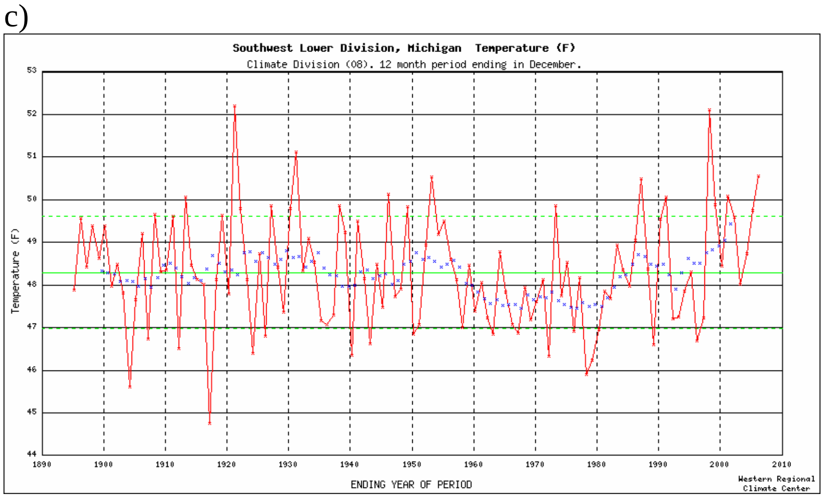


Figure 2.8. Temperature time series, 1895-2005, for selected regions in the GLKN. These include twelve-month average temperature (ending in December) (red), 10-year running mean (blue), mean (green), and plus/minus one standard deviation (green dotted). Locations include northeastern Minnesota (a), upper Michigan (b), and southwestern Michigan (c).

3.0. Methods

Having discussed the climatic characteristics of the GLKN, we now present the procedures that were used to obtain information for weather and climate stations within the GLKN. 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 climate records, including the main networks outlined in this section. The WRCC conducts live and periodic data collection (ingests) from all major national and western weather and climate networks. These networks include the COOP network, the Surface Airways Observation network (SAO) operated by NWS and the Federal Aviation Administration (FAA), the interagency RAWS network, and various smaller networks. The WRCC is expanding its capability to ingest information from other networks as resources permit and usefulness dictates. The WRCC 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 GLKN weather and climate stations identified from the ACIS database are available in file "GLKN_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. ACIS is a distributed system that 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. 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 GLKN weather and climate stations. Explanations are provided as appropriate.

Metadata Field	Notes
Station name	Station name associated with Weather/climate network (see below)
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 or climate network the station belongs to (COOP, RAWS, etc.).
NPS unit code	Four-letter code identifying park unit where station resides.
NPS unit name	Full name of park unit.
NPS unit type	National park, national monument, etc.
UTM zone	If UTM is the only coordinate system available.
Location notes	Useful information not already included in “station narrative.”
Climate variables	Temperature, precipitation, etc.
Installation date	Date of station installation.
Removal date	Date of station removal.
Station photograph	Digital image of station.
Photograph date	Date photograph was taken.
Photographer	Name of person who took the photograph.
Station narrative	Anything related to general site description; may include site exposure, characteristics of surrounding vegetation, driving directions, etc.
Contact name	Name of the person involved with station operation.
Organization	Group or agency affiliation of contact person.
Contact type	Designation that identifies contact person as the station owner, observer, maintenance person, data manager, etc.
Position/job title	Official position/job title of contact person.
Address	Address of contact person.
E-mail address	E-mail address of contact person.
Phone	Phone number of contact person (and extension if available).
Contact notes	Other information needed to reach contact person.

In addition to obtaining GLKN weather and climate station metadata from ACIS, metadata were obtained from NPS staff at the GLKN office in Ashland, Wisconsin. The metadata provided from the GLKN office are available in file “GLKN_NPS.tar.gz” (see Appendix F). Most of the stations noted by GLKN staff are already accounted for in ACIS.

Two types of information were used to complete the GLKN 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:

- 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 and/or lack of metadata).
- Networks having no available historic data.
- Networks having poor-quality metadata or poor access to metadata.
- Real-time networks having poor access to real-time data.

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

3.2. Criteria for Locating Stations

To identify weather and climate stations for each park unit in the GLKN we selected only those stations located within 30 km of the GLKN park units. This buffer distance was selected in an attempt to include automated stations from major networks such as RAWS and SAO, but also to keep the size of the stations lists down to a reasonable number.

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

4.0. Station Inventory

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

4.1. Climate and Weather Networks

Most stations in the GLKN region are associated with at least one of 13 major weather and climate networks (Table 4.1). Brief descriptions of each weather or climate network are provided below (see Appendix G for greater detail).

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

Acronym	Name
CANADA	Canadian weather/climate stations
CASTNet	Clean Air Status and Trends Network
COOP	NWS Cooperative Observer Program
CRN	NOAA Climate Reference Network
CWOP	Citizen Weather Observer Program
GPMP	NPS Gaseous Pollutant Monitoring Program
GPS-MET	NOAA ground-based GPS meteorology network
NADP	National Atmospheric Deposition Program
POMS	Portable Ozone Monitoring System
RAWS	Remote Automated Weather Station network
SAO	NWS/FAA Surface Airways Observation network
WIDOT	Wisconsin Department of Transportation network
WX4U	Weather For You network

4.1.1. Canadian Weather/Climate Stations (CANADA)

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

4.1.2. Clean Air Status and Trends Network (CASTNet)

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

4.1.3. NWS Cooperative Observer Program (COOP)

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

4.1.4. NOAA Climate Reference Network (CRN)

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

4.1.5. Citizen Weather Observer Program (CWOP)

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

4.1.6. Gaseous Pollutant Monitoring Program (GPMP)

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

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

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

4.1.8. 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 Mercury

Deposition Network (MDN) sites. Precipitation is the primary climate parameter measured at NADP sites.

4.1.9. Portable Ozone Monitoring System (POMS)

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

4.1.10. Remote Automated Weather Station (RAWS) Network

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

4.1.11. NWS Surface Airways Observation Network (SAO)

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

4.1.12. Wisconsin Department of Transportation (WIDOT) Network

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

4.1.13. Weather For You Network (WX4U)

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

4.1.14. Weather Bureau Army Navy (WBAN)

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

4.1.15. Other Networks

In addition to the major networks mentioned above, there are various networks that are operated for specific purposes by specific organizations or governmental agencies or scientific research projects. These networks could be present within GLKN 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)
- 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 GLKN (discussed in Section 4.1) have at most several stations at or inside each park unit (Table 4.2). Most of these are COOP stations.

Table 4.2. Number of stations within or nearby GLKN park units. Numbers are listed by park unit and by weather or climate network. See Table 4.1 for network acronym. Figures in parentheses indicate the numbers of stations within park boundaries.

Network	APIS	GRPO	INDU	ISRO	MISS	PIRO	SACN	SLBE	VOYA	Total
CANADA	**0**(0)	**0**(0)	**0**(0)	**1**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**1**(0)
CASTNet	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**1**(1)	**1**(1)
COOP	**8**(0)	**6**(0)	**44**(1)	**7**(4)	**52**(4)	**10**(0)	**58**(3)	**27**(5)	**4**(1)	**216**(18)
CRN	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**1**(0)	**0**(0)	**0**(0)	**0**(0)	**1**(0)
CWOP	**2**(0)	**0**(0)	**13**(0)	**0**(0)	**38**(1)	**0**(0)	**16**(1)	**1**(0)	**1**(0)	**71**(2)
GPMP	**0**(0)	**0**(0)	**1**(1)	**1**(1)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**1**(1)	**3**(3)
GPS-MET	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**6**(0)	**0**(0)	**3**(0)	**0**(0)	**0**(0)	**9**(0)
NADP	**0**(0)	**1**(0)	**1**(1)	**2**(2)	**1**(0)	**0**(0)	**2**(0)	**1**(0)	**1**(1)	**9**(4)
POMS	**0**(0)	**0**(0)	**0**(0)	**1**(1)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**1**(1)
RAWS	**2**(1)	**1**(0)	**1**(1)	**3**(2)	**1**(0)	**2**(0)	**7**(1)	**1**(0)	**2**(1)	**20**(6)
SAO	**2**(1)	**1**(0)	**5**(0)	**3**(2)	**11**(1)	**3**(0)	**8**(0)	**5**(0)	**2**(0)	**40**(4)
WIDOT	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**2**(0)	**0**(0)	**6**(1)	**0**(0)	**0**(0)	**8**(1)
WX4U	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**6**(0)	**0**(0)	**1**(0)	**0**(0)	**1**(0)	**8**(0)
Other	**0**(0)	**0**(0)	**3**(0)	**0**(0)	**2**(0)	**0**(0)	**2**(0)	**0**(0)	**0**(0)	**7**(0)
Total	**14**(2)	**9**(0)	**68**(4)	**18**(12)	**119**(6)	**16**(0)	**103**(6)	**35**(5)	**13**(5)	**395**(40)

Lists of stations have been compiled for the GLKN. As previously noted, 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 act *nearby* in terms of behavior and representativeness. What constitutes "useful" and "representative" are also significant questions, whose answers can vary according to application, type of element, period of record, procedural or methodological observation conventions, and the like.

4.2.1. Northern Minnesota and Lake Superior

The Midwest Hazecam (http://www.mwhazecam.net/grand.html) operates at GRPO and takes near-real-time weather observations in addition to its air quality monitoring activities. This station is not listed in Table 4.3 as unresolved issues with data access prevented this station from being included in the inventory. No other weather or climate stations were identified within the boundaries of GRPO (Table 4.3; Figure 4.1). Five COOP stations, two active, were identified within 30 km of GRPO. The COOP station "Grand Portage R.S." is located just south of GRPO and provides the longest data record we identified for GRPO, going back to 1895. Unfortunately,

Table 4.3. Weather and climate stations for the GLKN park units of northern Minnesota and Lake Superior. Stations inside park units and within 30 km of the park unit boundary are included. Missing entries are indicated by “M”.

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Grand Portage National Monument (GRPO)							
Grand Portage 5 NE	48.000	-89.583	192	COOP	7/1/1972	4/22/1976	No
Grand Portage R.S.	47.971	-89.691	223	COOP	1/10/1895	Present	No
Hovland	47.850	-89.967	192	COOP	6/2/1900	Present	No
Pigeon River Bridge	48.000	-89.700	290	COOP	8/1/1924	7/31/1950	No
Rock Of Ages	47.867	-89.317	184	COOP	9/1/1962	11/30/1977	No
Hovland	47.847	-89.963	224	NADP	12/31/1996	Present	No
Grand Portage	47.950	-89.780	366	RAWS	8/1/2004	Present	No
Rock Of Ages	47.867	-89.317	184	SAO	9/1/1962	11/30/1977	No
Isle Royale National Park (ISRO)							
Mott Island	48.100	-88.550	186	COOP	10/1/1940	Present	Yes
Passage Island	48.217	-88.367	200	COOP	4/1/1954	12/31/1977	Yes
Rock Of Ages	47.867	-89.317	184	COOP	9/1/1962	11/30/1977	Yes
Windigo Isle Royale	47.917	-89.150	198	COOP	8/1/1965	8/31/1976	Yes
Ojibway Fire Tower	48.109	-88.607	366	GPMP	6/1/1987	9/30/1995	Yes
Isle Royale NP-Wallace Lake	48.058	-88.634	201	NADP	5/22/1985	Present	Yes
Isle Royale NP-Windigo	47.915	-89.153	216	NADP	8/12/1980	10/22/1984	Yes
Ojibway Fire Tower portable	48.108	-88.606	347	POMS	7/1/2002	9/30/2004	Yes
Ojibway	48.109	-88.547	317	RAWS	10/1/2001	Present	Yes
Windigo	47.912	-89.155	213	RAWS	10/1/2001	Present	Yes
Passage Island	48.217	-88.367	200	SAO	4/1/1954	12/31/1977	Yes
Rock Of Ages	47.867	-89.317	184	SAO	9/1/1962	11/30/1977	Yes
Trowbridge (AUT)	48.300	-88.870	218	CANADA	M	Present	No
Grand Portage 5 NE	48.000	-89.583	192	COOP	7/1/1972	4/22/1976	No
Grand Portage R.S.	47.971	-89.691	223	COOP	1/10/1895	Present	No
Pigeon River Bridge	48.000	-89.700	290	COOP	8/1/1924	7/31/1950	No
Grand Portage	47.950	-89.780	366	RAWS	8/1/2004	Present	No
Trowbridge	48.300	-88.867	218	SAO	8/24/1984	Present	No
Voyageurs National Park (VOYA)							
Sullivan Bay	48.413	-92.829	429	CASTNet	6/12/1996	Present	Yes
Kettle	48.501	-92.644	342	COOP	8/6/1943	Present	Yes
Black Bay	48.588	-93.173	343	GPMP	4/1/1987	6/11/1996	Yes
Voyageurs NP-Sullivan Bay	48.413	-92.829	429	NADP	5/30/2000	Present	Yes
Ketfalls	48.503	-92.641	354	RAWS	6/1/2005	Present	Yes
Crane Lake R.S.	48.267	-92.467	342	COOP	1/1/1926	3/11/1981	No
International Falls	48.566	-93.398	359	COOP	3/1/1895	Present	No
Kabetogama	48.445	-93.029	349	COOP	8/8/1997	Present	No
CW1890 Ft. Frances	48.612	-93.415	335	CWOP	M	Present	No
Kabnam	48.442	-93.050	107	RAWS	3/1/2003	Present	No
Crane Lake	48.267	-93.117	341	SAO	7/1/1988	Present	No
International Falls	48.566	-93.398	359	SAO	3/1/1895	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Fort Frances	48.612	-93.414	349	WX4U	M	Present	No

this data record is largely incomplete before the 1950s. Numerous data gaps also occurred at this station during the 1970s and 1980s.

The COOP station "Hovland" is located 19 km southwest of GRPO. This data record (1900-present) is very incomplete, with many large gaps. A NADP station and a RAWS station also operate at Hovland. The Hovland RAWS station (2004-present) is the only source of near-real-time weather data we identified for GRPO. This RAWS station has data gaps during the first half of both 2004 and 2005.

We identified 13 stations (five active) within ISRO (Table 4.3; Figure 4.1). Five of the stations we identified in ISRO are COOP stations; only two are still active. The COOP station "Mott Is. Isle Royale" provides a data record going back to 1940.This data record is fairly complete, with scattered small gaps, during the months of May-October, with no wintertime observations. The COOP station "Mott Island" provides another fairly long data record in ISRO, going back to 1953. A GPMP station was operational within ISRO during the late 1980s and early 1990s. A POMS station was operational within ISRO from 2002-2004.

One NADP station and two RAWS stations currently operate within ISRO. The RAWS stations "Ojibway" and "Windigo" both have been operating since 2001. Both of these stations were summer-only stations until recently. "Ojibway" began taking year-round observations in 2005, while "Ojibway" began taking year-round observations in 2006. Two SAO stations were identified in ISRO, but neither of these stations are still active.

Due to its remote island location, few stations were identified within 30 km outside of ISRO, as much of this buffer zone falls in Lake Superior. The stations we did identify were primarily to the west of ISRO. "Trowbridge (AUT)" is a Canadian weather station 17 km north of ISRO that provides near-real-time data. This is collocated with the SAO station "Trowbridge," so these two sites may possibly refer to the same station. Of the three COOP stations we identified within 30 km of ISRO, only one is still active. This station, "Grand Portage R.S.," is 23 km southwest of ISRO and has been discussed previously. Besides the CANADA and SAO station we just discussed, another source for near-real-time weather data within 30 km of ISRO is the RAWS station "Grand Portage," discussed previously. This RAWS station is 29 km southwest of ISRO.

We identified five stations (four active) within VOYA (Table 4.3; Figure 4.1). The CASTNet station "Sullivan Bay" has been operating since 1996 and provides a source of near-real-time weather data. The primary climate record within the park unit comes from the COOP station "Kettle," which has been active since 1943. Unfortunately, the data record at "Kettle" appears to be unreliable. A GPMP site operated at Black Bay until 1996. The NADP station at Sullivan Bay has been operating since 2000. The RAWS station "Ketfalls," active since 2005, is the other primary source of near-real-time weather data for VOYA besides the CASTNet station at Sullivan Bay. Unfortunately, "Ketfalls" has only taken observations during the summer months.

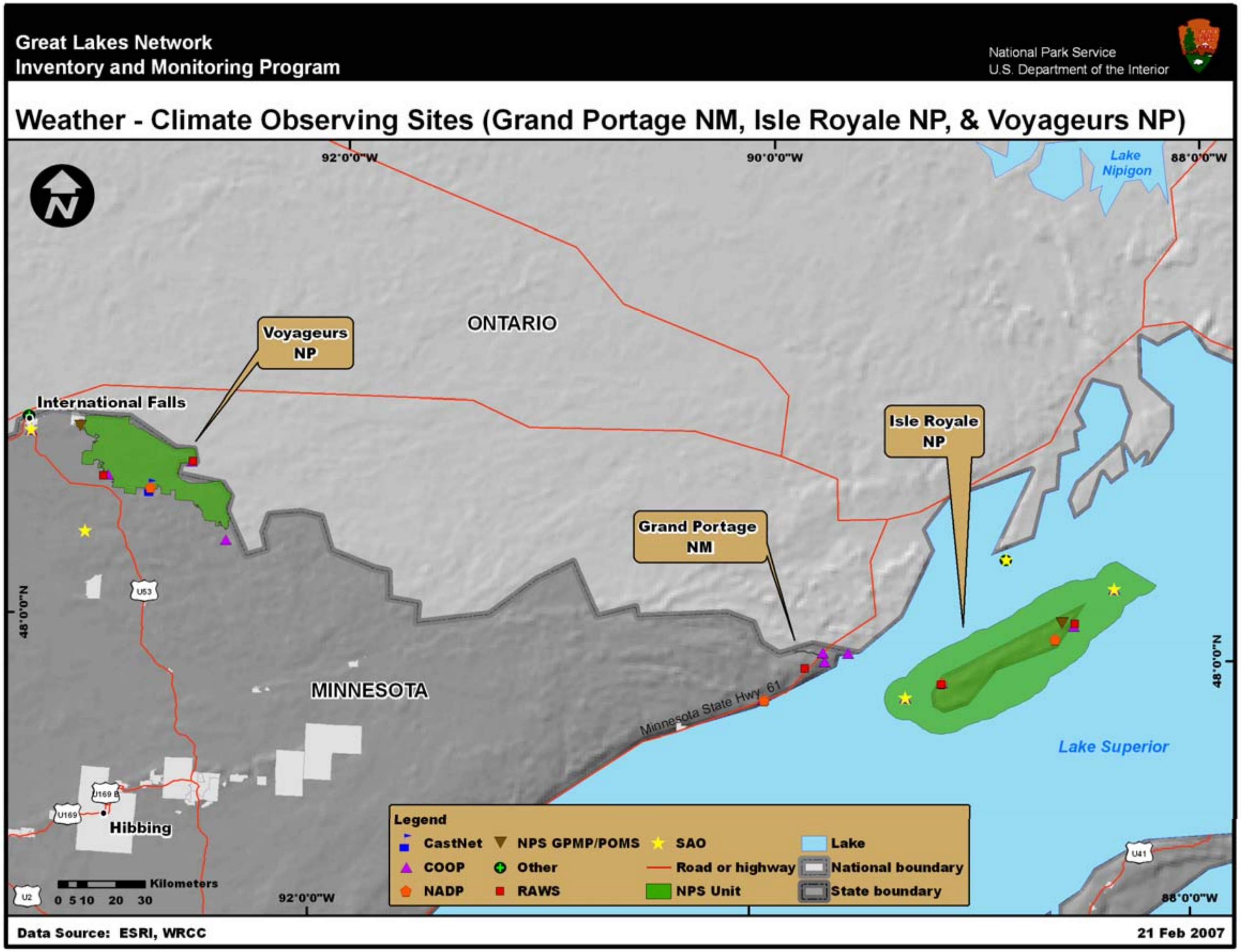


Figure 4.1. Station locations for the GLKN park units of northern Minnesota and Lake Superior.

Two active COOP stations were identified within 30 km of VOYA (Table 4.3). The closer of these two active COOP stations is “Kabetogama,” which is less than 1 km southwest of VOYA. This station has been operating since 1997. ”The COOP station “International Falls,” 15 km west of VOYA, has been operating since 1895 and provides a very reliable long-term record.

An SAO station is collocated with the International Falls COOP site and provides near-real-time weather data for the region. Another SAO station (Crane Lake) is located 18 km south of VOYA and has been operating since 1988. A third source of near-real-time data is the RAWS station “Kabnam,” which is less than 1 km south of VOYA and has been active since 2003. There are generally no observations at this RAWS site between January and March.

4.2.2. Northern Michigan

No weather or climate stations were identified within the boundaries of PIRO (Table 4.4; Figure 4.2). Ten COOP stations, seven active, were identified within 30 km of PIRO. The COOP station “Grand Marais 2 E” is the closest active COOP station to PIRO, located just east of the park unit. It also provides the longest data record we identified among the active COOP stations, going back to 1900. This data record is very complete. “Munising” is another long-term COOP station (1911-present) that we identified for PIRO. This station is 3 km southwest of PIRO. Unfortunately, the data record at “Munising” is very incomplete. The COOP station “Chatham 1 SE” (1940-present) is 25 km southwest of PIRO but it, too, has an unreliable data record, with many data gaps. Fortunately, a CRN station (also named “Chatham 1 SE”) has been operating at this same location for the past few years, with a reliable data record. The COOP station “Steuben Tower” (1953-present) is 25 km southwest of PIRO. The only source of near-real-time weather data we identified for PIRO is the RAWS station “Doe Lake,” located 20 km southwest of PIRO. This station has also been known as “Blue Lake.” The data record at “Doe Lake” goes back to 2002 and is very complete.

Table 4.4. Weather and climate stations for the GLKN park units in northern Michigan. Stations inside park units and within 30 km of the park unit boundary are included. Missing entries are indicated by “M”.

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Pictured Rocks National Lakeshore (PIRO)							
Chatham 1 SE	46.335	-86.920	273	COOP	3/1/1940	Present	No
Chatham Exp Farm 2	46.347	-86.929	265	COOP	7/9/1987	Present	No
Chatham Experiment Forest	46.350	-86.933	268	COOP	7/1/1900	7/1/1988	No
Deer Park State Forest	46.617	-85.617	204	COOP	6/18/1900	4/30/1954	No
Grand Marais	46.683	-85.967	183	COOP	10/1/1968	Present	No
Grand Marais 2 E	46.667	-85.950	190	COOP	6/7/1900	Present	No
Munising	46.412	-86.663	207	COOP	5/1/1911	Present	No
Munising Beach Inn	46.417	-86.667	189	COOP	M	Present	No
Steuben	46.183	-86.467	226	COOP	11/1/1938	9/1/1990	No
Steuben Tower	46.200	-86.433	186	COOP	4/1/1953	Present	No
Chatham 1 SE	46.335	-86.920	273	CRN	M	Present	No
Blue Lake	46.254	-86.714	248	RAWS	M	Present	No
Doe Lake	46.254	-86.714	248	RAWS	5/1/2002	Present	No
Chatham Exp. Farm 2	46.347	-86.929	265	SAO	7/9/1987	Present	No
Grand Marais	46.683	-85.967	183	SAO	10/1/1968	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Munsing Lakeshore	46.417	-86.650	187	SAO	10/13/2004	Present	No
Sleeping Bear Dunes National Lakeshore (SLBE)							
Empire 1 SSE	44.800	-86.050	232	COOP	4/1/1973	5/13/1987	Yes
Glen Arbor 4 NE	44.933	-85.917	192	COOP	8/1/1954	11/30/1958	Yes
North Manitou Island	45.117	-85.983	180	COOP	10/1/1954	8/20/1968	Yes
North Manitou Island	45.117	-86.050	204	COOP	11/1/1952	10/31/1968	Yes
South Manitou Island	45.017	-86.100	180	COOP	11/14/1952	Present	Yes
Beulah 7 SSW	44.532	-86.131	236	COOP	3/1/1974	Present	No
Cedar 6 SE	44.783	-85.700	317	COOP	11/11/1955	11/22/1957	No
Frankfort 2 NE	44.648	-86.210	289	COOP	3/1/1898	Present	No
Glen Arbor Leelanau	44.917	-85.967	186	COOP	1/1/1948	8/31/1954	No
Interlochen State Pa.	44.633	-85.767	M	COOP	7/1/1948	4/11/1958	No
Lake Leelanau 3 N	45.017	-85.717	235	COOP	2/28/1962	12/4/1991	No
Leland	45.050	-85.767	M	COOP	M	Present	No
Maple City	44.855	-85.835	244	COOP	1/1/1959	Present	No
Northport	45.133	-85.617	M	COOP	2/1/1889	12/31/1933	No
Northport 2 W	45.132	-85.647	227	COOP	5/13/1987	Present	No
NW Michigan Res. Farm	44.883	-85.675	250	COOP	4/16/1980	Present	No
Old Mission 3 SSW	44.922	-85.516	200	COOP	2/1/1962	Present	No
Point Betsie	44.700	-86.250	182	COOP	10/1/1953	Present	No
South Fox Island	45.383	-85.833	189	COOP	9/1/1963	10/31/1968	No
Suttons Bay 4 NW	45.017	-85.700	250	COOP	12/1/1938	10/24/1968	No
Suttons Bay Co. Garage	44.967	-85.500	M	COOP	11/1/1957	2/28/1972	No
Thompsonville	44.517	-85.933	242	COOP	11/1/1938	1/3/1984	No
Traverse City	44.761	-85.644	194	COOP	7/11/2001	Present	No
Traverse City	44.769	-85.576	184	COOP	9/1/1963	Present	No
Traverse City	44.741	-85.583	188	COOP	6/1/1896	Present	No
Traverse City 2	44.783	-85.633	M	COOP	9/14/1988	4/1/1992	No
Traverse City Arpt. #2	44.745	-85.584	190	COOP	1/1/1999	10/1/2001	No
CW2151 Honor	44.661	-86.020	184	CWOP	M	Present	No
Peshawbestown	45.029	-85.629	229	NADP	1/22/2002	Present	No
Bear	44.468	-86.053	274	RAWS	4/1/2002	Present	No
Dow Mem. Arpt.	44.626	-86.201	193	SAO	2/2/2005	Present	No
Frankfort	44.633	-86.250	174	SAO	9/1/1972	Present	No
North Manitou Shoals	45.017	-85.950	177	SAO	9/1/1972	Present	No
Point Betsie	44.700	-86.250	182	SAO	10/1/1953	Present	No
Traverse City	44.741	-85.583	188	SAO	6/1/1896	Present	No

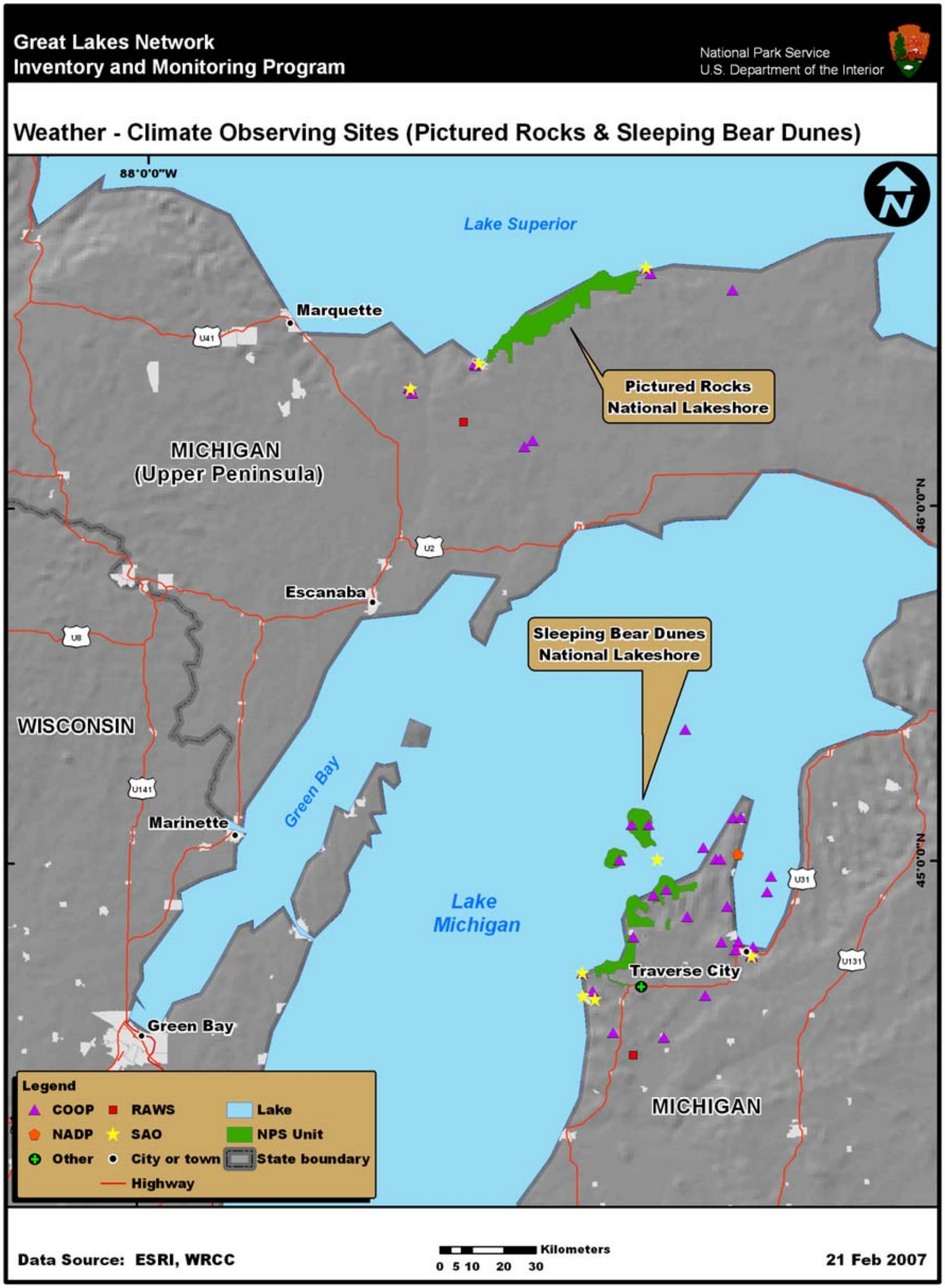


Figure 4.2. Station locations for the GLKN park units in northern Michigan.

Five stations have been identified within SLBE. All of these are COOP stations and one of these stations is still active. The COOP station "South Manitou Island" has been active since 1952. This station has a data record that is of uncertain reliability, particularly since the 1970s. The Integrated Atmospheric Deposition Network (IADN; http://www.nsc.ec.gc.ca/iadn/index_e.html) operates an air quality station within SLBE. However, data access for this IADN site could not be verified so it was not included in the station inventories presented in Table 4.4.

Out of the 22 COOP stations we identified within 30 km of the boundaries of SLBE, 11 are active (Table 4.4). The longest record we identified was from a COOP station in Traverse City, Michigan, which is 28 km southeast of SLBE and has been active since 1896. This record was complete until July 2001, after which it has become quite unreliable. Interestingly, there is another COOP station we identified in Traverse City which has a data record starting in July 2001. This leads to the possibility that these two records may actually be from the same station, a station that has had changes such as a station move or an instrumentation change. Another long-term record was identified at the COOP station "Frankfort 2 NE," which is 5 km southwest of SLBE. This station has had a very reliable data record since the early 1960s. Two active COOP stations within 30 km of SLBE have data records going back to the 1950s. "Maple City" (1959-present) is 6 km east of SLBE and "Point Betsie" (1953-present) is 4 km southwest of SLBE. The data record at "Maple City" is very reliable while the record at "Point Betsie" is not reliable. The remaining active COOP stations we identified had data records starting in the 1960s or later.

Seven other stations were identified within 30 km of SLBE. The NADP station "Peshawbestown," 16 km east of SLBE, has been active since 2002. One RAWS station and five SAO stations provide near-real-time data for the area. The RAWS station "Bear" has been active since at least 2002, with a very complete data record. Earlier records at "Bear" possibly extend back to the early 1990s. Of the SAO stations we identified, the longest record comes from the site at Traverse City (1896-present), 28 km southeast of SLBE. Another useful SAO station for SLBE is "North Manitou Shoals" (1972-present), which isn't officially located within SLBE (and is in fact 4 km from the closest SLBE boundary) but is located in the strait between North Manitou Island and Pyramid Point.

4.2.3. Wisconsin and Central Minnesota

Two stations were identified within APIS (Table 4.5; Figure 4.3). Both of these are near-real-time stations. The RAWS station "Apostle Island" has been active since 2004, with data gaps during the first halves of both 2004 and 2005. The SAO station "Devils Island" has been active since 1968.

Eight COOP stations have been identified within 30 km of the boundaries of APIS. Six of these are still active (Table 4.5). The closest active COOP station to APIS that we identified was "Bayfield No. 2," which is 4 km southwest of APIS. Two climate stations recently stopped taking observations, which is very unfortunate. The COOP station "Ashland Exp. Farm" (1893-2005) was 21 km south of APIS. The COOP station "Bayfield 6 N," 5 km from APIS, had taken observations since 1893 but stopped operating in May 2005. The COOP station "Madeline Island," 5 km from APIS, has been active since 1944. There were numerous data gaps at this site in the 1980s, lessening the usefulness of an otherwise-complete data record. The COOP station

Table 4.5. Weather and climate stations for GLKN park units in Wisconsin and central Minnesota. Stations inside park units and within 30 km of the park unit boundary are included. Missing entries are indicated by “M”.

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Apostle Islands National Lakeshore (APIS)							
Apostle Island	46.930	-90.753	198	RAWS	1/1/2004	Present	Yes
Devils Island	47.083	-90.733	192	SAO	10/1/1968	Present	Yes
Ashland	46.600	-90.883	201	COOP	3/1/1955	Present	No
Ashland	46.552	-90.916	252	COOP	7/1/1998	Present	No
Ashland Exp. Farm	46.573	-90.971	198	COOP	3/1/1893	4/21/2005	No
Bayfield 6 N	46.883	-90.817	250	COOP	1/1/1893	5/23/2005	No
Bayfield No. 2	46.817	-90.817	M	COOP	M	Present	No
Cornucopia 3 E	46.867	-91.083	195	COOP	5/1/1912	11/23/1937	No
Madeline Island	46.783	-90.767	201	COOP	6/10/1944	Present	No
Port Wing	46.778	-91.386	198	COOP	7/1/1947	Present	No
KB0THN-2 Winona	46.784	-90.707	189	CWOP	M	Present	No
W9PPN Bayfield	46.811	-90.848	349	CWOP	M	Present	No
Washburn	46.636	-91.201	384	RAWS	4/1/1997	Present	No
Ashland	46.549	-90.919	252	SAO	6/1/1959	Present	No
Mississippi National River and Recreation Area (MISS)							
Hastings Dam 2	44.760	-92.869	212	COOP	8/1/1893	Present	Yes
Hastings Lock 2	44.767	-92.867	M	COOP	7/1/1948	Present	Yes
Minneapolis	45.043	-93.280	247	COOP	7/1/1948	Present	Yes
St. Paul	44.930	-93.048	220	COOP	1/1/1871	Present	Yes
K0JA Coon Rapids	45.170	-93.351	261	CWOP	M	Present	Yes
St. Paul	44.930	-93.048	220	SAO	1/1/1871	Present	Yes
Bloomington	44.817	-93.317	253	COOP	M	8/31/1973	No
Buffalo	45.178	-93.880	300	COOP	5/8/1940	Present	No
Cedar	45.322	-93.284	276	COOP	11/1/1962	Present	No
Cedat	45.167	-93.067	271	COOP	8/1/1919	11/30/1927	No
Chanhassen	44.851	-93.565	288	COOP	12/1/1995	Present	No
Coon Rapids	45.150	-93.300	256	COOP	5/1/1966	8/31/1973	No
Deep Haven	44.933	-93.517	M	COOP	11/1/1897	11/30/1904	No
Elk River	45.305	-93.585	277	COOP	5/10/1940	Present	No
Ellsworth 1 E	44.730	-92.459	314	COOP	3/1/1908	Present	No
Excelsior	44.900	-93.567	287	COOP	M	12/31/1978	No
Farmington 1 W	44.633	-93.167	281	COOP	4/1/1957	9/1/1970	No
Farmington 3 NW	44.670	-93.170	299	COOP	4/1/1888	Present	No
Golden Valley	44.994	-93.408	277	COOP	4/1/1963	Present	No
Hager City	44.583	-92.517	220	COOP	10/1/1932	Present	No
Hudson	44.933	-92.767	222	COOP	2/8/1891	9/15/1897	No
Lakeville AAWO	44.717	-93.300	304	COOP	4/1/1993	5/23/1994	No
Lower St. Anthony Fal.	44.978	-93.247	230	COOP	9/1/1991	Present	No
Maple Plain	45.000	-93.650	296	COOP	1/1/1892	1/1/1989	No
Maplewood	44.950	-93.517	415	COOP	12/1/1895	11/30/1896	No
Minneapolis Aschenbeck	45.000	-93.317	M	COOP	12/1/1887	12/31/1920	No
Minneapolis Cheney	44.967	-93.333	M	COOP	5/1/1893	6/30/191	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Minneapolis WB	44.983	-93.300	M	COOP	1/1/1891	6/30/1948	No
Minneapolis-St. Paul	44.883	-93.229	266	COOP	1/1/1891	Present	No
Minnegasco River Plt.	44.967	-93.250	250	COOP	5/3/1953	1/31/1972	No
New Hope	45.010	-93.379	287	COOP	10/1/1968	Present	No
Red Wing	44.610	-92.610	206	COOP	7/1/1948	Present	No
Red Wing	44.571	-92.528	210	COOP	5/1/1893	Present	No
Red Wing Dam 3 L G	44.617	-92.617	M	COOP	7/1/1948	Present	No
Red Wing River	44.567	-92.567	201	COOP	5/1/1971	Present	No
Red Wing School	44.567	-92.533	M	COOP	1/1/1901	12/31/1909	No
River Falls	44.854	-92.612	284	COOP	4/1/1918	Present	No
Robbinsdale	45.033	-93.333	275	COOP	M	10/31/1968	No
Rockford	45.083	-93.734	293	COOP	10/18/1954	Present	No
Rosemount Agri. Exp. Stn.	44.718	-93.098	290	COOP	2/6/1943	Present	No
Savage	44.783	-93.317	210	COOP	M	Present	No
South St. Paul	44.867	-93.033	229	COOP	M	3/31/1978	No
St. Francis	45.388	-93.359	274	COOP	3/1/1990	Present	No
St. Francis 4 S	45.333	-93.367	262	COOP	10/1/1954	Present	No
St. Paul	44.946	-93.030	274	COOP	5/1/1893	5/1/2006	No
St. Paul	44.950	-93.083	208	COOP	8/27/1926	Present	No
St. Paul 3 SW	44.931	-93.154	286	COOP	5/1/2006	Present	No
St. Paul Univ. Farm	45.000	-93.167	290	COOP	8/1/1916	6/30/1951	No
Stillwater 1 SE	45.042	-92.798	216	COOP	12/28/1904	2/1/2006	No
Stillwater 2 SW	45.045	-92.852	274	COOP	12/14/2005	Present	No
Univ. Of Minn. St. Paul	44.985	-93.177	296	COOP	1/1/1961	Present	No
Vadnais Lake	45.049	-93.096	271	COOP	5/1/1966	Present	No
White Bear Lake AAWO	45.050	-93.000	296	COOP	4/1/1993	5/23/1994	No
Woodbury AAWO	44.917	-92.950	320	COOP	4/1/1993	5/23/1994	No
CW0217 Ramsey	45.226	-93.419	266	CWOP	M	Present	No
CW0468 Farmington	44.694	-93.202	330	CWOP	M	Present	No
CW0561 Coon Rapids	45.159	-93.272	274	CWOP	M	Present	No
CW0698 Apple Valley	44.762	-93.224	343	CWOP	M	Present	No
CW0796 Savage	44.758	-93.344	265	CWOP	M	Present	No
CW1898 St. Paul	44.990	-93.077	277	CWOP	M	Present	No
CW2250 Medina	45.047	-93.528	265	CWOP	M	Present	No
CW2379 Saint Paul	44.936	-93.179	280	CWOP	M	Present	No
CW2935 Dayton	45.228	-93.526	265	CWOP	M	Present	No
CW3319 Woodbury	44.888	-92.965	311	CWOP	M	Present	No
CW3353 Brooklyn Park	45.107	-93.376	260	CWOP	M	Present	No
CW3494 Eden Prairie	44.878	-93.454	291	CWOP	M	Present	No
CW3910 Blaine	45.131	-93.171	904	CWOP	M	Present	No
CW4026 Cannon Falls	44.523	-92.934	255	CWOP	M	Present	No
CW4659 Inver Grove Hts.	44.854	-93.072	286	CWOP	M	Present	No
CW4785 Saint Paul Park	44.836	-92.990	242	CWOP	M	Present	No
CW4965 Eagan	44.802	-93.160	259	CWOP	M	Present	No
CW5102 Minnetonka	44.926	-93.475	305	CWOP	M	Present	No
CW5120 Prior Lake	44.642	-93.370	327	CWOP	M	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
CW5560 Saint Paul	44.938	-93.115	244	CWOP	M	Present	No
CW5689 Lakeland	44.925	-92.764	710	CWOP	M	Present	No
CW5773 Lakeville	44.701	-93.221	300	CWOP	M	Present	No
CW5776 Deephaven	44.926	-93.541	291	CWOP	M	Present	No
CW5791 Minnetonka	44.926	-93.484	295	CWOP	M	Present	No
CW5900 Eagan	44.814	-93.134	291	CWOP	M	Present	No
KB0PXE Minneapolis	44.898	-93.303	282	CWOP	M	Present	No
KC0LBV Farmington	44.694	-93.202	300	CWOP	M	Present	No
KC0OPD Lino Lakes	45.158	-93.134	277	CWOP	M	Present	No
KC5LXC Stillwater	45.040	-92.861	279	CWOP	M	Present	No
KF0ZH Shakopee	44.784	-93.491	244	CWOP	M	Present	No
KK6BT Plymouth	45.055	-93.515	305	CWOP	M	Present	No
N0BHC Savage	44.757	-93.344	244	CWOP	M	Present	No
N0OQA Elk River	45.345	-93.592	287	CWOP	M	Present	No
N0PFY Northfield	44.568	-93.130	291	CWOP	M	Present	No
W0LED-1 Crystal	45.046	-93.346	277	CWOP	M	Present	No
WA2VOI Minneapolis	45.025	-93.200	290	CWOP	M	Present	No
WA8GAZ Minnetonka	44.952	-93.443	300	CWOP	M	Present	No
Albertville	45.260	-93.700	303	GPS-MET	M	Present	No
Apple Valley	44.730	-93.210	307	GPS-MET	M	Present	No
Arden Hills	45.110	-93.180	281	GPS-MET	M	Present	No
Golden Valley	45.000	-93.350	278	GPS-MET	M	Present	No
Oakdale	45.000	-92.960	319	GPS-MET	M	Present	No
Red Wings	44.560	-92.530	248	GPS-MET	M	Present	No
Cedar Creek	45.413	-93.213	280	NADP	12/31/1996	Present	No
Carlos Avery	45.303	-93.101	274	RAWS	5/1/2003	Present	No
Buffalo Muni. Arpt.	45.159	-93.843	295	SAO	4/20/2004	Present	No
Minneapolis	44.883	-93.217	255	SAO	9/1/1942	12/31/1970	No
Minneapolis	44.883	-93.217	262	SAO	1/1/1948	9/30/1960	No
Minneapolis	45.063	-93.351	272	SAO	5/1/1963	Present	No
Minneapolis	44.827	-93.457	288	SAO	5/1/1963	Present	No
Minneapolis Airlake Arpt.	44.628	-93.228	293	SAO	11/1/1992	Present	No
Minneapolis Anoka Co. Arpt.	45.150	-93.217	278	SAO	3/16/1989	Present	No
Minneapolis-St. Paul	44.883	-93.229	266	SAO	1/1/1891	Present	No
Red Wing Regl. Arpt.	44.589	-92.485	238	SAO	1/1/1992	Present	No
South St. Paul Muni. Arpt.	44.857	-93.033	250	SAO	M	Present	No
Minneapolis	44.983	-93.300	278	WBAN	1/1/1892	12/31/1964	No
St. Paul	44.950	-93.083	266	WBAN	6/1/1888	6/30/1933	No
Hudson - I-94 @ St. Croix River	44.963	-92.758	226	WIDOT	M	Present	No
River Falls - STH 35 @ Glover	44.914	-92.667	273	WIDOT	M	Present	No
Apple Valley	44.762	-93.225	291	WX4U	M	Present	No
Blaine	45.172	-93.257	307	WX4U	M	Present	No
Bloomington	44.810	-93.310	239	WX4U	M	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Monticello	45.306	-93.794	310	WX4U	M	Present	No
Savage	44.762	-93.353	241	WX4U	M	Present	No
Vadnais Heights	45.087	-93.085	290	WX4U	M	Present	No
St. Croix National Scenic Riverway (SACN)							
Hudson	44.933	-92.767	222	COOP	2/8/1891	9/15/1897	Yes
St. Croix Falls	45.412	-92.646	235	COOP	1/1/1950	Present	Yes
Taylors Falls 1 NE	45.417	-92.650	232	COOP	9/1/1906	12/31/1949	Yes
CW5689 Lakeland	44.925	-92.764	710	CWOP	M	Present	Yes
Hayward	46.031	-91.450	370	RAWS	9/1/1998	Present	Yes
Hudson - I-94 @ St. Croix River	44.963	-92.758	226	WIDOT	M	Present	Yes
Amery	45.301	-92.363	326	COOP	1/1/1922	Present	No
Baldwin	44.963	-92.391	335	COOP	10/1/1947	Present	No
Beaver Brook	45.783	-91.833	369	COOP	7/1/1916	12/26/1996	No
Cambridge 5 ESE	45.551	-93.126	293	COOP	5/13/1892	Present	No
Cedat	45.167	-93.067	271	COOP	8/1/1919	11/30/1927	No
Clam Lake 10 SW	46.046	-91.070	420	COOP	8/1/1998	Present	No
Couderay 7 W	45.800	-91.459	396	COOP	8/1/1948	Present	No
Danbury	46.008	-92.370	282	COOP	9/1/1919	Present	No
Deer Park	45.200	-92.400	323	COOP	5/13/1941	1/21/1952	No
Drummond	46.333	-91.267	408	COOP	8/1/1948	5/22/2006	No
Ellsworth 1 E	44.730	-92.459	314	COOP	3/1/1908	Present	No
Farmington 1 W	44.633	-93.167	281	COOP	4/1/1957	9/1/1970	No
Farmington 3 NW	44.670	-93.170	299	COOP	4/1/1888	Present	No
Forest Lake 5 NE	45.343	-92.922	293	COOP	10/1/1958	Present	No
Foxboro 6 SSE	46.417	-92.250	384	COOP	8/1/1960	11/30/1963	No
Frederic	45.650	-92.467	378	COOP	5/1/1944	5/13/1971	No
Gordon	46.245	-91.805	317	COOP	9/1/1951	Present	No
Grantsburg	45.773	-92.689	302	COOP	10/1/1949	Present	No
Grantsburg	45.783	-92.683	336	COOP	1/1/1893	7/31/1950	No
Hager City	44.583	-92.517	220	COOP	10/1/1932	Present	No
Hastings Dam 2	44.760	-92.869	212	COOP	8/1/1893	Present	No
Hastings Lock 2	44.767	-92.867	M	COOP	7/1/1948	Present	No
Hayward R.S.	46.000	-91.508	366	COOP	3/1/1893	Present	No
Hinckley	46.017	-92.950	317	COOP	2/1/1951	6/30/1960	No
Hinckley	45.992	-92.993	315	COOP	2/1/1893	Present	No
Luck	45.573	-92.485	372	COOP	5/1/1971	Present	No
Minong 5 WSW	46.067	-91.867	328	COOP	7/1/1961	6/30/2006	No
Minong R.S.	46.101	-91.818	329	COOP	8/1/1948	Present	No
New Richmond	45.117	-92.564	305	COOP	M	Present	No
Osceola	45.367	-92.750	246	COOP	4/1/1891	1/31/1921	No
Pine City River	45.833	-92.900	280	COOP	6/1/1994	Present	No
Red Wing	44.610	-92.610	206	COOP	7/1/1948	Present	No
Red Wing	44.571	-92.528	210	COOP	5/1/1893	Present	No
Red Wing Dam 3 L G	44.617	-92.617	M	COOP	7/1/1948	Present	No
Red Wing River	44.567	-92.567	201	COOP	5/1/1971	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Red Wing School	44.567	-92.533	M	COOP	1/1/1901	12/31/1909	No
River Falls	44.854	-92.612	284	COOP	4/1/1918	Present	No
Rosemount Agri. Exp. Stn.	44.718	-93.098	290	COOP	2/6/1943	Present	No
Shell Lake	45.767	-91.933	376	COOP	4/6/1891	7/31/1893	No
Solon Springs	46.350	-91.817	329	COOP	5/1/1906	Present	No
South St. Paul	44.867	-93.033	229	COOP	M	3/31/1978	No
Spooner	45.833	-91.883	336	COOP	4/1/1953	Present	No
Spooner Exp. Farm	45.824	-91.876	335	COOP	4/1/1894	Present	No
St. Paul	44.946	-93.030	274	COOP	5/1/1893	5/1/2006	No
St. Paul	44.950	-93.083	208	COOP	8/27/1926	Present	No
St. Paul	44.930	-93.048	220	COOP	1/1/1871	Present	No
St. Paul 3 SW	44.931	-93.154	286	COOP	5/1/2006	Present	No
St. Paul Univ. Farm	45.000	-93.167	290	COOP	8/1/1916	6/30/1951	No
Stillwater 1 SE	45.042	-92.798	216	COOP	12/28/1904	2/1/2006	No
Stillwater 2 SW	45.045	-92.852	274	COOP	12/14/2005	Present	No
Vadnais Lake	45.049	-93.096	271	COOP	5/1/1966	Present	No
Webster	45.788	-92.233	306	COOP	6/1/1998	Present	No
White Bear Lake AAWO	45.050	-93.000	296	COOP	4/1/1993	5/23/1994	No
Wild River St. Park	45.523	-92.749	287	COOP	4/29/1988	Present	No
Woodbury AAWO	44.917	-92.950	320	COOP	4/1/1993	5/23/1994	No
CW1898 St. Paul	44.990	-93.077	277	CWOP	M	Present	No
CW3319 Woodbury	44.888	-92.965	311	CWOP	M	Present	No
CW3910 Blaine	45.131	-93.171	904	CWOP	M	Present	No
CW4026 Cannon Falls	44.523	-92.934	255	CWOP	M	Present	No
CW4279 Almelund	45.554	-92.798	270	CWOP	M	Present	No
CW4659 Inver Grove Hts.	44.854	-93.072	286	CWOP	M	Present	No
CW4785 Saint Paul Park	44.836	-92.990	242	CWOP	M	Present	No
CW4965 Eagan	44.802	-93.160	259	CWOP	M	Present	No
CW5560 Saint Paul	44.938	-93.115	244	CWOP	M	Present	No
CW5900 Eagan	44.814	-93.134	291	CWOP	M	Present	No
K0DMF N. Branch	45.540	-92.978	282	CWOP	M	Present	No
KB9RQD Hawthorne	46.464	-91.975	354	CWOP	M	Present	No
KC0OPD Lino Lakes	45.158	-93.134	277	CWOP	M	Present	No
KC5LXC Stillwater	45.040	-92.861	279	CWOP	M	Present	No
KC9JWM Clam Lake	46.169	-90.981	461	CWOP	M	Present	No
Arden Hills	45.110	-93.180	281	GPS-MET	M	Present	No
Oakdale	45.000	-92.960	319	GPS-MET	M	Present	No
Red Wings	44.560	-92.530	248	GPS-MET	M	Present	No
Lac Courte Oreilles Reservation	45.994	-91.371	418	NADP	11/27/2001	3/22/2005	No
Spooner	45.823	-91.874	331	NADP	6/3/1980	Present	No
Barnes	46.400	-91.500	369	RAWS	2/1/1999	Present	No
Carlos Avery	45.303	-93.101	274	RAWS	5/1/2003	Present	No
Clam Lake	46.198	-90.970	459	RAWS	1/1/2004	Present	No
Lind	45.740	-92.796	248	RAWS	12/1/2004	Present	No
Minong	46.136	-91.981	323	RAWS	11/1/1998	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Trade River	45.653	-92.693	269	RAWS	10/1/1998	5/31/2005	No
Cambridge Muni. Arpt.	45.559	-93.265	288	SAO	1/1/1992	Present	No
Hayward	46.026	-91.444	367	SAO	6/1/1969	Present	No
New Richmond	45.150	-92.533	304	SAO	11/2/1995	Present	No
Rush City Regl. Arpt.	45.698	-92.953	281	SAO	6/1/1998	Present	No
Simenstad Muni. Arpt.	45.308	-92.690	275	SAO	4/25/2005	Present	No
Siren Burnett Co. Arpt.	45.823	-92.373	301	SAO	M	Present	No
South St. Paul Muni. Arpt.	44.857	-93.033	250	SAO	M	Present	No
St. Paul	44.930	-93.048	220	SAO	1/1/1871	Present	No
Hinckley	46.017	-92.950	321	WBAN	1/1/1937	9/30/1946	No
St. Paul	44.950	-93.083	266	WBAN	6/1/1888	6/30/1933	No
Cable - USH 63 south of Cable	46.165	-91.324	409	WIDOT	M	Present	No
Grantsburg - STH 70 W of Grant	45.773	-92.717	284	WIDOT	M	Present	No
Haugen - USH 53 @ 30th Ave.	45.639	-91.782	390	WIDOT	M	Present	No
River Falls - STH 35 @ Glover	44.914	-92.667	273	WIDOT	M	Present	No
St. Croix Falls - USH 8	45.397	-92.591	363	WIDOT	M	Present	No
Vadnais Heights	45.087	-93.085	290	WX4U	M	Present	No

"Port Wing," 28 km southwest of APIS, has been active since 1947, but its data record is generally unreliable. We identified four near-real-time stations outside of APIS but within 30 km of the park boundaries. CWOP stations are located at Bayfield and Winona. The RAWS station "Washburn" (1997-present) is 29 km south of APIS and was a summer-only site until 2003. A data gap also occurred in January-February of 2005. The SAO station in Ashland has been active since 1959.

Six weather and climate stations were identified within MISS (Table 4.5; Figure 4.3). All of these stations are active currently. Four of these stations are COOP sites. "St. Paul" provides the longest data record (1871-present) but the completeness of this record is questionable. A SAO station is collocated with the COOP station "St. Paul." A more complete long-term record comes from the COOP station "Hastings Dam 2," active since 1893. This station measured only precipitation until November 1988, with a very complete record. After 1988, this station has measured temperature as well as precipitation and the data record has been fairly complete, with gaps occurring in July 1998 and in April-May 2005. The other two COOP stations we identified, "Hastings Lock 2" and "Minneapolis," have data records going back to 1948.

Out of the 48 COOP stations identified within 30 km of the boundaries of MISS, 26 are active (Table 4.5). Of these stations, the longest record we identified was from the COOP station "Farmington 3 NW," which is 16 km southwest of MISS and has been active since 1888. This station has had a very complete record except for a gap from September 2003 to September 2004. Another reliable long-term record was identified at the COOP station "Minneapolis-St.

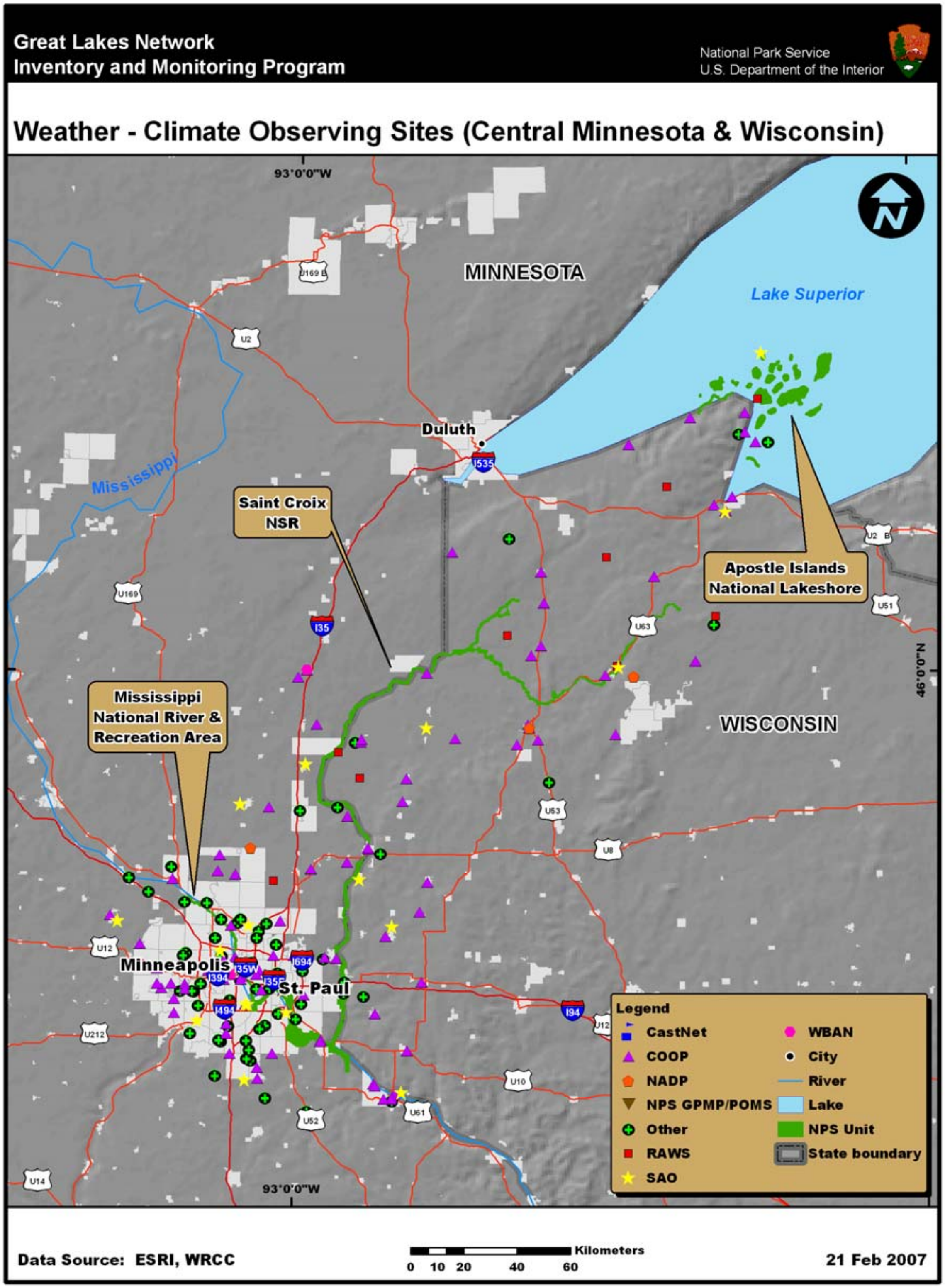


Figure 4.3. Station locations for the GLKN park units in Wisconsin and central Minnesota.

Paul," which is 3 km southwest of MISS at the Minneapolis-St. Paul International Airport. This site has been active since 1891. The COOP station "Red Wing" is a precipitation-only site 19 km southeast of MISS, whose data record (1893-present) is very complete. The COOP station "Ellsworth 1 E," which is 22 km east of MISS, has been active since 1908 and has a fairly complete data record except for a large gap from August 1978 to September 1980. The COOP station "River Falls" (1918-present) is 18 km from MISS and has a very complete data record. Several other COOP stations were identified that have data records going back to the 1940s or earlier.

One NADP station was identified within 30 km of MISS. "Cedar Creek" has been active since 1996 and is located 28 km north of MISS.

Several networks in the MISS area are sources of near-real-time weather data. Numerous CWOP and WX4U stations were identified, mostly in the Minneapolis St. Paul metropolitan area (Table 4.5; Figure 4.3). One active RAWS station was identified, 23 km northeast of MISS. This station (Carlos Avery) has been active since 2003 and has a very complete data record. Ten SAO stations, all but two of which are active, were identified within 30 km of MISS. The SAO station "Minneapolis-St. Paul," located at the Minneapolis-St. Paul International Airport, provides a reliable and long data record (1891-present). The closest SAO station to MISS is "South St. Paul Muni. Arpt.," located less than 1 km west of MISS. Other near-real-time networks we identified that have stations in the vicinity of MISS include GPS-MET and WIDOT.

Six weather and climate stations were identified within SACN (Table 4.5; Figure 4.3). Four of these stations are active currently. The COOP station "St. Croix Falls" provides the longest data record of these stations (1950-present) and the record is very complete. A CWOP station at Lakeland provides near-real-time data near the south end of SACN. The RAWS station "Hayward," in the northeastern portion of SACN, has been operating since 1998 but has numerous data gaps. A WIDOT station is located in southern SACN along Interstate 94, at its bridge over the St. Croix River.

Out of the 55 COOP stations identified within 30 km of the boundaries of SACN, 36 are active (Table 4.5). The longest record among these stations is at the COOP station "St. Paul" (1871-present), discussed previously, which is 23 km southwest of SACN. The COOP station "Farmington 3 NW" (1888-present), discussed previously, is 30 km southwest of SACN. The COOP station "Red Wing" (1893-present), discussed previously, is 29 km southeast of SACN. The COOP station "Hastings Dam 2" (1893-present), discussed previously, is 4 km west of SACN. The COOP station "Cambridge 5 ESE" is 18 km west of SACN and has been active since 1892. The data record at this station was fairly complete before 2002. However, observations have not been made reliably since 2002. The COOP station "Hayward R.S." (1893-present) is less than 1 km from SACN. The data record at this station was not reliable before 1997. However, after November 1997, the record has been very complete. The COOP station "Hinckley" (1893-present) is 22 km northwest of SACN. The data record at this station was quite complete until 2000, after which there have been numerous data gaps. The COOP station "Spooner Exp. Farm" is 9 km south of SACN. This station has been active since 1894, with a very complete data record. Numerous other COOP stations were identified that have data records going back to the first half of the twentieth century.

One active NADP station was identified within 30 km of SACN. “Spooner” has been active since 1980. Another NADP station (Lac Courte Oreilles Reservation) operated between 2001 and 2005 and was located 7 km east of SACN.

Several networks provide near-real-time weather data within 30 km of SACN. Fifteen CWOP stations and two WX4U stations were identified, mostly in the Minneapolis St. Paul metropolitan area (Table 4.5; Figure 4.3). Stations with the GPS-MET and WIDOT networks were also identified. Six active RAWS station were identified within 30 km of SACN boundaries. Five of these RAWS stations are active. “Barnes” (1999-present) is 27 km from SACN. This station’s data record was very incomplete until April 2003. The RAWS station “Carlos Avery” (2003-present), discussed previously, is 26 km from SACN. The RAWS station “Clam Lake” is 13 km from SACN and has been operating since 2004. This station’s data record has a gap from February to April of 2004. “Lind” (2004-present) is less than 1 km from SACN. This station’s data record has a large data gap from January to June of 2005, but has been quite reliable since that time. The RAWS station “Minong” (1998-present) is 7 km from SACN and has a data record that has had scattered data gaps. The last such gap occurred in June 2005.

Eight SAO stations, all of which are active, were identified within 30 km of SACN. The SAO station “St. Paul” provides the longest data record among these SAO stations (1871-present) but the completeness of this record is uncertain. The next-longest record we identified comes from the SAO station “Hayward” (1969-present), located less than 1 km south of SACN.

4.2.4. Indiana Dunes National Lakeshore

Four weather and climate stations, three of which are active, were identified within INDU (Table 4.6; Figure 4.4). The COOP station “Indiana Dunes Nat. Lk.” has been active since 1989 and provides a fairly complete data record with the exception of a gap in May and June of 2003. The NADP station “Indiana Dunes” has been active since 2000. The only source of near-real-time data we identified within INDU is the RAWS station “Bailly,” which has been active since 2003. This station’s data record is very complete.

Out of the 43 COOP stations identified within 30 km of the boundaries of INDU, only 13 are active (Table 4.6). The longest record among these stations is at the COOP station “La Porte” (1897-present), which is 9 km southeast of INDU. The data record at this station is fairly complete, although there have been recent data gaps, most notably in March-April of 2003 and in June 2003. Unfortunately, a long-term COOP station in Valparaiso recently stopped operating (Valparaiso Waterworks; 1890-2005). The COOP station “Crown Point 1 N” is 10 km southwest of INDU and has been operating since 1916. This site measures only precipitation. Its data record has only been reliable since 1992. The COOP station “Crete” is 15 km southwest of INDU and has been active since 1948. The data record at this station is unreliable. Another long climate record is found at the WBAN station “Gary” (1907-present), located 7 km west of INDU.

Five SAO stations, all of which are active, were identified within 30 km of INDU (Table 4.6). These are the primary sources of near-real-time data for INDU. The SAO station “Crete,” 15 km southwest of INDU, has been active since 1948. The other SAO stations we identified have only been active since the 1960s or later. Only one SAO station was identified east of INDU

(Michigan City), while the remaining SAO stations were located in the urban areas to the south and west of INDU (Figure 4.4). Thirteen CWOP stations also provide near-real-time data within 30 km of INDU.

Table 4.6. Weather and climate stations for INDU. Stations inside INDU and within 30 km of INDU are included. Missing entries are indicated by "M".

Indiana Dunes National Lakeshore (INDU)							
Name	**Lat.**	**Lon.**	**Elev. (m)**	**Network**	**Start**	**End**	**In Park?**
Indiana Dunes Nat. Lk.	41.632	-87.088	207	COOP	5/24/1989	Present	Yes
Indiana Dunes HQ	41.631	-87.087	208	GPMP	7/1/1981	10/31/1995	Yes
Indiana Dunes	41.633	-87.088	208	NADP	10/27/2000	Present	Yes
Bailly	41.632	-87.088	197	RAWS	2/1/2003	Present	Yes
Chicago Cal. Treat. Wk.	41.667	-87.617	180	COOP	7/1/1948	5/1/1998	No
Chicago Dan Ryan Woo.	41.733	-87.683	201	COOP	4/1/1973	5/1/1998	No
Chicago Hazelcrest	41.583	-87.650	186	COOP	4/1/1973	5/1/1998	No
Chicago Heights	41.500	-87.633	192	COOP	6/3/1901	6/30/1952	No
Chicago Homewood	41.567	-87.667	207	COOP	4/1/1963	5/31/1974	No
Chicago Lake Calumet	41.667	-87.583	180	COOP	10/1/1956	11/30/1972	No
Chicago Roseland Pum.	41.700	-87.633	201	COOP	7/1/1948	3/31/1980	No
Chicago S. Wtr. Filt. Plt.	41.750	-87.550	186	COOP	7/1/1948	3/31/1980	No
Crete	41.449	-87.622	202	COOP	7/1/1948	Present	No
Crown Point 1 N	41.436	-87.360	210	COOP	3/1/1916	Present	No
Davis	41.400	-86.701	203	COOP	1/18/1983	Present	No
East Chicago Heights	41.517	-87.583	192	COOP	4/1/1973	5/27/1982	No
Flossmoor	41.540	-87.649	188	COOP	2/23/1988	9/1/1999	No
Gary	41.617	-87.383	183	COOP	6/1/1936	1/12/1979	No
Gary Buffington Harb.	41.650	-87.417	M	COOP	M	Present	No
Gary Miller	41.617	-87.267	M	COOP	M	11/30/1972	No
Gary Steel Works	41.617	-87.333	M	COOP	3/1/1954	11/30/1972	No
Hammond	41.567	-87.500	182	COOP	12/1/1891	3/31/1919	No
Hebron 4 S	41.260	-87.200	197	COOP	7/15/1988	7/1/2002	No
Highland 1 WSW	41.550	-87.467	187	COOP	6/1/1993	6/30/1993	No
Hobart 2 WNW	41.542	-87.288	195	COOP	7/1/1919	8/1/2000	No
Kingsbury 1 N	41.537	-86.702	230	COOP	7/1/1992	Present	No
La Porte	41.612	-86.730	258	COOP	4/1/1897	Present	No
La Porte Sewage Plant	41.583	-86.700	235	COOP	12/1/1961	1/31/1964	No
Lansing	41.542	-87.541	189	COOP	6/25/2005	Present	No
Laporte 2	41.600	-86.717	M	COOP	3/1/1994	3/1/1998	No
Lowell	41.265	-87.418	203	COOP	7/1/1963	Present	No
Merrillville	41.500	-87.333	195	COOP	2/1/1993	2/1/1994	No
Merrillville	41.479	-87.376	201	COOP	7/24/2003	1/1/2004	No
Michigan City	41.700	-86.817	198	COOP	6/1/1959	4/11/1972	No
Monee Reservoir	41.393	-87.765	226	COOP	4/1/1994	Present	No
New Buffalo	41.783	-86.750	180	COOP	M	7/31/1967	No

Indiana Dunes National Lakeshore (INDU)							
Name	**Lat.**	**Lon.**	**Elev. (m)**	**Network**	**Start**	**End**	**In Park?**
New Carlisle	41.708	-86.503	232	COOP	1/17/1991	Present	No
Ogden Dunes	41.617	-87.183	186	COOP	10/1/1951	5/24/1989	No
Park Forest	41.493	-87.680	216	COOP	6/1/1952	Present	No
South Chicago Lbstn.	41.717	-87.533	M	COOP	M	11/30/1972	No
Thornton	41.568	-87.625	179	COOP	2/23/1988	9/1/1999	No
Valparaiso 5 NNE	41.544	-87.032	265	COOP	5/5/2003	Present	No
Valparaiso Technical	41.467	-87.067	229	COOP	6/1/1966	3/31/1978	No
Valparaiso Waterworks	41.511	-87.038	244	COOP	4/1/1890	6/8/2005	No
Wakarusa 1 NNE	41.566	-86.998	251	COOP	3/1/1994	10/22/2002	No
Wanatah 2 WNW	41.444	-86.930	224	COOP	11/1/1960	Present	No
Whiting	41.650	-87.483	189	COOP	10/1/1909	5/31/1962	No
CW0783 Valparaiso	41.417	-87.154	213	CWOP	M	Present	No
CW2311 Crete	41.400	-87.600	195	CWOP	M	Present	No
CW2722 Crown Point	41.378	-87.349	235	CWOP	M	Present	No
CW3332 Chicago	41.702	-87.685	216	CWOP	M	Present	No
CW3792 Merrillville	41.484	-87.263	210	CWOP	M	Present	No
CW3904 New Carlisle	41.665	-86.506	263	CWOP	M	Present	No
CW5059 Hobart	41.536	-87.244	192	CWOP	M	Present	No
CW5229 Glenwood	41.533	-87.600	189	CWOP	M	Present	No
CW5742 Michigan City	41.666	-86.868	190	CWOP	M	Present	No
CW5929 Munster	41.534	-87.487	184	CWOP	M	Present	No
N9ZIP Michigan City	41.702	-86.874	192	CWOP	M	Present	No
W9EMA Crown Point	41.450	-87.367	221	CWOP	M	Present	No
W9EWA Valparaiso/Cobbs Corn	41.434	-87.112	231	CWOP	M	Present	No
Chicago Dunne Crib.	41.783	-87.533	177	SAO	12/1/1972	Present	No
Chicago Lansing Municipal Arpt.	41.540	-87.532	188	SAO	11/1/1993	Present	No
Crete	41.449	-87.622	202	SAO	7/1/1948	Present	No
Michigan City	41.717	-86.900	177	SAO	6/1/1970	Present	No
Valparaiso	41.453	-87.006	235	SAO	7/1/1968	Present	No
Calumet Harbor	41.717	-87.533	198	WBAN	1/1/1973	6/30/1980	No
Gary	41.617	-87.417	180	WBAN	3/1/1907	Present	No
McCool	41.550	-87.167	199	WBAN	7/1/1929	12/31/1946	No

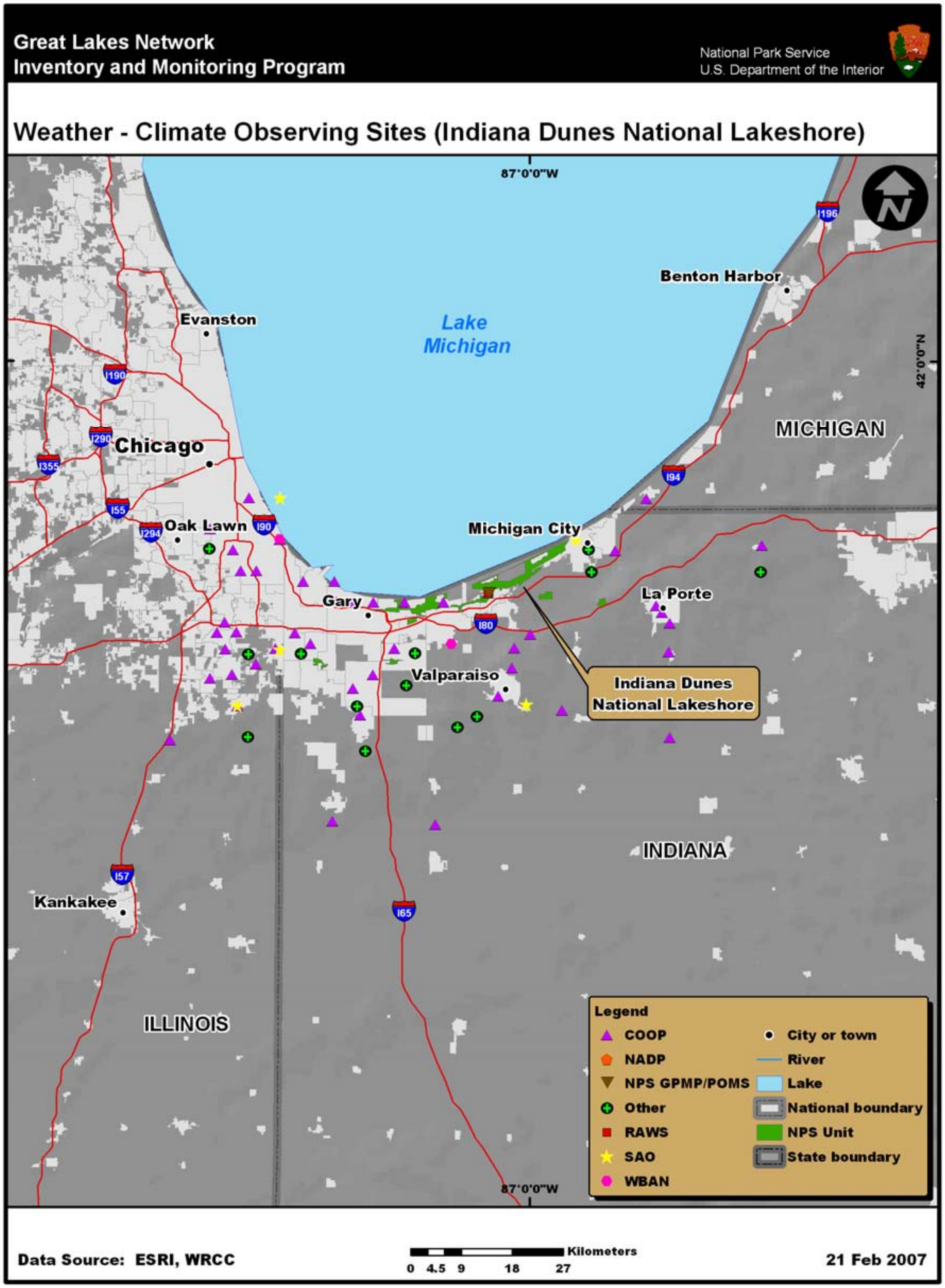


Figure 4.4. Station locations for INDU.

5.0. Conclusions and Recommendations

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

5.1. Great Lakes Inventory and Monitoring Network

One GLKN park units, PIRO, had no weather or climate stations identified within their boundaries. Climate monitoring efforts in PIRO would likely benefit from installing additional weather and climate stations inside the park unit, which is located in an area with high spatial precipitation variability associated with lake effect rain/snow events and sharp lake-interior gradients. Currently, the closest stations to PIRO are just near the edges of the park unit.

The Midwest Hazecam (http://www.mwhazecam.net/grand.html) provides near-real-time weather station at GRPO; however, no climate records are available at the park unit. Therefore, GRPO must rely heavily on outside sources of climate data for its climate monitoring efforts. The COOP station at Grand Portage Ranger Station, just south of GRPO, provides the closest long-term climate record for the park. It is unfortunate that the climate record at this station has had many data gaps, despite being fairly complete since 1997. Climate monitoring efforts within GRPO will benefit by encouraging continuous observations at Grand Portage Ranger Station, as this record will provide valuable documentation of ongoing climate changes at GRPO park units. Weather monitoring efforts would be furthered by encouraging the continued operation of the RAWS station "Grand Portage."

Weather and climate station coverage is present but severely deficient in a few other GLKN park units. In SLBE, although we identified a few active COOP stations, it is not clear how reliable their data records are. There are no automated stations within the park unit. The SAO station "N. Manitou Shoals" is technically not in SLBE, being located between N. Manitou Island and Pyramid Point. SLBE currently has limited options for automated weather stations and long-term climate stations; therefore, the park unit must rely heavily on nearby outside stations, located mostly to the south and west. A CRN station may possibly be installed near SLBE in the near future. The Devils Island SAO is the longest climate record in APIS. It is therefore imperative that this record be continued, which will benefit ongoing monitoring efforts at APIS. There are some known gaps in the existing coverage of weather stations at ISRO and the GLKN has funded upgrades to two RAWS at ISRO to help address these coverage gaps (Route and Elias 2007). We anticipate that additional sites at ISRO and other parks may be desirable. For example, the middle portions of ISRO lack station coverage currently, leaving much uncertainty regarding precipitation patterns in these areas. For VOYA, the weather and climate stations we identified are located at the primary access points along the fringes of the park unit. We identified little in the way of station coverage in the more remote interior portions of VOYA. The reliable long-term records we identified within 30 km of VOYA were near International Falls, well to the west of the park unit. The closest long-term stations to INDU, such as the COOP station in LaPorte, are roughly 10 km inland from the shore of Lake Michigan. No stations were identified right near the lake shore in INDU. Climate monitoring efforts in INDU will likely benefit greatly by keeping the COOP station in INDU (Indiana Dunes Nat. Lk.)

operational, at its present location, in order to build up a much-needed climate record within the park unit.

Long-term climate stations have recently ceased operating near some of the GLKN park units. This unfortunately hurts climate monitoring efforts to document climate changes across the GLKN. These losses are particularly noticeable for APIS, INDU, MISS, and SACN. For APIS, the COOP stations "Ashland Exp. Farm" and "Bayfield 6 N" recently stopped taking measurements (1893-2005). The COOP station "Valparaiso Waterworks," near INDU, was a valuable long-term climate record that stopped recently (1890-2005). For MISS and SACN, one of the St. Paul COOP sites we identified ceased taking measurements in 2006. It had been active since 1893.

Even when long-term sites have been identified that are still active, there are sometimes questions about whether these records actually come from multiple stations. One example of this situation is near SLBE, where two COOP stations identified in Traverse City, Michigan, may actually be the same station. One of these COOP stations has a purportedly active data record that extends back to 1896. However, the data record has become very incomplete since July 2001, leading us to suspect how active this station still is. Interestingly, the second Traverse City COOP station in question had a data record that started in July 2001, so this may be a continuation of the first station we discussed. This can be verified by contacting NCDC (http://www.ncdc.noaa.gov). Caution must be exercised when utilizing these records. With this in mind, whenever active stations having longer climate records are identified, climate monitoring efforts within the GLKN will benefit by encouraging their continuous operation at a single location, as such records provide valuable documentation of ongoing climate changes within GLKN park units.

In contrast to the above discussion, the GLKN park units in central Minnesota and Wisconsin have much better weather and climate station coverage. The urban setting of MISS (the Minneapolis-St. Paul metropolitan area) provides many sources of long-term climate records and automated sites. The southern portions of SACN also benefit from the denser station coverage around Minneapolis-St. Paul. However, fewer stations, especially near-real-time sites, are present along northern portions of SACN. Consideration could be given to the idea of adding RAWS stations at various points along northern SACN, since the RAWS network already has a substantial presence in the area. Climate monitoring efforts for northern SACN would benefit by encouraging the continued operation of those active long-term climate stations that are already present in the area. Since both MISS and SACN protect riverways, NPS may want to consider using existing stations and any new stations to monitor spatial variations in temperature and precipitation along the riverways. This may be especially valuable for SACN, which winds its way through large portions of central Minnesota along with central and northern Wisconsin. However, as previously mentioned, northern portions of SACN may need to add additional stations to accomplish this. Such transects would likely be fairly easy to implement for MISS, due to the numerous stations available in its urban setting.

Water plays a key role in maintaining the ecosystems of the GLKN park units. Precipitation strongly influences the availability of water for GKLN ecosystems and has a high degree of spatial variability, particularly in those GLKN park units located on the south and east shores of the Great Lakes (e.g., INDO, PIRO, and SLBE). However, as previously discussed, weather/station coverage in many of these park units is quite limited, with the result that local precipitation patterns, such as those due to lake effect events, are severely undersampled. It is therefore critical that NPS and the GLKN consider ways in which to increase the coverage of precipitation measurements throughout GLKN units along the Great Lakes. Due to the region's substantial winter snowfalls, one possibility may be to work with USDA/NRCS to introduce SNOTEL stations into the Great Lakes area. Another possibility may be to work with the Great Lakes Environmental Research Laboratory (GLERL) to install weather stations that can better sample precipitation characteristics in the region.

Another reason that winter precipitation is severely undersampled in the GLKN park units is that many of the weather and climate stations we identified currently only take observations in the summer. We identified both COOP and RAWS stations that fall in this category. This is particularly common in GLKN park units in northernmost Minnesota (e.g., VOYA) and in upper Michigan (e.g., ISRO). It has been encouraging to see recent shifts to year-round observations, particularly with several of the RAWS stations in these areas. Hopefully other COOP and RAWS stations will follow this example and also convert to year-round stations.

5.2. Spatial Variations in Mean Climate

The Great Lakes themselves introduces considerable fine-scale structure to mean climate (temperature and precipitation) within the GLKN park units. The lake-effect rain and snow events common in post-frontal airmasses over the Great Lakes introduce large precipitation variations over very short distances along southern and eastern shores of the Great Lakes. Large gradients in temperature over short distances are common between the lakes and interior locations. Issues encountered in mapping mean climate are discussed in Appendix D and in Redmond et al. (2005).

For areas where new stations will be installed, if only a few new stations will be emplaced, the primary goal should be overall characterization of the main climate elements (temperature and precipitation and their joint relative, snow). This level of characterization generally requires that (a) stations should not be located in deep valley bottoms (cold air drainage pockets) or near excessively steep slopes and (b) stations should be distributed spatially in the major biomes of each park. New station installations should target locations where preferred lake-effect banding occurs, if these locations are not already sampled. Stations should also be present in adjacent areas that tend to be drier. This would help document the characteristic scales of precipitation variability associated with lake-effect events. If stations already are present in a given area, 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.

5.3. Climate Change Detection

There is much interest in the adaptation of GLKN ecosystems in response to possible future climate change (Post and Stenseth 1999; Davis et al. 2000; Kling et al. 2003; Route and Elias 2007). In particular, there are concerns about snowpack trends and changes in lake-effect event frequencies as a result of larger scale climate changes (Kunkel et al. 2002; Route and Elias 2007).

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

5.4. Aesthetics

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

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

5.5. Information Access

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

Decisions about improvements in monitoring capacity are facilitated greatly by the ability to examine available climate information. Various methods are being created at WRCC to improve access to that information. Web pages providing historic and ongoing climate data, and information from GLKN 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 GLKN park units but also to climate-monitoring efforts for GLKN. 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

- Precipitation characteristics in many GLKN park units (e.g., PIRO, SLBE) are undersampled. Expanded coverage of precipitation observations would benefit climate monitoring efforts in GLKN. Partnerships with GLERL and the NRCS SNOTEL network may be useful.
- Many identified stations (both COOP and RAWS) take measurements only in summer months, particularly in GKLN park units in northern Minnesota and Michigan. Winter weather conditions are not sampled as a result. Encouragingly, several such stations have switched to year-round observations in recent years.
- Climate transects may be useful monitoring tools for riverway park units like MISS and SACN.
- The Minneapolis-St. Paul metropolitan area provides ample weather and climate station coverage for MISS and southern portions of SACN.
- The recent loss of active long-term climate records around some GLKN park units (e.g., APIS, INDU) negatively affects ability to document climate changes across the GLKN. Some long-term records near GLKN park units (e.g., SLBE) may be composed of records from multiple stations.
- Climate monitoring efforts in GLKN will benefit by continuing the operation of those long-term climate stations identified in and near GLKN park units.

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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 weather/ climate network

C.1. Climate versus Weather

- Climate measurements require *consistency through time.*

C.2. Network Purpose

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

C.3. Site Identification and Selection

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

C.4. Station Hardware

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

C.5. Communications

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

C.6. Maintenance

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

C.7. Maintaining Programmatic Continuity and Corporate Knowledge

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

C.8. Data Flow

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

C.9. Products

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

C.10. Funding

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

C.11. Final Comments

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

Source: Western Regional Climate Center (WRCC)

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

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

D.1. Introduction

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

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

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

D.1.1. Network Purpose

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

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

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

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

D.1.2. Robustness

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

D.1.3. Weather versus Climate

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

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

D.1.4. Physical Setting

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

D.1.5. Measurement Intervals

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

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

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

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

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

D.1.6. Mixed Time Scales

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

D.1.7. Elements

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

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

D.1.8. Wind Standards

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

D.1.9. Wind Nomenclature

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

D.1.10. Frozen Precipitation

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

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

D.1.11. Save or Lose

A second consideration with precipitation is determining if the measurement should be saved (as in weighing systems) or lost (as in tipping-bucket systems). With tipping buckets, after the water has passed through the tipping mechanism, it usually just drops to the ground. Thus, there is no checksum to ensure that the sum of all the tips adds up to what has been saved in a reservoir at some location. By contrast, the weighing gauges continually accumulate until the reservoir is emptied, the reported value is the total reservoir content (for example, the height of the liquid column in a tube), and the incremental precipitation is the difference in depth between two known times. These weighing gauges do not always have the same fine resolution. Some gauges only record to the nearest centimeter, which is usually acceptable for hydrology but not necessarily for other needs. (For reference, a millimeter of precipitation can get a person in street clothes quite wet.) Other weighing gauges are capable of measuring to the 0.25-mm (0.01-in.) resolution but do not have as much capacity and must be emptied more often. Day/night and storm-related thermal expansion and contraction and sometimes wind shaking can cause fluid pressure from accumulated totals to go up and down in SNOTEL gauges by small increments (commonly 0.3-3 cm, or 0.01–0.10 ft) leading to “negative precipitation” followed by similarly non-real light precipitation when, in fact, no change took place in the amount of accumulated precipitation.

D.1.12. Time

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

D.1.13. Automated versus Manual

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

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

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

D.1.14. Manual Conventions

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

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

D.2. Representativeness

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

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

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

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

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

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

D.2.1. Temporal Behavior

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

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

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

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

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

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

D.2.2. Spatial Behavior

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

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

D.2.3. Climate-Change Detection

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

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

D.2.4. Element-Specific Differences

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

D.2.5. Logistics and Practical Factors

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

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

D.2.6. Personnel Factors

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

D.3. Site Selection

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

D.3.1. Equipment and Exposure Factors

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

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

D.3.1.3. Elevation: Mountain climates do not vary in time in exactly the same manner as adjoining valley climates. This concept is emphasized when temperature inversions are present to a greater degree and during precipitation when winds rise up the slopes at the same angle.

There is considerable concern that mountain climates will be (or already are) changing and perhaps changing differently than lowland climates, which has direct and indirect consequences for plant and animal life in the more extreme zones. Elevations of special significance are those that are near the mean rain/snow line for winter, near the tree line, and near the mean annual freezing level (all of these may not be quite the same). Because the lapse rates in wet climates often are nearly moist-adiabatic during the main precipitation seasons, measurements at one elevation may be extrapolated to nearby elevations. In drier climates and in the winter, temperature and to a lesser extent wind will show various elevation profiles.

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

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

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

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

D.3.2. Element-Specific Factors

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

D.3.3. Long-Term Comparability and Consistency

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

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

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

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

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

Appendix F. Electronic supplements

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

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

Appendix G. Descriptions of weather/climate monitoring networks

G.1. Canadian weather/climate stations (CANADA)

- Purpose of network: provide weather/climate data for forecasting and climate-monitoring efforts in Canada.
- Primary management agency: The Meteorological Service of Canada.
- Data website: http://www.weatheroffice.ec.gc.ca/canada_e.html.
- Measured weather/climate elements:
  - Air temperature.
  - Barometric pressure.
  - Relative humidity and dewpoint temperature.
  - Precipitation.
  - Wind speed and direction.
  - Wind gust and direction.
  - Solar radiation.
  - Sky Cover.
  - Ceiling.
  - Visibility.
- Sampling frequency: hourly.
- Reporting frequency: hourly.
- Estimated station cost: unknown.
- Network strengths:
  - Data are of high quality.
  - Periods of record are relatively long.
  - Sites are well-maintained.
- Network weaknesses:
  - Sites are only in Canada, so usefulness limited to northern NPS park units.
  - Limited data access.

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

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.

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

G.3. NWS Cooperative Observer Program (COOP)

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

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

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

G.4. NOAA Climate Reference Network (CRN)

- Purpose of network: provide long-term homogeneous measurements of temperature and precipitation that can be coupled with long-term historic observations to monitor present and future climate change.
- Primary management agency: NOAA.
- Data website: http://www.ncdc.noaa.gov/crn/.
- Measured weather/climate elements:
    - Air temperature (triply redundant, aspirated).
    - Precipitation (three-wire Geonor gauge).
    - Wind speed.
    - Solar radiation.
    - Ground surface temperature.
- Sampling frequency: precipitation can be sampled either 5 or 15 minutes. Temperature sampled every 5 minutes. All other elements sampled every 15 minutes.
- Reporting frequency: hourly or every three hours.
- Estimated station cost: $30000 with maintenance costs around $2000/year.
- Network strengths:
    - Station siting is excellent (appropriate for long-term climate monitoring).
    - Data quality is excellent.
    - Site maintenance is excellent.
- Network weaknesses:
    - CRN network is still developing.
    - Period of record is short compared to other automated networks.
    - Station coverage is limited.
    - Not intended for snowy climates.

Data from the CRN are used in operational climate-monitoring activities and are used to place current climate patterns into a historic perspective. The CRN is intended as a reference network for the U.S. that meets the requirements of the Global Climate Observing System. Up to 115

CRN sites are planned for installation, but the actual number of installed sites will depend on available funding.

G.5. Citizen Weather Observer Program (CWOP)

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

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

G.6. NPS Gaseous Pollutant Monitoring Program (GPMP)

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

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

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

G.7. NOAA Ground-Based GPS Meteorology (GPS-MET) Network

- Purpose of network:
  - Measure atmospheric water vapor using ground-based GPS receivers.
  - Facilitate use of these data operational and in other research and applications.
  - Provides data for weather forecasting, atmospheric modeling and prediction, climate monitoring, calibrating and validation other observing systems including radiosondes and satellites, and research.
- Primary management agency: NOAA Earth System Research Laboratory.
- Data website: http://gpsmet.noaa.gov/jsp/index.jsp.
- Measurements:
  - Dual frequency carrier phase measurements every 30 seconds.
- Ancillary weather/climate observations:
  - Air temperature.
  - Relative humidity.
  - Barometric pressure.
- Reporting frequency: currently 30 min.
- Estimated station cost: $0-$10000, depending on approach. Data from dual frequency GPS receivers installed for conventional applications (e.g., high accuracy surveying) can be used without modification.
- Network strengths:
  - Frequent, high-quality measurements.
  - High reliability.
  - All-weather operability.
  - Many uses.

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

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

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

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

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

G.8. National Atmospheric Deposition Program (NADP)

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

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

G.9. Portable Ozone Monitoring System (POMS)

- Purpose of network: provide seasonal, short-term (1-5 years) monitoring of near-surface atmospheric ozone levels in remote locations.
- Primary management agency: NPS.
- Data website: http://www2.nature.nps.gov/air/studies/portO3.htm.
- Measured weather/climate elements:
  - Air temperature.
  - Precipitation.
  - Relative humidity.
  - Wind speed and direction.
  - Solar radiation.
- Sampling frequency: hourly.
- Reporting frequency: hourly.
- Estimated station cost: $20000 with operation and maintenance costs of up to $10000/year.
- Network strengths:
  - High-quality data.
  - Site maintenance is excellent.
- Network weaknesses:
  - No long-term sites, so not as useful for climate monitoring.
  - Sites are somewhat expensive to operate.

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

G.10. Remote Automated Weather Station (RAWS) Network

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

- Purpose of network: provide near-real-time (hourly or near hourly) measurements of meteorological variables and are used both for airport operations and weather forecasting.
- Primary management agency: NOAA, FAA.
- Data website: data are available from state climate offices, RCCs (e.g., WRCC, http://www.wrcc.dri.edu), and NCDC (http://www.ncdc.noaa.gov).
- Measured weather/climate elements:
  - Air temperature.
  - Dewpoint and/or relative humidity.
  - Wind speed.
  - Wind direction.
  - Wind gust.
  - Gust direction.
  - Barometric pressure.
  - Precipitation (not at many FAA sites).
  - Sky cover.
  - Ceiling (cloud height).
  - Visibility.
- Sampling frequency: element-dependent.
- Reporting frequency: element-dependent.
- Estimated station cost: $100000–$200000, with maintenance costs approximately $10000/year.
- Network strengths:
  - Records generally extend over several decades.
  - Consistent maintenance and station operations.
  - Data record is reasonably complete and usually high quality.
  - Hourly or sub-hourly data.
- Network weaknesses:
  - Nearly all sites are located at airports.
  - Data quality can be related to size of airport—smaller airports tend to have poorer datasets.
  - Influences from urbanization and other land-use changes.

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

G.12. Wisconsin Department of Transportation (WIDOT) Network

- Purpose of network: provide weather data to support management of Wisconsin's transportation network.
- Primary management agency: WIDOT.

- Data website: http://www.met.utah.edu/jhorel/html/mesonet.
- Measured weather/climate elements:
  - Air temperature.
  - Relative humidity.
  - Wind speed and direction.
  - Wind gust and direction.
- Sampling frequency: unknown.
- Reporting frequency: unknown.
- Estimated station cost: unknown.
- Network strengths:
  - Real-time data.
  - Routine station maintenance.
- Network weaknesses:
  - Coverage is limited to the state of Wisconsin.
  - Access to archived data can be difficult.

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

G.13. Weather For You Network (WX4U)

- Purpose of network: allow volunteer weather enthusiasts around the U.S. to observe and share weather data.
- Data website: http://www.met.utah.edu/jhorel/html/mesonet.
- Measured weather/climate elements:
  - Air temperature.
  - Relative humidity and dewpoint temperature.
  - Precipitation.
  - Wind speed and direction.
  - Wind gust and direction.
- Sampling frequency: 10 minutes.
- Reporting frequency: 10 minutes.
- Estimated station cost: unknown.
- Network strengths:
  - Stations are located throughout the U.S.
  - Stations provide near-real-time observations.
- Network weaknesses:
  - Instrumentation platforms can be variable.
  - Data are sometimes of questionable quality.

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

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