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Weather and Climate Inventory National Park Service North Coast and Cascades Network

Natural Resource Technical Report NPS/NCCN/NRTR—2006/010

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Natural Resource Technical Report NPS/NCCN/NRTR—2006/010
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NPS/NCCN/NRTR—2006/010, October 2006

Contents

Figures

Page

Tables

Page

Appendixes

Acronyms

AASC	American Association of State Climatologists
ACIS	Applied Climate Information System
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
EBLA	Ebey's Landing National Historical Reserve
ENSO	El Niño Southern Oscillation
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FIPS	Federal Information Processing Standards
FOVA	Fort Vancouver National Historic Site
GMT	Greenwich Mean Time
GOES	Geostationary Operational Environmental Satellite
GPMP	Gaseous Pollutant Monitoring Program
GPS	Global Positioning System
GPS-MET	NOAA ground-based GPS meteorology
I&M	NPS Inventory and Monitoring Program
LEO	Low Earth Orbit
LEWI	Lewis and Clark National Historical Park
LST	local standard time
MORA	Mount Rainier National Park
NADP	National Atmospheric Deposition Program
NCCN	North Coast and Cascades Inventory and Monitoring Network
NCDC	National Climatic Data Center
NDBC	National Data Buoy Center
NetCDF	Network Common Data Form
NOAA	National Oceanic and Atmospheric Administration
NOCA	North Cascades National Park Service Complex
NPS	National Park Service
NRCS	Natural Resources Conservation Service
NRCS-SC	Natural Resources Conservation Service snowcourse network
NWAVAL	Northwest Weather and Avalanche Center Network
NWS	National Weather Service
ODEQ	Oregon Department of Environmental Quality
ODOT	Oregon Department of Transportation
OLYM	Olympic National Park
OLYM-MISC	Local network – Olympic National Park

PDO	Pacific Decadal Oscillation
PNA	Pacific-North America Oscillation
POMS	Portable Ozone Monitoring System
PRISM	Parameter Regression on Independent Slopes Model
RAWS	Remote Automated Weather Station Network
RCC	regional climate center
SAJH	San Juan Island National Historical Park
SAO	Surface Airways Observation Network
Surfrad	Surface Radiation Budget Network
SNOTEL	Snowfall Telemetry Network
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
UTC	Coordinated Universal Time
WA DOT	Washington State Department of Transportation
WAAQ	Washington State Department of Ecology – Air Quality Program
WBAN	Weather Bureau Army Navy
WRCC	Western Regional Climate Center
WX4U	Weather For You network

Executive Summary

Climate is a dominant factor driving the physical and ecologic processes affecting the North Coast and Cascades Inventory and Monitoring Network (NCCN). Climate variations are responsible for short- and long-term changes in ecosystem fluxes of energy and matter and have profound effects on underlying geomorphic and biogeochemical processes. The NCCN is characterized by large environmental gradients, such as in climate and topography. These gradients result in a large variety of plant and animal communities and ecosystems. The widespread glaciated areas in the NCCN are very sensitive to global-scale climate changes and provide useful locations to monitor such changes. Because of its influence on the ecology of NCCN park units and the surrounding areas, climate was identified as a high-priority, vital sign for NCCN, and climate is one of the 12 basic inventories to be completed for all National Park Service (NPS) Inventory and Monitoring Program (I&M) networks.

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

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

The NCCN climate is complex, encompassing environments ranging from alpine zones to lower-elevation basins exhibiting sharp transitions in various places. Mean annual temperatures range from under -2°C for upper elevations of Mount Rainier National Park (MORA), up to around 10°C at Fort Vancouver National Historic Site (FOVA). Much of the NCCN is cool and wet, lying at or west of the crest of the Cascade Mountains. The wettest locations are in Olympic National Park (OLYM), where mean annual precipitation is over 5000 mm in some places. The NCCN does, however, include an anomalously warm and dry region on the northeastern Olympic Peninsula and the nearby islands in Puget Sound, created primarily by the rainshadowing effects of the Olympic Mountains. Ebey’s Landing National Historical Reserve (EBLA) is located in this rainshadow and has a mean annual precipitation of just over 500 mm. At higher elevations of the Olympic and Cascade mountain ranges, mean annual snowfall totals can regularly exceed 15 m. The annual snowfall record for the entire nation occurred during the winter of 1998-1999, when the Mount Baker Ski Area received 1140 inches (2896 cm) of snowfall. The Pacific/North American Oscillation (PNA) is an important contributor to variability of storm frequencies and tracks during a given year. Both the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) cause interannual climate variations in the NCCN. While precipitation time series in the NCCN do not show a significant trend, temperature time series do clearly show warming, especially in the last 3 decades. Some studies also suggest that mountain snowpack in the region has decreased over the last several decades.

Through a search of national databases and inquiries to NPS staff, we have identified 70 weather and climate stations within NCCN park units. These include two stations in EBLA, one station in Lewis and Clark National Historical Park (LEWI), 17 stations in MORA, 19 stations in North Cascades National Park Service Complex (NOCA), and 31 stations in OLYM. Metadata and data records for most of the weather and climate stations within NCCN are sufficiently complete and of satisfactory quality. This is due largely to the extensive previous efforts by NCCN to identify weather and climate stations.

The NCCN park units located along the Columbia River and the Puget Sound region have satisfactory station coverage. Reliable real-time weather observations are provided by Surface Airways Observation Network (SAO) stations at airports near each of these parks. Existing manual sites with long data records that are near these park units should be retained for the purpose of long-term climate monitoring. Of these park units, San Juan Island National Historical Park (SAJH) has the least satisfactory coverage of weather/climate stations. There are no long-term climate records on San Juan Island; the closest long-term records are from stations that are almost 20-30 km away. The SAO stations on San Juan Island (Friday Harbor Airport, Roche Harbor SPB) provide the most applicable weather observations for SAJH.

The current and past weather and climate stations in NCCN sample atmospheric conditions over a large portion of the land area and ecosystem zones. However, weather and climate stations are not present in some montane and alpine ecosystems in the NCCN. These include large portions of southeastern OLYM, northern NOCA, and northern MORA. Additional stations in these areas would enhance understanding of climate patterns and variability in the region and better monitor montane and alpine ecosystem responses to climate change, particularly in glaciated areas.

We recommend that the NPS partner with the U.S. Department of Agriculture's Natural Resources Conservation Service (USDA/NRCS) to install one enhanced Snowfall Telemetry network (SNOTEL) station in each of these three areas, particularly in OLYM and NOCA. In OLYM, such an installation would help to understand the characteristics of the sharp precipitation gradient that occurs between Puget Sound and the crest of the Olympic Mountains. The snowcourses currently located in the northern unit of North Cascades National Park this unit do not measure enough weather and climate elements to adequately describe the unit's local climate characteristics. Since the snowcourses only measure snowdepth a few times during the winter season, they also do not provide enough data to adequately monitor the unit's climate patterns and variability, especially at seasonal time scales and shorter. We suggest that one of the snowcourses in the northern unit of North Cascades National Park be enhanced with a full SNOTEL station, preferably at one of the more accessible locations such as Beaver Pass.

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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; Weber et al. 2005).

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

The purpose of this report is to determine the current status of weather and climate monitoring within NCCN (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 NCCN park units.
- Inventory of locations for all weather stations in and near NCCN park units that are relevant to the NPS I&M networks.
- Results of metadata inventory for each station, including weather-monitoring network affiliations, types of recorded measurements, and information about actual measurements (length of record, etc.).
- Initial evaluation of the adequacy of coverage for existing weather stations and recommendations for improvements in monitoring weather and climate.

Table 1.1. Park units in the NCCN.

Acronym	Name
EBLA	Ebey’s Landing National Historical Reserve
FOVA	Fort Vancouver National Historic Site
LEWI	Lewis and Clark National Historical Park
MORA	Mount Rainier National Park
NOCA	North Cascades National Park Service Complex
OLYM	Olympic National Park
SAJH	San Juan Island National Historical Park

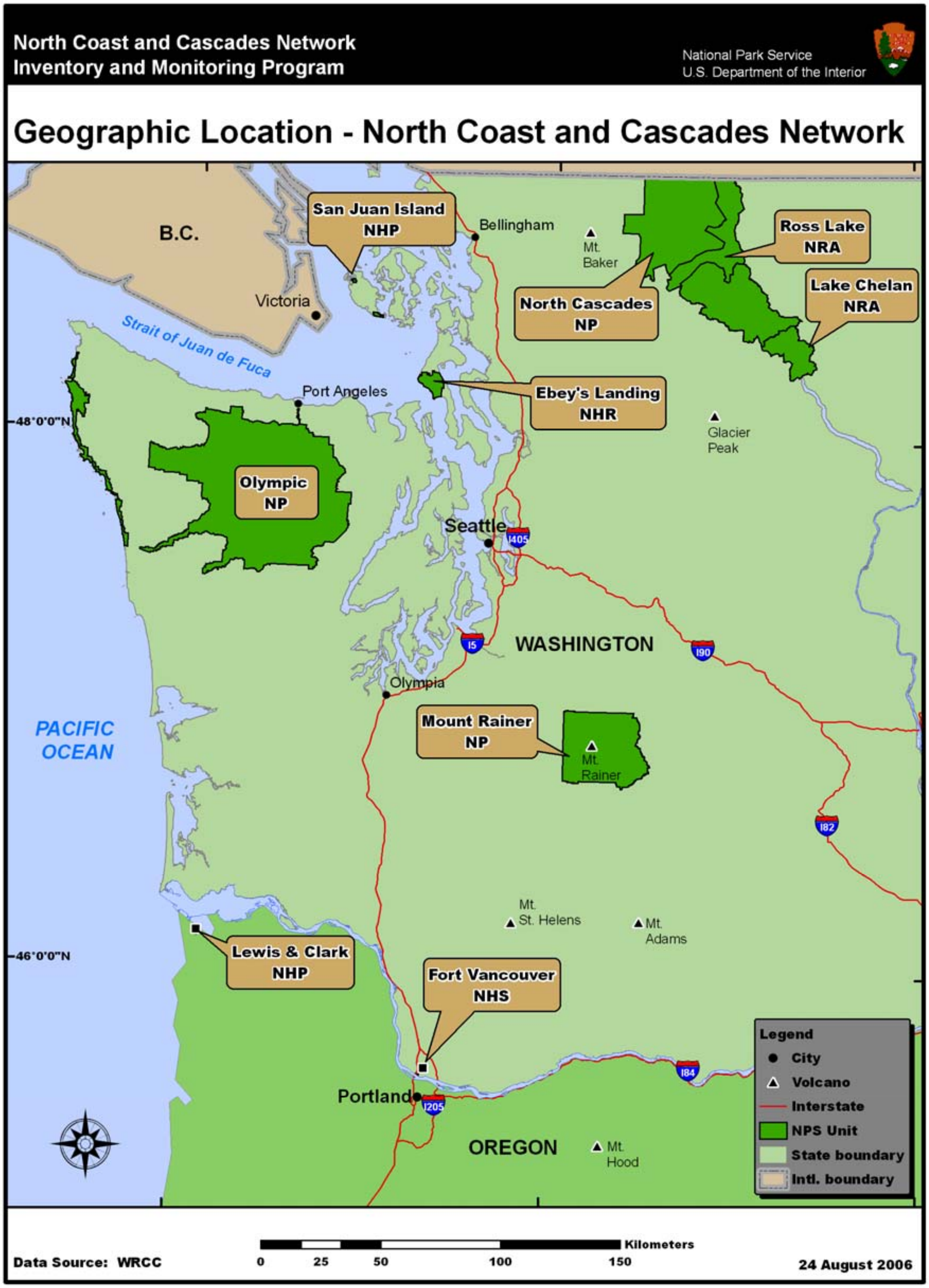


Figure 1.1. Map of the North Coast and Cascades Network.

It is essential that park units within the North Coast and Cascades Inventory and Monitoring Network (NCCN) have an effective climate-monitoring system in place to track climate changes and to aid in management decisions relating to these changes. The primary objectives for climate- and weather-monitoring in NCCN are as follows (Weber et al. 2005):

A. To determine parkwide spatial (climate zone, elevation, aspect) and temporal (monthly, seasonal, annual, decadal) trends in air temperature, precipitation (including snow, snow depth, and snow water equivalent), wind speed, wind direction, soil moisture, relative humidity and solar radiation in each park.
B. To determine parkwide trends in the annual and decadal extent of snowpack in MORA, NOCA, and OLYM.
C. To determine parkwide spatial and temporal (annual and decadal) trends in lake ice-out in MORA, NOCA, and OLYM (index lakes are the sites selected by the aquatic technical working group for monitoring long-term trends in montane lakes.

1.1. Network Terminology

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

1.1.1. Weather/Climate Station Networks

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

1.1.2. NPS I&M Networks

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

1.2. Weather versus Climate Definitions

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

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

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

1.3. Purpose of Measurements

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

- What is the purpose of weather and climate measurements?

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

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

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

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

1.4. Design of Climate-Monitoring Programs

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

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

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

1.4.1. Need for Consistency

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

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

1.4.2. Metadata

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

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

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

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

1.4.3. Maintenance

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

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

1.4.4. Automated versus Manual Stations

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

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

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, Type I errors are deemed far less desirable than Type II errors.

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

1.4.7. Standards

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

1.4.8. Who Makes the Measurements?

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

2.0. Climate Background

2.1. Climate and the NCCN Environment

The climatic characteristics of the NCCN region are strongly influenced by topographic constraints (Weber et al. 2005). The elevations represented in the NCCN parks range from just below sea level to over 4300 m (14000 ft), with correspondingly large gradients in temperature and precipitation (Weber et al. 2005). The Cascade and Olympic mountain ranges act as major barriers that intercept much of the moisture from storms off of the Pacific Ocean, creating a large gradient in precipitation between the western slopes (wet) and eastern slopes (dry) of these ranges. These environmental gradients result in a large variety of plant and animal communities and ecosystems in the NCCN (Weber et al. 2005), as showcased by the three largest parks: MORA, NOCA, and OLYM. Climate is fundamental in determining the physical template for vegetation, wildlife habitat and aquatic systems. Climate also strongly influences natural processes and disturbances that dynamically govern the characteristics of these natural systems. Commonly occurring climate-related disturbances in the NCCN include fire, wind throw, flooding, and glacial activity. Climate can also influence secondary disturbance effects from insects, pathogens, diseases, and parasitism (Weber et al. 2005).

In addition to the rich biodiversity in the freshwater systems of the NCCN, the marine areas of the NCCN hold the most bio-diverse marine region on the west coast of North America (Weber et al. 2005). Climate change may significantly alter hydrologic cycles, temporal patterns in thermal regimes, productivity, and distributions and abundance of aquatic biota. In the riparian areas of the NCCN, flood-level flows can occur every few years and significantly reshape local channel characteristics (Weber et al. 2005). These also affect the supply and delivery of water, sediment and large woody debris to stream channels (Ziemer and Lisle 1998), influencing the rate and characteristics of changes to the physical, chemical and biotic features of streams (Bilby and Bisson 1998).

Glaciers are a significant resource of many mountainous areas of the world, including much of the NCCN. Glaciers greatly influence the habitat and hydrology characteristics of these regions. Glaciers are the sole habitat for certain species (Hartzell 2003). Many aquatic species in the NCCN benefit from the buffering hydrological influences that glaciers provide to many mountainous hydrologic systems, particularly during seasonal and interannual droughts (Meier 1969; Meier and Roots 1982).

Next to Alaska, the state of Washington has the highest amount of glacier cover in the United States (Weber et al. 2005). The glaciers in the NCCN are, however, melting rapidly in response to recent climate changes. Some estimates in NOCA indicate that glacier area has declined 44 percent in the last 150 years (Granshaw 2001). The sensitive and dynamic response of glaciers to variations in both temperature and precipitation makes them excellent indicators of regional and global climate change at multiple time scales (Bitz and Battisti 1999; Pelto and Riedel 2001). In many higher-elevation regions, where climate measurements are not often readily available, this is especially valuable for tracking long-term climate changes (Paterson 1981).

While the air quality of the Pacific Northwest is generally considered better than other areas of the U.S., there is potential for both long-term and short-term degradation that could affect human health, vegetation, aquatic resources, and biogeochemical processes (Weber et al. 2005). Parks with the NCCN are subject to regional long-distance transport of air pollutants (sulfur and nitrogen oxides, ozone, particulates, toxic pollutants) from a large area, but especially from the metropolitan areas of Seattle-Tacoma and Portland. Trans-Pacific transport of persistent organic pollutants is also occurring (Blais et al. 1998; Jaffe et al. 1999; Bailey et al. 2000). Because most NCCN parks are remote and mountainous, atmospheric deposition is likely the most important source of contamination in the NCCN (Biddleman 1999). Sulfur and nitrogen deposition in MORA and NOCA is believed to be exceeding acceptable levels based on modeling and field studies (Vimont 1996; Clow and Samora 2001). Potential effects of atmospheric deposition on park resources include:

- Tropospheric ozone, which is highest during the summer and at higher elevations, may damage vegetation and reduce respiratory function in humans (EPA 1996);
- Acidic deposition, which could increase the acidity of poorly buffered aquatic systems and soils over the long term, may affect fish, amphibians, and soil dependent organisms (Allan 2001); and
- Particulate pollutants, which reduce visibility of scenic views, may cause respiratory distress in some visitors (Wilson 1996).

2.2. Spatial Variability

The overall climate characteristics of the NCCN are influenced by the region's topography and by its proximity to the Pacific Ocean (Weber et al. 2005). The topographical characteristics of the NCCN introduce significant spatial variability in the region's climate, while the Pacific Ocean moderates this variability, especially on the western side of the Cascade Mountains. Many of the storms that affect the NCCN are winter storms that are associated with the semi-permanent Aleutian Low generally positioned in the Gulf of Alaska. Slopes on the west sides of the Cascade and Olympic mountains receive heavy precipitation which in some places exceeds 5000 mm (200 in) annually (Figure 2.1). Locations on the east sides of these ranges receive annual precipitation as low as 500 mm. Mean annual precipitation in the park units of the NCCN ranges from just over 500 mm near EBLA to over 5000 mm in portions of OLYM. Much of this precipitation at higher elevations falls as snow. In response to these precipitation patterns, rivers and streams in the NCCN generally have one peak of runoff in the spring months, with timing depending on elevation (Weber et al. 2005).

At higher elevations of the Olympic and Cascade mountain ranges, annual snowfall totals can regularly exceed 15 m (Figure 2.2). The annual snowfall record for the entire nation is at Mt. Baker Ski Area, just northwest of NOCA. During the winter of 1998-1999, the ski area received 1140 inches (2896 cm) of snowfall, which was verified by the National Climate Extremes Committee (Leffler et al. 2001). This broke the previous record of 1122 inches (2850 cm) in one year, set at Paradise Ranger Station at MORA in the winter of 1971-1972 (Ruscha 1972).

Much of the NCCN is cool and wet, lying at or west of the crest of the Cascade Mountains. The NCCN does, however, include an anomalously warm and dry region on the northeastern Olympic Peninsula and the nearby islands in Puget Sound. This region includes EBLA on Whidbey Island. These conditions are created primarily by the rainshadowing effects of the

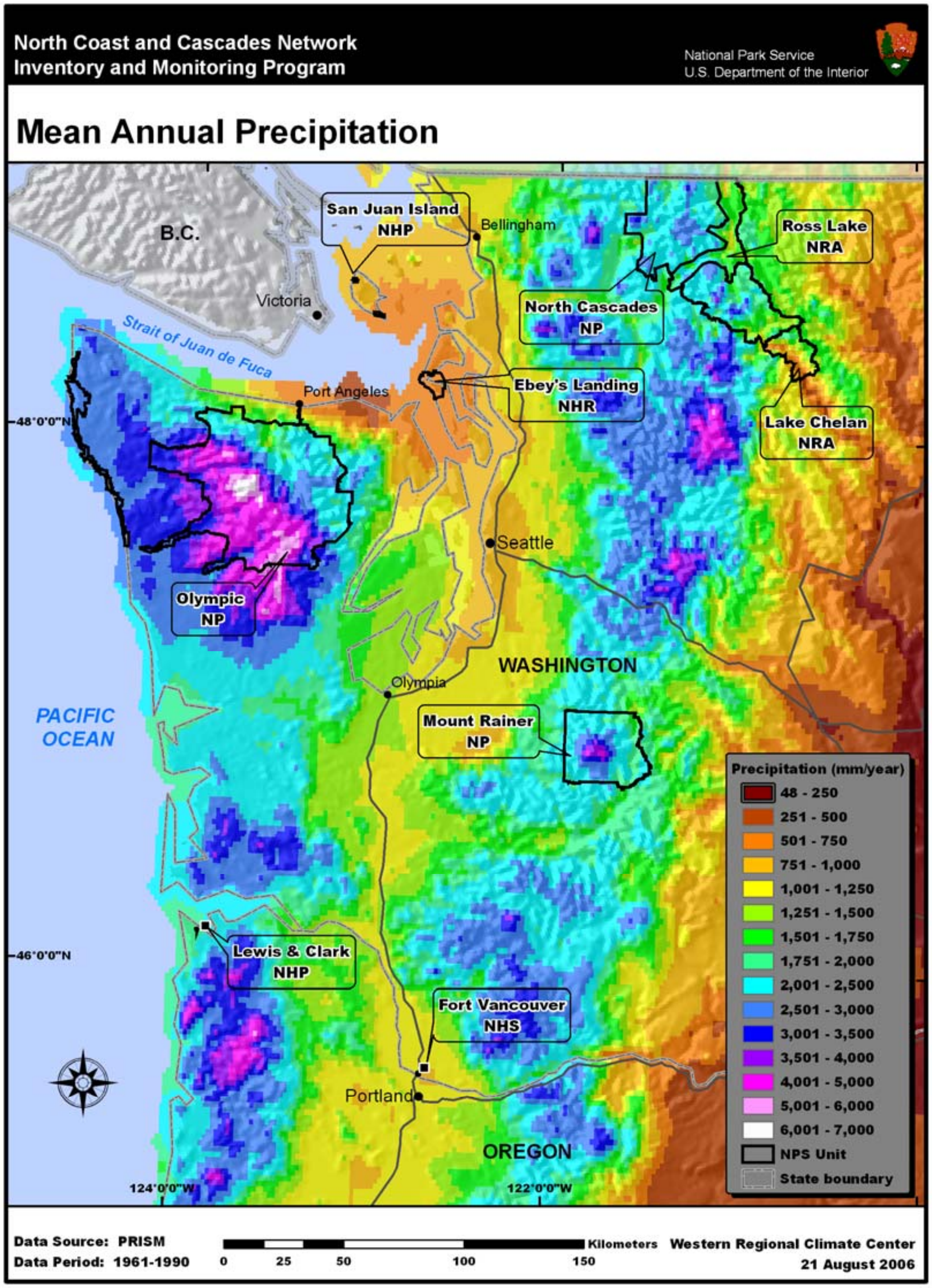


Figure 2.1. Mean annual precipitation, 1961-1990, for the NCCN.

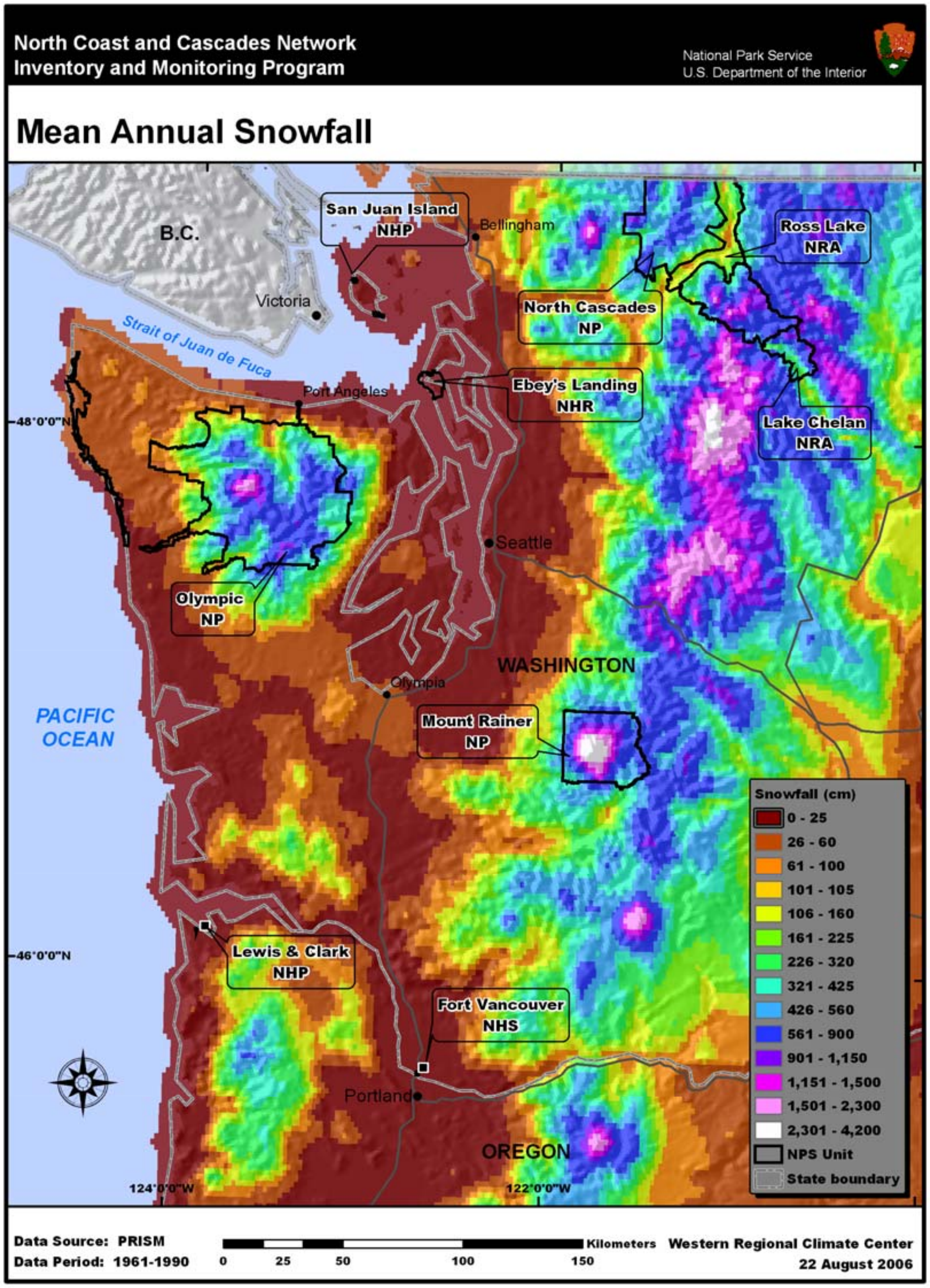


Figure 2.2. Mean annual snowfall, 1961-1990, for the NCCN.

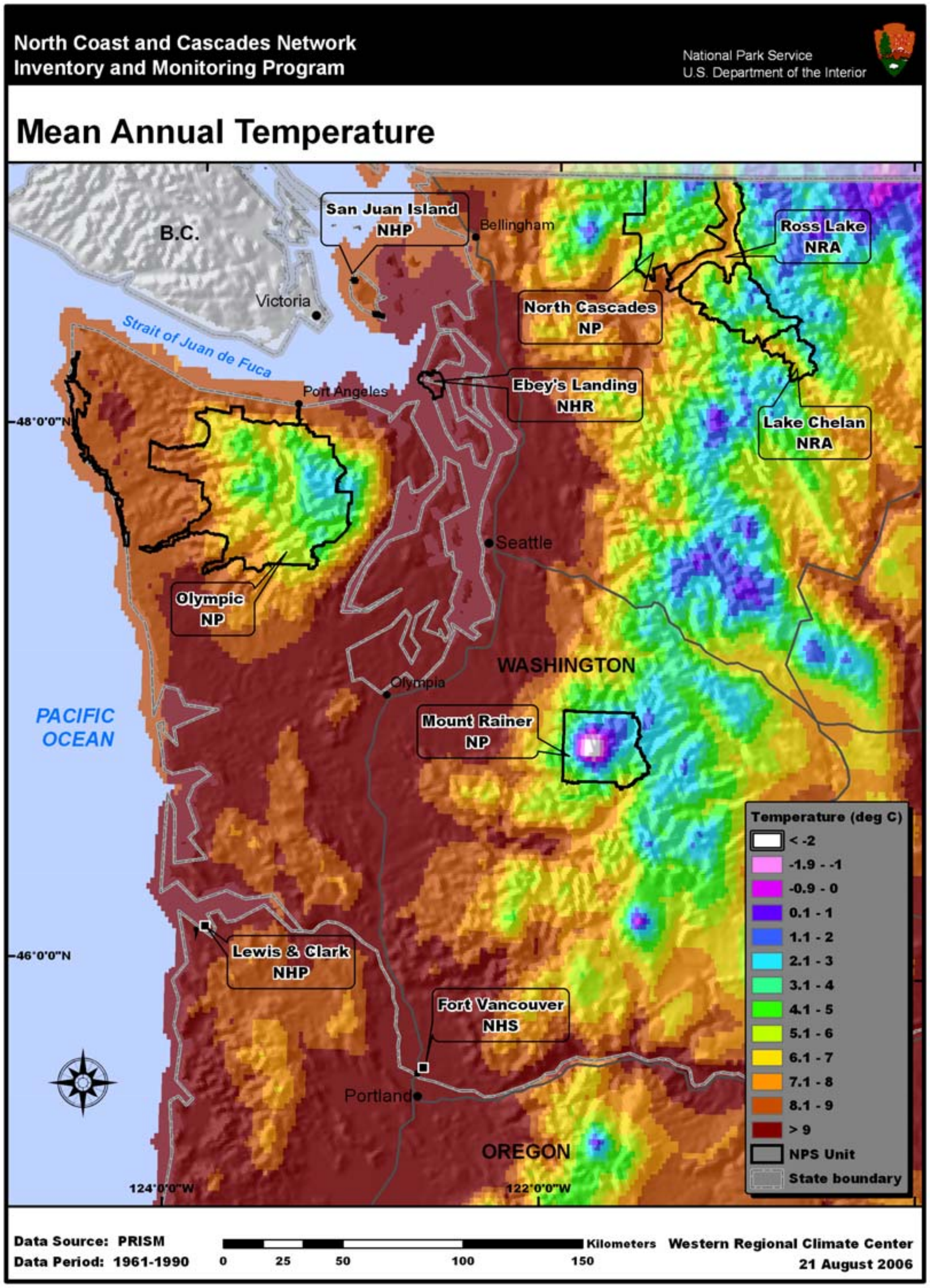


Figure 2.3. Mean annual temperature, 1961-1990, for the NCCN.

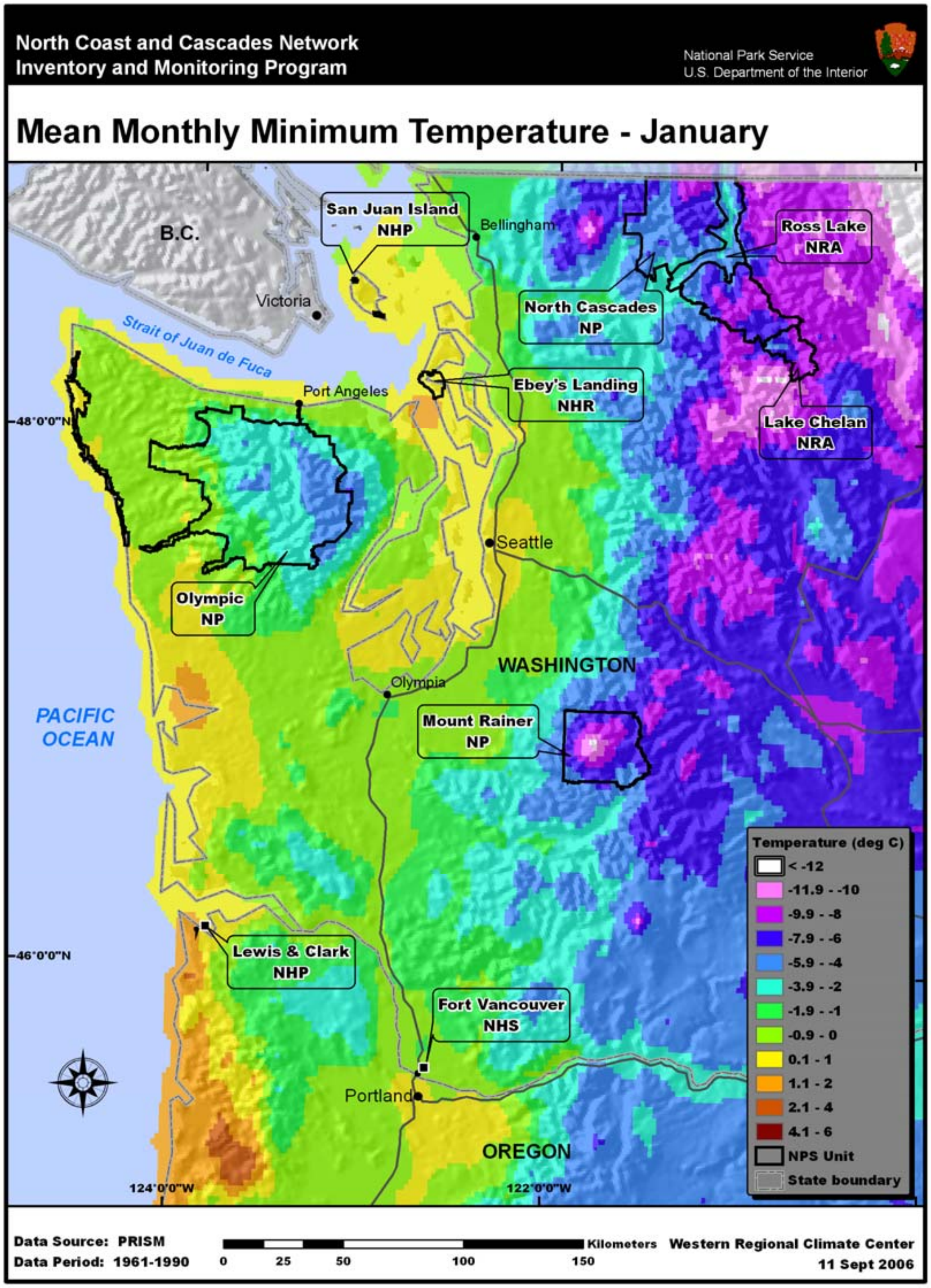


Figure 2.4. Mean January minimum temperature, 1961-1990, for the NCCN.

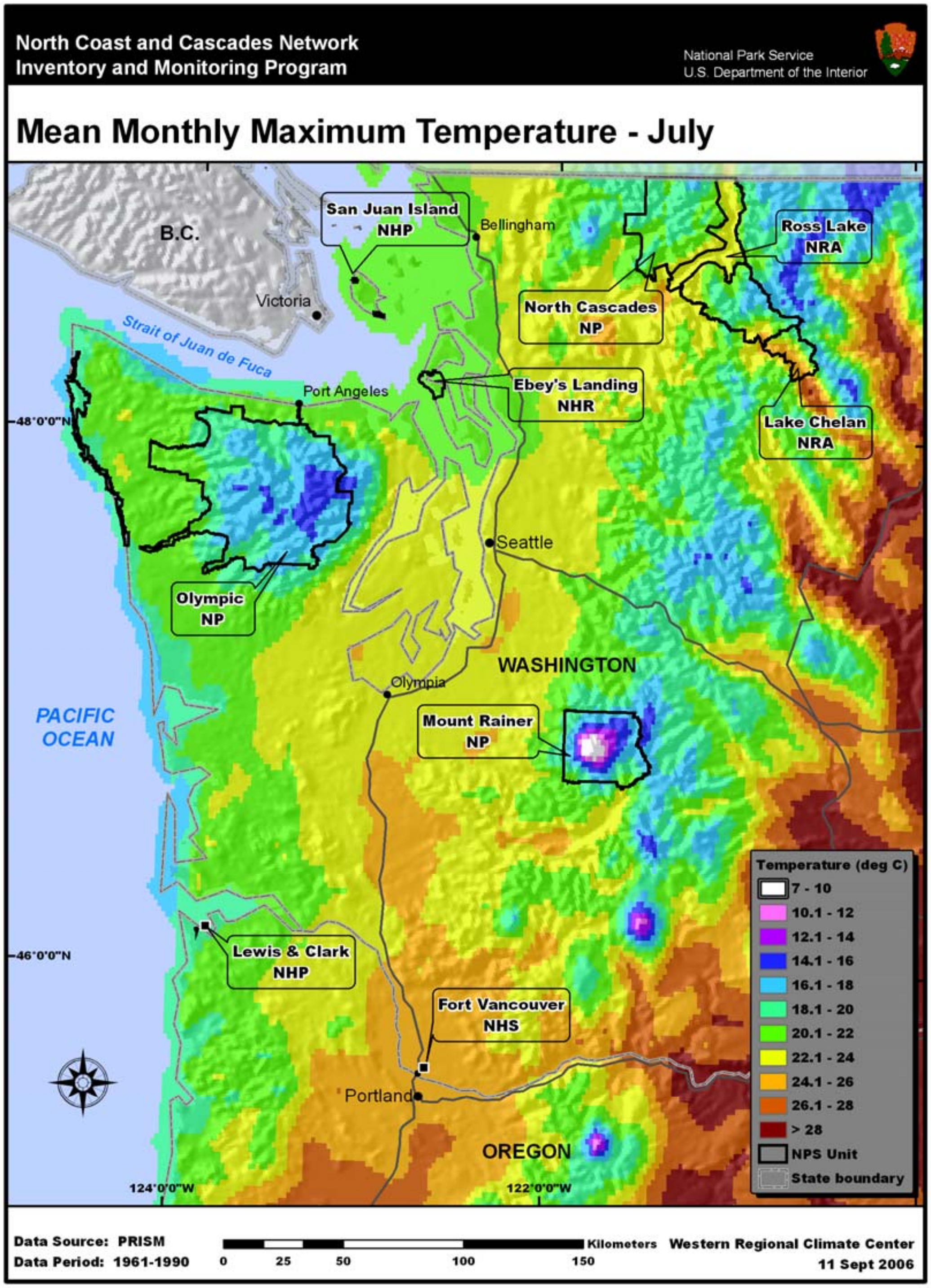
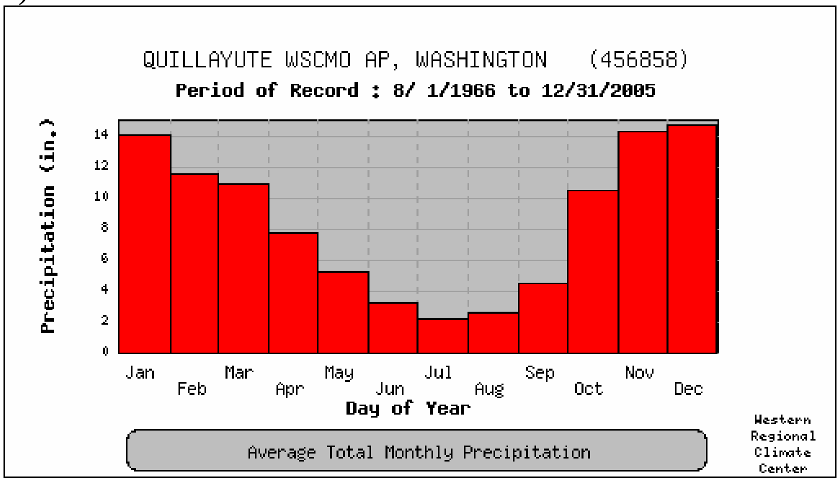
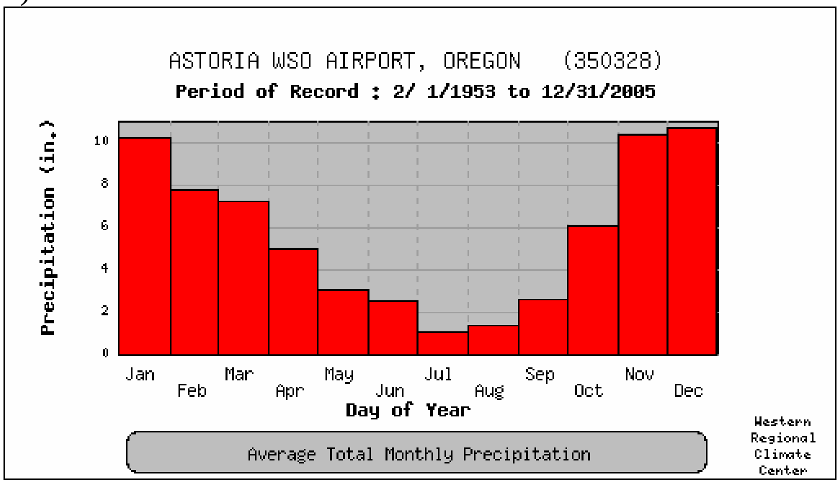


Figure 2.5. Mean July maximum temperature, 1961-1990, for the NCCN.

a)



b)



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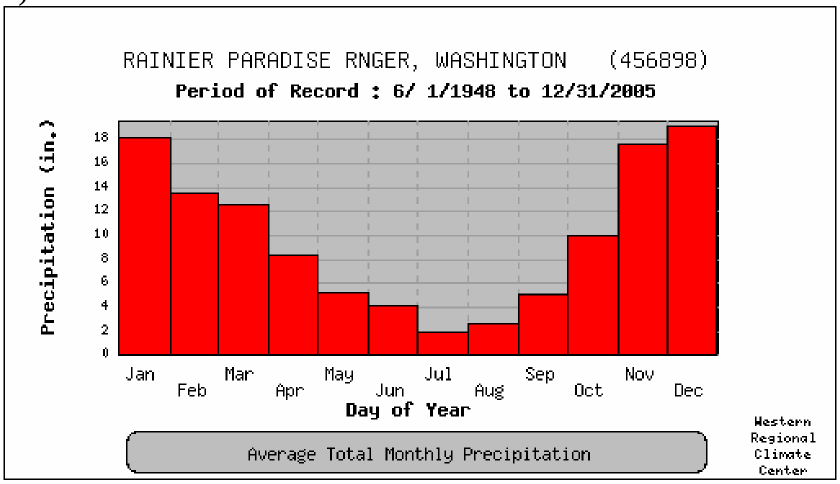


Figure 2.6. Mean monthly precipitation at selected locations in the NCCN. The locations are Quillayute, Washington, near OLYM (a); Astoria, Oregon, near LEWI (b); and MORA (c).

Olympic Mountains. Mean annual precipitation in these locations is as low as 500 mm and is accompanied by mild mean annual temperatures (Figure 2.3).

These mild temperatures are shared at most of the lower elevations of the NCCN, where mean annual temperatures are around 9°C (e.g., SAJH) or higher (e.g. FOVA). Higher elevations do of course have colder temperatures, with the coldest annually-averaged temperatures dropping below -2°C in portions of MORA.

The coldest mountain locations in NCCN can see winter temperatures that regularly drop below -10°C (Figure 2.4). Arctic cold-air outbreaks are relatively rare in the NCCN but the normally mild temperatures of winter are occasionally interrupted by cold outbreaks. In northern portions of the NCCN, these cold air masses usually come down the Fraser River Valley in Canada and bring prolonged periods of snow and temperatures below freezing. Southern portions of the NCCN, particularly along the west edge of the Columbia River Gorge (includes FOVA), experience occasional cold outbreaks. The cold outbreaks along the Columbia River Gorge often are associated with severe ice storms.

Summer temperatures are mild to warm throughout the NCCN and generally increase from north to south (Figure 2.5). The Pacific Ocean moderates temperatures near the coast. July maximum temperatures range from under 10°C at upper elevations of MORA, to around 25°C at FOVA.

Most precipitation in the NCCN falls during the late fall and winter months (Figure 2.6). With the exception of the western slopes of OLYM and northwest portions of NOCA, the summer months are universally dry regardless of location within the NCCN.

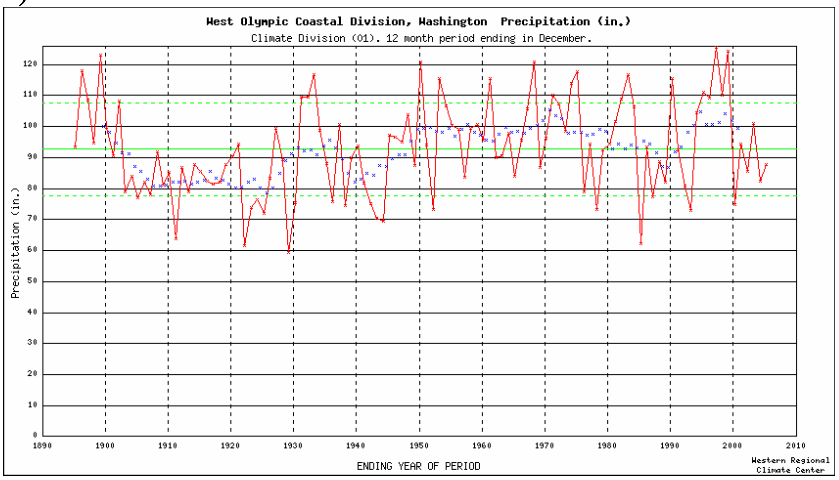
2.3. Temporal Variability

The Pacific-North America Oscillation (PNA; Wallace and Gutzler 1981) is an important contributor to variability of storm frequencies and tracks during a given year, with variations that occur on the order of weeks. Negative phases of the PNA are generally associated with cooler temperatures and increased storminess over the NCCN.

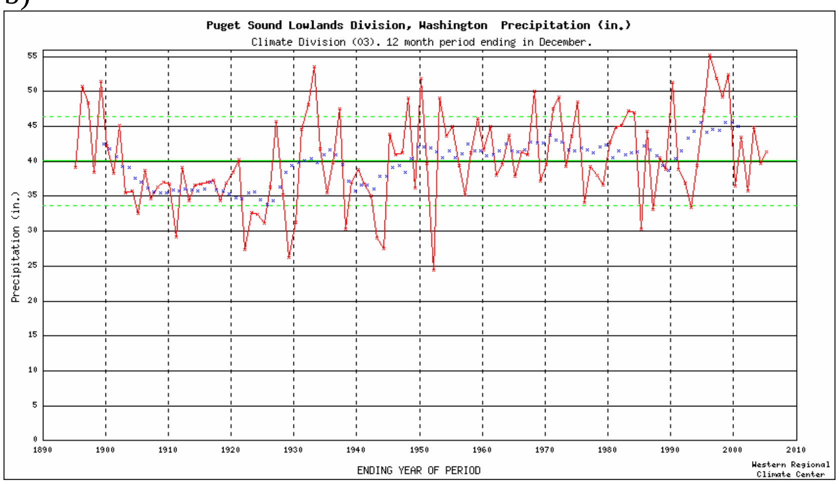
Both the El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) cause interannual climate variations in the NCCN (Mock 1996; Mantua et al. 1997; Cayan et al. 1998; Mantua 2000). El Niño conditions and/or positive phases of the PDO are associated with warmer and drier than normal conditions in the NCCN, while La Niña conditions and/or negative phases of the PDO are associated with cooler and wetter than normal conditions.

Precipitation time series in the region do not appear to show any significant trend (Figure 2.7). Long-term temperature time series, however, do clearly show warming, especially in the last three decades (Figure 2.8). It is estimated that surface temperatures in the Pacific Northwest have warmed by 1-3°C over the last century (Weber et al. 2005). At the same time, some studies suggest that mountain snowpack in the region has decreased over the last several decades (Mote et al. 2005).

a)



b)



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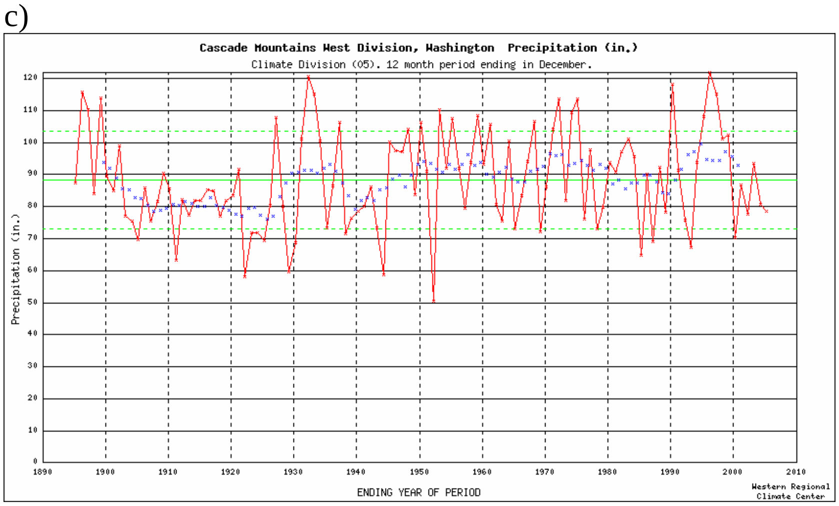
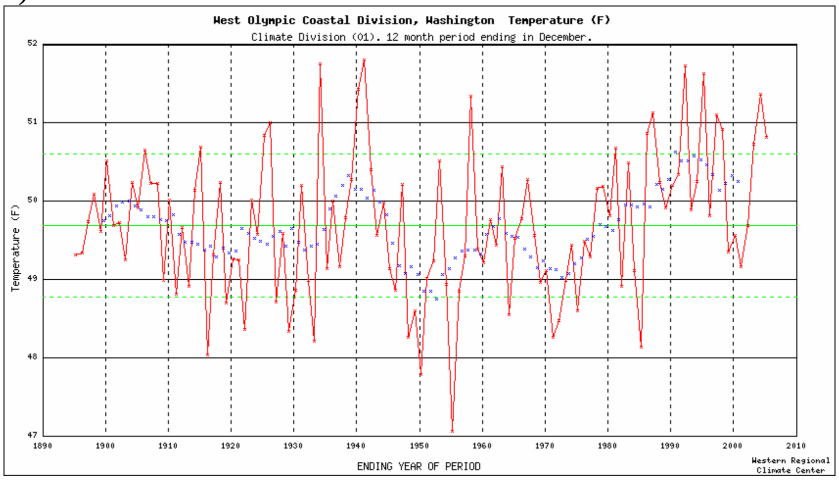
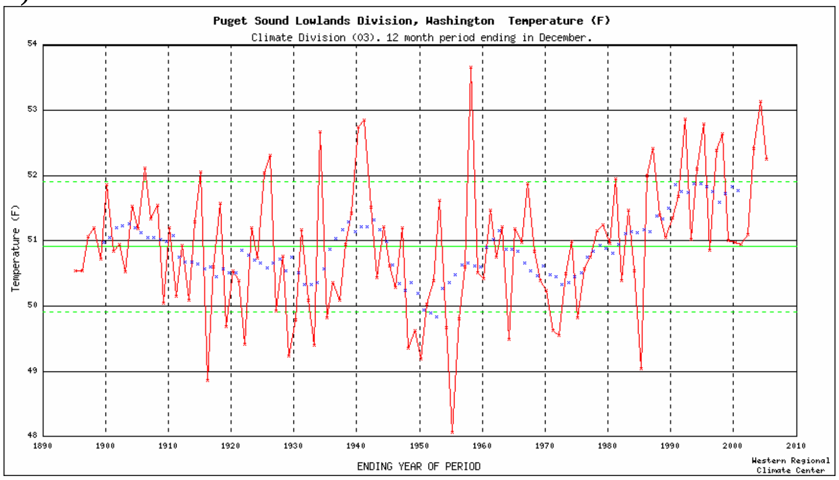


Figure 2.7. Precipitation time series, 1895-2005, for selected regions in the NCCN. These include twelve-month precipitation (ending in December) (red), 10-year running mean (blue), mean (green), and plus/minus one standard deviation (green dotted). Locations include the western Olympic Mountains (a), Puget Sound (b), and the western Cascade Mountains (c).

a)



b)



c)

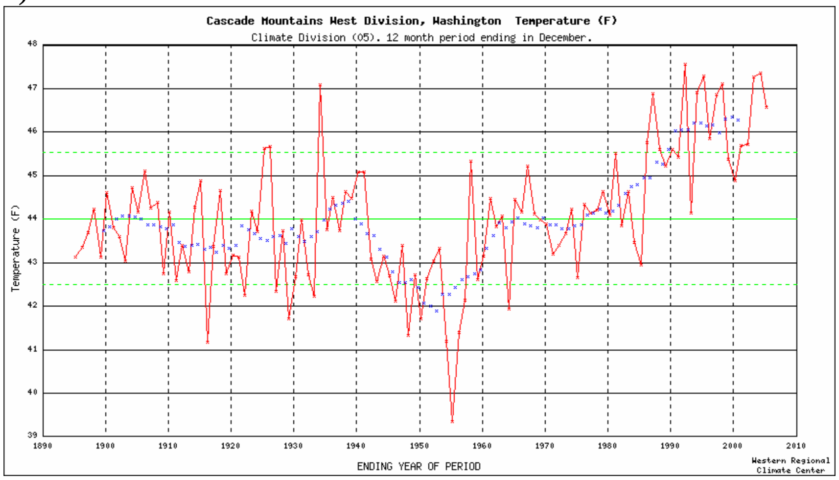


Figure 2.8. Temperature time series, 1895-2005, for selected regions in the NCCN. These include twelve-month temperature (ending in December) (red), 10-year running mean (blue), mean (green), and plus/minus one standard deviation (green dotted). Locations include the western Olympic Mountains (a), Puget Sound (b), and the western Cascade Mountains (c).

2.4. Parameter Regression on Independent Slopes Model

The climate maps presented here were generated using the Parameter Regression on Independent Slopes Model (PRISM). This model was developed to address the extreme spatial and elevation gradients exhibited by the climate of the western United States (Daly et al. 1994; 2002; Gibson et al. 2002; Doggett et al. 2004). The maps produced through PRISM have undergone rigorous evaluation in the western 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.

3.0. Methods

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

3.1. Metadata Retrieval

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

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

This report has relied primarily on metadata stored in the Applied Climate Information System (ACIS), a joint effort among RCCs and other NOAA entities. Metadata for NCCN weather/climate stations identified from the ACIS database are available in file "NCCN_from_ACIS.tar.gz" (see Appendix G). Historic metadata pertaining to major climate- and weather-observing systems in the United States are stored in ACIS where metadata are linked to the observed data. A distributed system, ACIS is synchronized among the RCCs. Mainstream software is utilized, including Postgress, Python™, and Java™ programming languages; CORBA®-compliant network software; and industry-standard, nonproprietary hardware and software. Metadata and data for all major national climate and weather networks have been entered into the ACIS database. The available metadata from many smaller networks also have been entered but in most cases the data from these smaller networks have not yet been entered. Data sets are in the NetCDF (Network Common Data Form) format, but the design allows for integration with legacy systems, including non-NetCDF files (used at WRCC) and additional metadata (added for this project). The ACIS also supports a suite of products to visualize or summarize data from these data sets. National climate-monitoring maps are updated daily using the ACIS data feed. The developmental phases of ACIS have utilized metadata

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

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

supplied by the NCDC and NWS with many tens of thousands of entries, screened as well as possible for duplications, mistakes, and omissions.

In addition to obtaining NCCN weather/climate station metadata from ACIS, metadata also were obtained from the NCCN office at MORA and Bill Baccus at OLYM. The metadata provided from these NPS personnel are available in file "NCCN_NPS.tar.gz" (see Appendix G). Note that there is some overlap between metadata provided from NCCN and metadata obtained from ACIS. Personnel from the EPA Western Ecology Division Laboratory and the University of Washington's College of Forest Resources (Table 3.2) provided additional information on weather stations in OLYM that were formally associated with the EPA General Ecosystem Model. We have also relied on information supplied at various times in the past by the BLM, NPS, NCDC, and NWS.

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

Name	Position	Phone Number	Email Address
Robert McKane	EPA Research Ecologist	(541)754-4631	mckane.bob@epa.gov
Robert Edmonds	Prof., Coll. of Forest Resources, Univ. of Washington	(206)685-0953	bobe@u.washington.edu

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

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

- Private networks with proprietary access and/or inability to obtain or provide sufficient metadata.

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

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

3.2. Criteria for Locating Stations

To identify stations for each park unit in NCCN, we first identified the centroid for each park unit. The centroid is defined as the average latitude and longitude of vertices defining the boundary of the park unit. We then calculated the diagonal distance of the park-unit bounding box (a box defined by the maximum and minimum latitude and longitude for the park unit). Next we identified all weather and climate stations, past and present, whose distances from the centroid were less than twice the diagonal distance of the park-unit bounding box.

From these stations, we selected only those that were located within a specified buffer distance of the NCCN park units. This buffer distance was 10 km for FOVA, due to its urban setting in the Portland-Vancouver metropolitan area. For all other NCCN parks, this buffer distance was set at 30 km. We selected these buffer distances in an attempt to include at least a few automated stations from major networks. For the NCCN park units that are closer to populated areas, these commonly included SAO stations. For the more remote NCCN parks, these stations generally were RAWS and SNOTEL stations. We also chose these buffer distances in order to keep the size of the stations lists under 500 stations per park unit.

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

4.0. Station Inventory

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

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

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	Gaseous Pollutant Monitoring Program
GPS-MET	NOAA ground-based GPS meteorology
NDBC	NOAA National Data Buoy Center
NRCS-SC	USDA/NRCS Snowcourse network
NWAVAL	Northwest Weather and Avalanche Center network
ODEQ	Oregon Department of Environmental Quality
ODOT	Oregon Department of Transportation
OLYM-MISC	Local network - Olympic National Park
POMS	Portable Ozone Monitoring System
RAWS	Remote Automated Weather Station network
SAO	NWS/FAA Surface Airways Observation Program
SNOTEL	USDA/NRCS Snowfall Telemetry Network
WA DOT	Washington Department of Transportation
WAAQ	Washington St. Dept. of Ecology – Air Quality Program
WX4U	Weather For You network

4.1.1. Canadian Weather/Climate Stations (CANADA)

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, 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 United States that meets the requirements of the Global Climate Observing System. Up to 115 CRN sites are planned for installation, but the actual number of installed sites will depend on available funding. 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 Observation 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 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 1-2 decades in length.

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

The GPS-MET network is the first network of its kind dedicated to GPS meteorology (see Duan et al. 1996). GPS meteorology utilizes the radio signals broadcast by the satellite Global Positioning System for atmospheric remote sensing. GPS meteorology applications have evolved along two paths: ground-based (Bevis et al. 1992) and space-based (Yuan et al. 1993). 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 Data Buoy Center (NDBC)

This network is administered by NWS and provides hourly atmospheric and oceanic observations in marine environments in support of forecasting activities. All stations measure temperature, barometric pressure, wind speed and direction, and wind gust and direction.

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

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

4.1.10. Northwest Weather and Avalanche Center Network (NWAVAL)

The Northwest Weather and Avalanche Center (NWAC) operates a network of weather stations in the mountainous areas of the Pacific Northwest, primarily in Washington. These stations are operated in support of NWAC’s primary mission of monitoring avalanche conditions in the mountains of Washington and northern Oregon. Hourly weather and climate elements that are measured include temperature, humidity, wind, and precipitation. Daily measurements are made of snowfall and snowdepth.

4.1.11. Oregon Department of Environmental Quality (ODEQ)

The primary mission of ODEQ is to protect and enhance Oregon’s air and water quality. Weather and climate elements are measured by ODEQ stations in support of this primary mission. Measured meteorological elements include temperature, precipitation, wind, and relative humidity.

4.1.12. Oregon Department of Transportation (ODOT)

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

4.1.13. Local Network – Olympic National Park (OLYM-MISC)

Olympic National Park (OLYM) administers a collection of weather stations within its park boundaries that were previously administered by other agencies. Some of these stations were associated with the EPA Marine Biological Laboratory’s General Ecosystem Model (GEM). Research projects with GEM have investigated the effects of atmospheric conditions on plant and soil processes. The University of Washington’s College of Forest Resources has also operated a few stations in OLYM to monitor forest health. Meteorological elements measured at these stations generally include temperature, precipitation, wind, and humidity.

4.1.14. 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.

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

4.1.16. NWS/FAA Surface Airways Observation Network (SAO)
These stations are located usually at major airports and military bases. These include Automated Surface Observing System (ASOS) and Automated Weather Observing System (AWOS) sites. Almost all SAO sites are automated. The hourly data measured at these sites include temperature, precipitation, humidity, wind, pressure, sky cover, ceiling, visibility, and current weather. Most data records begin during or after the 1940s, and these data are generally of excellent quality.

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

4.1.18. Washington State Department of Ecology - Air Quality Program (WAAQ)
The primary mission of this program is to protect and enhance Washington’s air quality. Weather and climate elements are measured by WAAQ stations in support of this primary mission. Measured meteorological elements include temperature, precipitation, wind, and relative humidity.

4.1.19. Washington State Department of Transportation network (WA DOT)
These weather stations are operated by the Washington State Department of Transportation in support of management activities for Washington’s transportation network. Measured meteorological elements include temperature, precipitation, wind, and relative humidity.

4.1.20. 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.

4.1.21. 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 NCCN but have not been identified in this report. Some of the commonly used networks include the following:

- NOAA upper-air stations
- National Atmospheric Deposition Program (NADP)
- National Science Foundation Long-Term Ecologic Research Network
- U.S. Department of Energy Surface Radiation Budget Network (Surfrad)
- U.S. Geological Survey (USGS) hydrologic stations
- Additional park-specific-monitoring networks and stations
- Other research or project networks having many possible owners

4.2. Station Locations

The major weather/climate networks in NCCN (discussed in Section 4.1) have up to several dozen stations in each park unit (Table 4.2). Most of these stations are associated with the COOP network or with snow-monitoring networks (NRCS-SC, NWAVAL, SNOTEL).

Table 4.2. Number of stations near (in) NCCN park units. Numbers are listed by park unit and by weather/climate network.

Network	EBLA	FOVA	LEWI	MORA	NOCA	OLYM	SAJH
CANADA	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**2**(0)	**10**(0)
CASTNet	**0**(0)	**0**(0)	**0**(0)	**1**(0)	**1**(0)	**1**(0)	**0**(0)
COOP	**13**(1)	**5**(0)	**15**(1)	**26**(5)	**32**(5)	**59**(11)	**4**(0)
CRN	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**1**(0)	**0**(0)	**0**(0)
CWOP	**9**(0)	**4**(0)	**5**(0)	**5**(0)	**3**(0)	**16**(0)	**5**(0)
GPMP	**0**(0)	**0**(0)	**0**(0)	**2**(1)	**0**(0)	**2**(1)	**0**(0)
GPS-MET	**1**(0)	**0**(0)	**1**(0)	**0**(0)	**1**(0)	**2**(1)	**2**(0)
NDBC	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**5**(0)	**0**(0)
NRCS-SC	**0**(0)	**0**(0)	**0**(0)	**12**(2)	**32**(10)	**4**(3)	**0**(0)
NWAVAL	**0**(0)	**0**(0)	**0**(0)	**13**(6)	**5**(0)	**1**(1)	**0**(0)
ODEQ	**0**(0)	**1**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)
ODOT	**0**(0)	**5**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)
OLYM-MISC	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**0**(0)	**10**(9)	**0**(0)
POMS	**0**(0)	**0**(0)	**0**(0)	**1**(1)	**0**(0)	**1**(1)	**0**(0)
RAWS	**0**(0)	**0**(0)	**1**(0)	**6**(1)	**8**(2)	**18**(3)	**0**(0)
SAO	**7**(1)	**3**(0)	**2**(0)	**0**(0)	**1**(0)	**15**(0)	**8**(0)
SNOTEL	**0**(0)	**0**(0)	**0**(0)	**10**(1)	**10**(2)	**3**(1)	**0**(0)
WA DOT	**2**(0)	**0**(0)	**0**(0)	**1**(0)	**1**(0)	**8**(0)	**1**(0)
WAAQ	**1**(0)	**1**(0)	**0**(0)	**2**(0)	**0**(0)	**3**(0)	**0**(0)
WX4U	**3**(0)	**1**(0)	**1**(0)	**0**(0)	**0**(0)	**3**(0)	**0**(0)
Other	**1**(0)	**2**(0)	**3**(0)	**0**(0)	**0**(0)	**3**(0)	**2**(0)
Total	**37**(2)	**22**(0)	**28**(1)	**78**(17)	**95**(19)	**154**(31)	**32**(0)

4.2.1. Olympic Peninsula and Puget Sound

Ebey’s Landing National Historical Reserve has two weather/climate stations located within its boundaries (Table 4.3; Figure 4.1). One of these is a long-term COOP station (Coupeville 1 S) while the other is a SAO station at Oak Harbor Air Park. The COOP station “Coupeville 1 S” has a fairly complete data record, although there are some gaps during the years 1990-95. In particular, there is an eight-month gap at this site during the latter half of 1991 and into January, 1992. The SAO station (Oak Harbor Air Park) has provided data since 1981 and is a reliable source of near-real-time data for EBLA.

In addition to these two stations, we have identified 27 active stations within 30 km of EBLA (Table 4.3). Of these stations, six are COOP stations and five are SAO stations. The longest data record among the active COOP stations is found at "Port Townsend", a station that is directly across Admiralty Inlet from EBLA (10 km southwest of EBLA) and has been in operation since 1891. A significant portion of this data record is missing in the late 1960s and early 1970s. Occasional data gaps of one to three months have occurred during the fall about once every 5-10 years. With the exception of missing data in March 2000, the data record at Port Townsend has been quite reliable for the past 15 years. The COOP station at "Anacortes" also has a long data record, with observations beginning in 1892. This station is 30 km north of EBLA. A significant data gap occurred during the period 1991-92. Other than this gap, the data record at the Anacortes COOP has been quite reliable. Long-term climate records are also indicated for the COOP stations "Chimacum 4 S" (1926-present) and "Point No Point USCG Light Stn." (1930-present). The data at "Chimacum 4 S" are of questionable quality.

Two SAO stations within 30 km of EBLA have data records going back to the 1930s and 1940s. These SAO stations are "Point No Point USCG Light Stn." (1930-present) and "Whidbey Island NAS" (1943-present). The data records for the other three active SAO stations around EBLA are much shorter but are still respectable, ranging from 25 years up to 43 years in length. In addition to these SAO stations, near-real-time data are provided by at least 15 other stations within 30 km of EBLA, including nine CWOP stations, two WA DOT stations, a WAAQ station, and three WX4U stations, although the quality of the data from these stations is sometimes questionable.

We have identified 31 weather/climate stations in OLYM (Tables 4.2; 4.3); however, only 17 of these stations are known to be still active. Only two COOP stations are still active within OLYM: "Elwha Ranger Station" and "Hoh Ranger Station". The COOP station at Elwha Ranger Station, located in northern OLYM about 15 km southwest of Port Angeles (Figure 4.1), has the longest data record of any of the currently active stations within OLYM. This station has been operating since 1942. This site has occasionally had missing data through much of its history, although the data record has been much more complete since 1990. The other active COOP station, "Hoh Ranger Station", has only been in operation since 2004. The concentration of weather/climate stations in OLYM is greatest in the northern and western portions of the park unit; in contrast, there are very few stations located in the southern and eastern portions of OLYM.

Three NRCS-SC sites are located in OLYM (Table 4.3). These are all currently active and are located in the northeast portion of OLYM (Figure 4.1). We have identified a SNOTEL station within OLYM (Waterhole), also located in northeastern OLYM, but it is not clear if this site is currently active. The NWAVAL network has an automated station operating at Hurricane Ridge, about 15 km south of Port Angeles. Three RAWS stations are currently operating in OLYM.

In addition to these stations, there are nine automated stations that OLYM operates (OLYM-MISC; see Table 4.3). Eight of these sites are still operating. As with many of the other networks we've discussed so far, the stations operated by OLYM are concentrated primarily in the northern and western portions of the park unit.

There are numerous weather/climate stations located within 30 km of OLYM. Two of these stations are Canadian stations located on Vancouver Island, around 30 km north of the northern boundary of OLYM. A CASTNet site operated just outside of OLYM, near Port Angeles (Figure 4.1), from 1986 to 2005 (Table 4.3). We have identified 26 active COOP stations within 30 km of OLYM. Several of these COOP stations have data records going back to the 1800s. Two of these stations, "Coupeville 1 S" and "Port Townsend", were discussed with EBLA. "Port Angeles" is another long-term COOP station on the north side of OLYM. This station has been active since 1885, with a very complete data record. The remaining COOP stations with the longest data records are located along the western side of OLYM. The longest data record for all the stations we have identified for OLYM is the COOP station on Tatoosh Island, which is about 10 km north of the northern edge of the coastal portion of OLYM. This station has operated since 1883. However, data have not been reliable at this site since the 1960s. Quinault Ranger Station has had a COOP since 1906 but has an unreliable data record. The COOP station "Forks 1 E" has operated since 1907, with a very reliable data record. "Clearwater" is a COOP station that has operated since 1895. There are several data gaps in the late 1970s but the station's data record has been largely complete for the past 20 years.

Five NDBC stations are within 30 km of OLYM. These are buoy sites located primarily in the Strait of Juan de Fuca and the Pacific Ocean (Figure 4.1). Most of these stations began operating in the 1980s or later (Table 4.3)

Seven active RAWS stations have been identified within 30 km of OLYM, primarily north and west of OLYM (Figure 4.1). The data records from these stations are generally quite reliable, with data records beginning in the 1980s or later (Table 4.3). There are at least 13 active SAO stations providing near-time data within 30 km of OLYM. The longest records are provided by "Tatoosh Island" (1883-present) and "Port Angeles WB AP" (1885-present).

Table 4.3. Weather/climate stations for NCCN park units in Puget Sound and on the Olympic Peninsula. Stations inside park unit boundaries and within 30 km of the park unit boundary are included. Each listing includes station name, location, and elevation; weather/climate network associated with station; operational start/end dates for station; and flag to indicate if station is located inside park unit boundaries. Missing entries are indicated by "M".

Name	**Lat.**	**Lon.**	**Elev. (m)**	**Network**	**Start**	**End**	**In Park?**
Ebey's Landing National Historical Reserve - EBLA							
Coupeville 1 S	48.207	-122.691	15	COOP	11/1/1895	Present	Yes
Oak Harbor Air Park	48.250	-122.667	40	SAO	1/22/1981	Present	Yes
Anacortes	48.512	-122.614	6	COOP	9/1/1892	Present	No
Chimacum 4 S	47.952	-122.791	43	COOP	10/1/1926	Present	No
Mount Vernon	48.467	-122.433	0	COOP	7/1/1948	11/30/1973	No
Mount Vernon 3 WNW	48.440	-122.387	4	COOP	1/1/1956	3/9/2005	No
New Dungeness Light	48.183	-123.117	0	COOP	9/1/1963	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Point No Point USCG Light Stn.	47.917	-122.533	4	COOP	5/1/1930	Present	No
Port Townsend	48.116	-122.759	30	COOP	10/1/1891	Present	No
Port Townsend 2	48.100	-122.750	31	COOP	M	1/31/1969	No
Port Townsend 6 SSW	48.050	-122.817	49	COOP	2/1/1970	8/31/1974	No
Richardson 3 SE	48.433	-122.833	9	COOP	12/1/1948	8/31/1958	No
Sequim	48.083	-123.100	55	COOP	6/1/1916	9/17/1980	No
Sequim 2 E	48.085	-123.064	15	COOP	9/17/1980	Present	No
CW1035 Port Townsend	48.125	-122.762	71	CWOP	M	Present	No
CW1625 Oak Harbor	48.307	-122.677	48	CWOP	M	Present	No
CW1824 Langley	47.997	-122.480	20	CWOP	M	Present	No
CW2882 Anacortes	48.501	-122.664	70	CWOP	M	Present	No
CW5398 Sequim	48.042	-122.972	79	CWOP	M	Present	No
CW5456 Hansville	47.920	-122.585	15	CWOP	M	Present	No
K5RCG Sequim	48.138	-123.176	42	CWOP	M	Present	No
N7LUF Hansville	47.988	-122.530	76	CWOP	M	Present	No
N7RIG-6 Mt Vernon	48.442	-122.471	3	CWOP	M	Present	No
Whidbey Island	48.310	-122.700	36	GPS-MET	M	Present	No
Burlington Skagit Regional-Bay	48.467	-122.417	43	SAO	3/1/1981	Present	No
New Dungeness Light	48.183	-123.117	0	SAO	9/1/1963	Present	No
Point No Point USCG Light Stn.	47.917	-122.533	4	SAO	5/1/1930	Present	No
Point Wilson	48.150	-122.750	15	SAO	7/1/1972	Present	No
Smith Island	48.317	-122.850	21	SAO	1/1/1962	8/1/1984	No
Whidbey Island NAS	48.350	-122.667	10	SAO	1/1/1943	Present	No
Anacortes	48.508	-122.676	10	WA DOT	M	Present	No
Diamond Point	48.050	-122.948	97	WA DOT	M	Present	No
Anacortes Bartholomew Ave.	48.470	-122.560	5	WAAQ	M	Present	No
Mount Vernon	48.467	-122.433	45	WBAN	10/1/1935	7/31/1951	No
Freeland WGM	48.015	-122.562	21	WX4U	M	Present	No
Greenbank	48.056	-122.578	151	WX4U	M	Present	No
Stanwood	48.272	-122.324	76	WX4U	M	Present	No
Olympic National Park - OLYM							
Blue Glacier	47.817	-123.767	2105	COOP	8/1/1957	11/1/1965	Yes
Elwha Ranger Station	48.016	-123.591	110	COOP	7/1/1942	Present	Yes
Heart O Hills	48.033	-123.417	561	COOP	6/1/1965	2/28/1970	Yes
Higley Peak	47.500	-123.883	1159	COOP	7/13/1942	7/31/1945	Yes
Hoh Ranger Station	47.861	-123.932	174	COOP	6/12/2004	Present	Yes
Kellys Ranch	47.600	-124.050	76	COOP	1/1/1932	10/31/1952	Yes
Low Divide	47.717	-123.567	1083	COOP	9/1/1965	9/30/1970	Yes
Port Angeles 11 S	47.967	-123.500	1556	COOP	12/1/1958	9/30/1976	Yes
Port Angeles 14 SE	47.950	-123.267	1607	COOP	6/1/1948	5/31/1958	Yes

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Quinault River	47.533	-123.683	122	COOP	9/1/1965	9/30/1974	Yes
Sol Duc Hot Springs	47.967	-123.867	503	COOP	7/1/1963	6/9/1965	Yes
Hurricane Ridge	47.968	-123.497	1596	GPMP	6/1/1998	9/1/1998	Yes
Mt. Olympus	47.820	-123.710	2039	GPS-MET	M	Present	Yes
Deer Park	47.950	-123.250	1585	NRCS-SC	1/1/1949	Present	Yes
Hurricane	47.967	-123.533	1372	NRCS-SC	1/1/1949	Present	Yes
Cox Valley	47.967	-123.483	1372	NRCS-SC	1/1/1968	Present	Yes
Hurricane Ridge	47.972	-123.503	1570	NWAVAL	M	Present	Yes
Ozette Ranger Station	48.155	-124.669	9	OLYM-MISC	10/31/2003	Present	Yes
Quinault Open Climate Site	47.537	-123.681	113	OLYM-MISC	10/5/1998	Present	Yes
Quinault Forested GEM Site	47.570	-123.658	173	OLYM-MISC	10/7/1998	Present	Yes
Hoh Forested GEM Site	47.836	-123.983	157	OLYM-MISC	10/8/1998	Present	Yes
Hoh West Twin	47.834	-124.013	246	OLYM-MISC	10/2/1999	9/28/2005	Yes
Lake Crescent Lab	48.092	-123.800	177	OLYM-MISC	7/15/2003	Present	Yes
Waterhole Forested GEM Site	47.945	-123.426	1522	OLYM-MISC	10/1/1999	Present	Yes
Deer Park Open Climate Site	47.981	-123.309	949	OLYM-MISC	8/20/1998	Present	Yes
Deer Park Forested GEM Site	47.976	-123.302	1008	OLYM-MISC	8/19/1998	Present	Yes
Hurricane Ridge	47.971	-123.503	1543	POMS	5/1/2004	10/20/2005	Yes
Denny AHL Seed Orchard	47.968	-123.635	1615	RAWS	6/1/1995	9/30/1995	Yes
Hurricane	47.968	-123.635	201	RAWS	6/1/1992	Present	Yes
Toms Creek	48.017	-123.917	732	RAWS	1/1/1985	Present	Yes
Waterhole	47.933	-123.417	1524	SNOTEL	M	M	Yes
Race Rocks Automatic	48.300	-123.533	5	CANADA	M	Present	No
Victoria Marine	48.367	-123.750	32	CANADA	M	Present	No
Olympic NP	48.098	-123.426	125	CASTNet	3/1/1986	2/28/2005	No
Aberdeen 20 NNE	47.261	-123.715	133	COOP	1/1/1927	Present	No
Amanda Park	47.467	-123.883	64	COOP	8/1/1957	9/30/1963	No
Anderson Butte	47.383	-123.567	1068	COOP	9/1/1963	Present	No
Beacon Point	47.600	-122.983	3	COOP	M	8/31/1963	No
Beaver	48.050	-124.317	122	COOP	4/1/1953	12/31/1958	No
Camp Grisdale	47.367	-123.600	250	COOP	9/1/1956	9/19/1985	No
Chimacum 4 S	47.952	-122.791	43	COOP	10/1/1926	Present	No
Clallam Bay 1 NNE	48.267	-124.250	9	COOP	11/1/1927	5/1/1976	No
Clearwater	47.571	-124.292	24	COOP	6/5/1895	Present	No
Coupeville 1 S	48.207	-122.691	15	COOP	11/1/1895	Present	No
Cushman Dam	47.424	-123.220	232	COOP	3/1/1914	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Cushman Powerhouse 2	47.371	-123.160	6	COOP	6/1/1973	Present	No
Destruction Island L	47.667	-124.483	21	COOP	3/1/1930	2/9/1960	No
Forks	47.967	-124.383	92	COOP	4/1/1959	Present	No
Forks 1 E	47.956	-124.354	107	COOP	11/1/1907	Present	No
Humptulips Salmn Hat	47.234	-123.990	43	COOP	7/1/1987	Present	No
Kloshe Nanitch	48.067	-124.133	1007	COOP	7/1/1942	8/31/1945	No
Lake Sutherland	48.083	-123.700	174	COOP	11/1/1928	6/1/1976	No
Matlock 3 W	47.233	-123.483	104	COOP	3/1/1959	9/19/1985	No
Mount Vernon	48.467	-122.433	0	COOP	7/1/1948	11/30/1973	No
Mount Vernon 3 WNW	48.440	-122.387	4	COOP	1/1/1956	3/9/2005	No
Neah Bay 1 E	48.367	-124.617	3	COOP	10/1/1929	8/25/1987	No
Neah Bay Lightboat S	48.367	-124.600	6	COOP	9/1/1963	Present	No
New Dungeness Light	48.183	-123.117	0	COOP	9/1/1963	Present	No
Point Grenville	47.300	-124.283	31	COOP	2/27/1947	12/31/1979	No
Point No Point USCG Light Stn.	47.917	-122.533	4	COOP	5/1/1930	Present	No
Port Angeles	48.114	-123.432	27	COOP	8/1/1933	Present	No
Port Angeles 8 SW	48.050	-123.583	61	COOP	9/1/1977	Present	No
Port Angeles WB AP	48.133	-123.400	5	COOP	4/1/1885	Present	No
Port Townsend	48.116	-122.759	30	COOP	10/1/1891	Present	No
Port Townsend 2	48.100	-122.750	31	COOP	M	1/31/1969	No
Port Townsend 6 SSW	48.050	-122.817	49	COOP	2/1/1970	8/31/1974	No
Pysht	48.200	-124.117	3	COOP	1/1/1926	1/31/1944	No
Quilcene 2 SW	47.809	-122.914	37	COOP	3/1/1920	Present	No
Quilcene 5 SW Dam	47.785	-122.980	313	COOP	6/1/1948	Present	No
Quilcene R.S.	47.833	-122.867	15	COOP	7/1/1953	Present	No
Quillayute River Lig	47.900	-124.633	3	COOP	9/1/1963	Present	No
Quillayute State Airport	47.938	-124.555	56	COOP	8/1/1966	Present	No
Quinault R.S.	47.475	-123.850	67	COOP	1/21/1906	Present	No
Richardson 3 SE	48.433	-122.833	9	COOP	12/1/1948	8/31/1958	No
Sappho 8 E	48.067	-124.117	232	COOP	9/1/1936	4/1/1998	No
Sequim	48.083	-123.100	55	COOP	6/1/1916	9/17/1980	No
Sequim 2 E	48.085	-123.064	15	COOP	9/17/1980	Present	No
South Olympic Tree F	47.233	-123.583	177	COOP	1/1/1945	9/30/1956	No
Spruce	47.800	-124.067	113	COOP	6/1/1925	12/31/1980	No
Tatoosh Island	48.383	-124.733	31	COOP	10/1/1883	Present	No
Umatilla Reef LV	48.167	-124.833	3	COOP	5/22/1989	Present	No
Wynoochee Oxbow	47.333	-123.633	204	COOP	12/1/1926	12/31/1940	No
CW1035 Port Townsend	48.125	-122.762	71	CWOP	M	Present	No
CW1625 Oak Harbor	48.307	-122.677	48	CWOP	M	Present	No
CW1824 Langley	47.997	-122.480	20	CWOP	M	Present	No
CW1868 Bremerton	47.598	-122.760	134	CWOP	M	Present	No
CW2568 Union	47.313	-123.128	145	CWOP	M	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
CW2882 Anacortes	48.501	-122.664	70	CWOP	M	Present	No
CW5398 Sequim	48.042	-122.972	79	CWOP	M	Present	No
CW5456 Hansville	47.920	-122.585	15	CWOP	M	Present	No
CW5915 Forks	47.958	-124.380	98	CWOP	M	Present	No
CW5931 Sekiu	48.266	-124.300	5	CWOP	M	Present	No
K5RCG Sequim	48.138	-123.176	42	CWOP	M	Present	No
KJ7XE Port Angeles	48.114	-123.441	39	CWOP	M	Present	No
N7LUF Hansville	47.988	-122.530	76	CWOP	M	Present	No
N7RIG-6 Mt Vernon	48.442	-122.471	3	CWOP	M	Present	No
N7YT Bremerton	47.553	-122.881	180	CWOP	M	Present	No
WW7RA Gold Mountain	47.548	-122.808	514	CWOP	M	Present	No
Olympic	48.098	-123.426	125	GPMP	8/1/1981	8/1/1997	No
Whidbey Island	48.310	-122.700	36	GPS-MET	M	Present	No
Destruction Is. Washington (CMAN)	47.680	-124.490	21	NDBC	8/1/1984	Present	No
Friday Harbor Washington	48.497	-124.563	0	NDBC	1/1/2004	Present	No
Neah Bay Washington	48.494	-124.727	0	NDBC	1/1/2004	Present	No
Smith Island Washington (CMAN)	48.320	-122.840	15	NDBC	8/1/1984	Present	No
Tatoosh Island Washington (CMAN)	48.390	-124.740	31	NDBC	8/1/1984	Present	No
Carrol Pass	47.500	-123.517	1113	NRCS-SC	1/1/1985	Present	No
Hoh Open Climate Site	47.815	-124.041	124	OLYM-MISC	12/11/1998	Present	No
Black Knob	47.414	-124.103	179	RAWS	3/1/2003	Present	No
Blue Mt.	48.063	-123.274	229	RAWS	6/1/2003	5/31/2005	No
Cougar Mountain	47.917	-123.117	914	RAWS	1/1/1985	Present	No
Crows Nest	47.763	-122.979	390	RAWS	10/1/1989	6/30/1992	No
Ellis Mt	48.158	-124.315	610	RAWS	5/1/2001	Present	No
Herb Ridge	48.166	-124.325	610	RAWS	5/1/1996	10/31/2000	No
Humptullips	47.367	-123.758	732	RAWS	1/1/1985	Present	No
Jefferson Creek	47.550	-123.167	671	RAWS	1/1/1985	Present	No
Owl Mountain (West)	47.767	-124.067	1036	RAWS	5/1/1985	Present	No
Quilcene	47.823	-122.883	19	RAWS	9/1/2001	Present	No
Quinault	47.450	-123.858	936	RAWS	6/1/1993	10/31/2000	No
Satsop	47.617	-123.967	640	RAWS	1/1/1985	1/31/1991	No
Sekiu Lookout	48.200	-124.467	591	RAWS	5/1/1985	10/31/1995	No
Sitkum	47.957	-124.263	390	RAWS	7/1/1985	9/30/1995	No
South Mountain	47.283	-123.342	936	RAWS	9/1/1991	11/30/1992	No
Burlington Skagit Regional-Bay	48.467	-122.417	43	SAO	3/1/1981	Present	No
Cape Flattery Light	48.383	-124.733	26	SAO	M	Present	No
Destruction Island L	47.667	-124.483	21	SAO	3/1/1930	2/9/1960	No
New Dungeness Light	48.183	-123.117	0	SAO	9/1/1963	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Oak Harbor Air Park	48.250	-122.667	40	SAO	1/22/1981	Present	No
Point No Point USCG Light Stn.	47.917	-122.533	4	SAO	5/1/1930	Present	No
Point Wilson	48.150	-122.750	15	SAO	7/1/1972	Present	No
Port Angeles Fairchild Intl. AP	48.120	-123.498	88	SAO	5/1/1947	Present	No
Port Angeles WB AP	48.133	-123.400	5	SAO	4/1/1885	Present	No
Quillayute River Lig	47.900	-124.633	3	SAO	9/1/1963	Present	No
Quillayute State Airport	47.938	-124.555	56	SAO	8/1/1966	Present	No
Smith Island	48.317	-122.850	21	SAO	1/1/1962	8/1/1984	No
Tatoosh Island	48.383	-124.733	31	SAO	10/1/1883	Present	No
Victoria Marine Radio	48.367	-123.750	38	SAO	11/1/1967	Present	No
Whidbey Island NAS	48.350	-122.667	10	SAO	1/1/1943	Present	No
Dungeness	47.883	-123.083	1250	SNOTEL			No
Mount Crag	47.750	-123.000	1234	SNOTEL	10/1/1989	Present	No
Anacortes	48.508	-122.676	10	WA DOT	M	Present	No
Diamond Point	48.050	-122.948	97	WA DOT	M	Present	No
Heckelville Shed	48.069	-124.047	283	WA DOT	M	Present	No
Indian Valley @ SR101	48.069	-123.626	0	WA DOT	M	Present	No
Mt. Walker	47.755	-122.893	143	WA DOT	M	Present	No
Pt. Grenville	47.303	-124.250	27	WA DOT	M	Present	No
Queets	47.536	-124.333	22	WA DOT	M	Present	No
Seibert Creek Bridge	48.093	-123.272	87	WA DOT	M	Present	No
Anacortes Bartholomew Ave.	48.470	-122.560	5	WAAQ	M	Present	No
Daishowa America Met 1815	48.133	-123.464	3	WAAQ	M	Present	No
Mason County - Shelton 20 NW	47.320	-123.350	914	WAAQ	M	Present	No
Mount Vernon	48.467	-122.433	45	WBAN	10/1/1935	7/31/1951	No
Olympic Peninsula Air Sample S	48.250	-124.417	488	WBAN	11/6/1984	5/30/1990	No
Quillayute NAAS	47.950	-124.533	62	WBAN	5/1/1944	8/31/1945	No
Freeland WGM	48.015	-122.562	21	WX4U	M	Present	No
Greenbank	48.056	-122.578	151	WX4U	M	Present	No
Stanwood	48.272	-122.324	76	WX4U	M	Present	No

4.2.2. North Cascades and San Juan Islands

Of the 18 stations we have identified within the North Cascades National Park Complex (NOCA; Figure 4.2) 17 of these are currently active (Table 4.4). The active COOP stations within NOCA are near Stehekin, at the northwest tip of Lake Chelan, and along State Highway 20. Weather/climate station coverage is currently limited in the north portion of NOCA, with all but two stations being NRCS-SC stations, measuring snowdepth only a couple of times during each winter season. There are currently no RAWS stations within North Cascades National Park, but there are two SNOTEL sites in the southern unit of North Cascades National Park.

The active COOP stations within NOCA are also the primary source of long-term climate records for NOCA. The COOP station “Stehekin 4 NW” has been operating since 1906 (Table 4.4). Data gaps occurred at this station for all climate elements during the winters from 1950-1953. The longest data gap occurred during the winter of 1952-1953, lasting from December, 1952 to June, 1953. This station has also experienced other sporadic data gaps, most of which only last for one month. The most recent gaps occurred in February-March, 2006 and May, 2006. There are three COOP stations with long data records along State Highway 20. The longest data record of these stations is found at “Newhalem”, which is also the westernmost COOP station of the three (see Figure 4.2). The COOP station “Newhalem” has been operating since 1909. The data record from “Newhalem” has been very complete since 1988, when the last significant data gaps occurred. The next COOP station to the east is “Diablo Dam”, which has operated since 1914. This COOP station has a reliable data record, although there are occasional one-month gaps that occur once about every 5-10 years. The most recent data gaps occurred in March and September of 1997. The COOP station “Ross Dam” has been operating since1947 and has a reliable data record.

Two active RAWS stations have been identified in the park (Table 4.4; Figure 4.2). One of these (Stehekin) is located within a kilometer of the COOP station “Stehekin 4 NW”. The other RAWS (Hozomeen) is located at the northern edge of Ross Lake, in northeastern NOCA. However, both of these stations have limited periods of record, extending back only to 2004. Other sources of near-real-time data are provided by the SNOTEL sites in the southern unit of North Cascades National Park. These two stations, “Park Creek Ridge” and “Thunder Basin”, have data records going back to 1978 and 1987, respectively.

The majority of stations within NOCA are NRCS-SC sites. Most of these stations have data records of several decades in length (Table 4.4). However, these sites only measure snow depth a few times every season, so their climate data is very limited.

There are several active COOP stations within 30 km of NOCA that have long data records. The COOP station “Concrete Ppl. Fish Stn.”, about 20 km west of central NOCA (Figure 4.2), has been active since 1905 (Table 4.4), with a largely-reliable data record. Before the mid-1960s, no weekend observations were made at this COOP station. There have been occasional data gaps of one or two months in length during the 1990s and early 2000s. These gaps, when they have occurred, have usually occurred in the summer and fall months. A data record of similar length is found at “Winthrop 1 WSW”, a COOP station that is 30 km east of NOCA and has been active since 1906. This site has a reliable data record. However, occasional one-month data gaps are present for this station, usually occurring about once every five years. The most recent data gap occurred in November, 2005. About 25 km northwest of “Winthrop 1 WSW”, along State Highway 20, the COOP station “Mazama” has operated since 1948. Data were very limited from this station before the early 1970s, but since then, the data record at “Mazama” has been very complete for all climate elements. The COOP station “Glacier R S” has been operating since 1914. This station is located on State Highway 542, about 15 km northwest of Mount Baker and 20 km west of the Heather Meadows Visitor Center. Unfortunately, this site does not have a reliable data record.

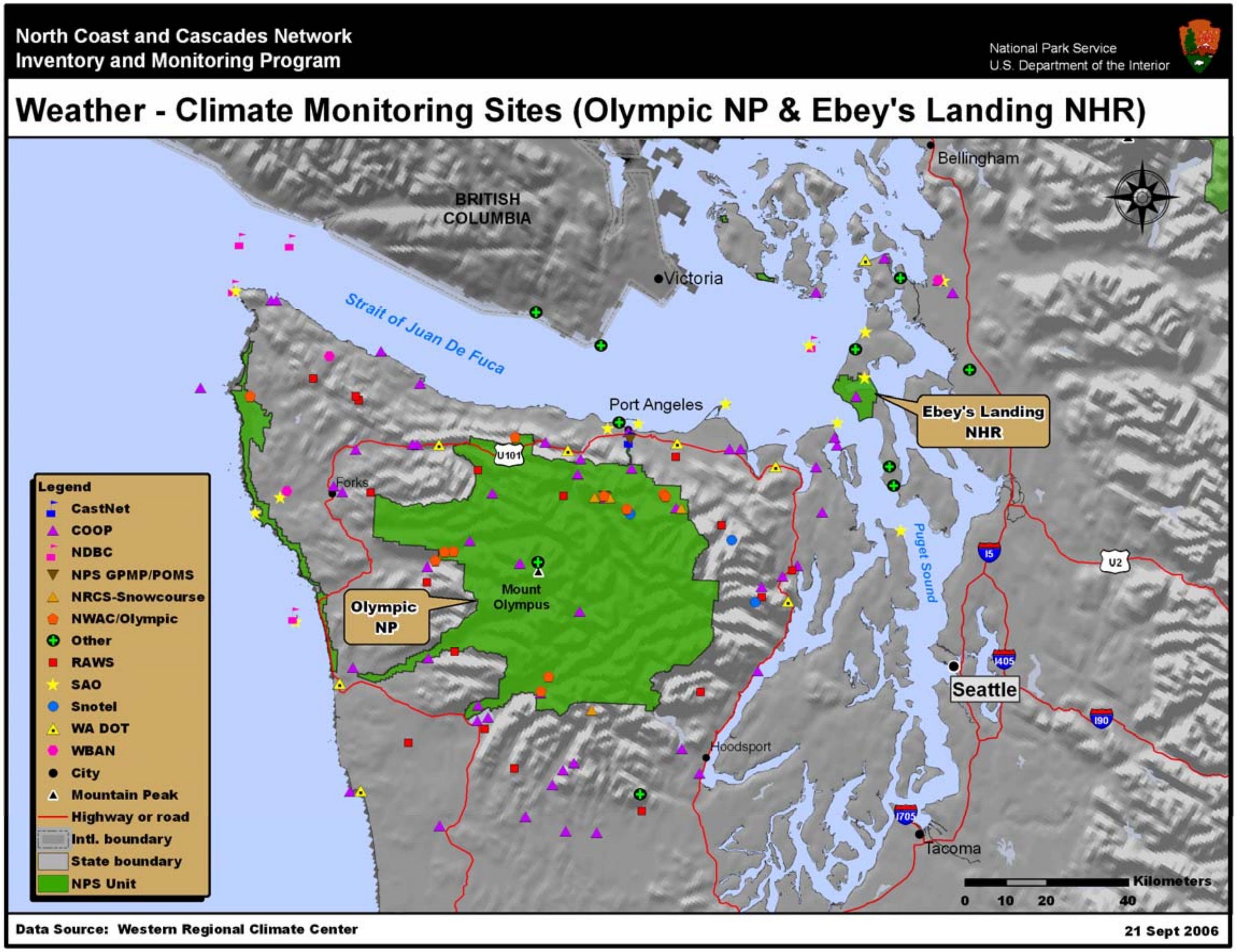


Figure 4.1. Station locations for NCCN park units in Puget Sound and on the Olympic Peninsula.

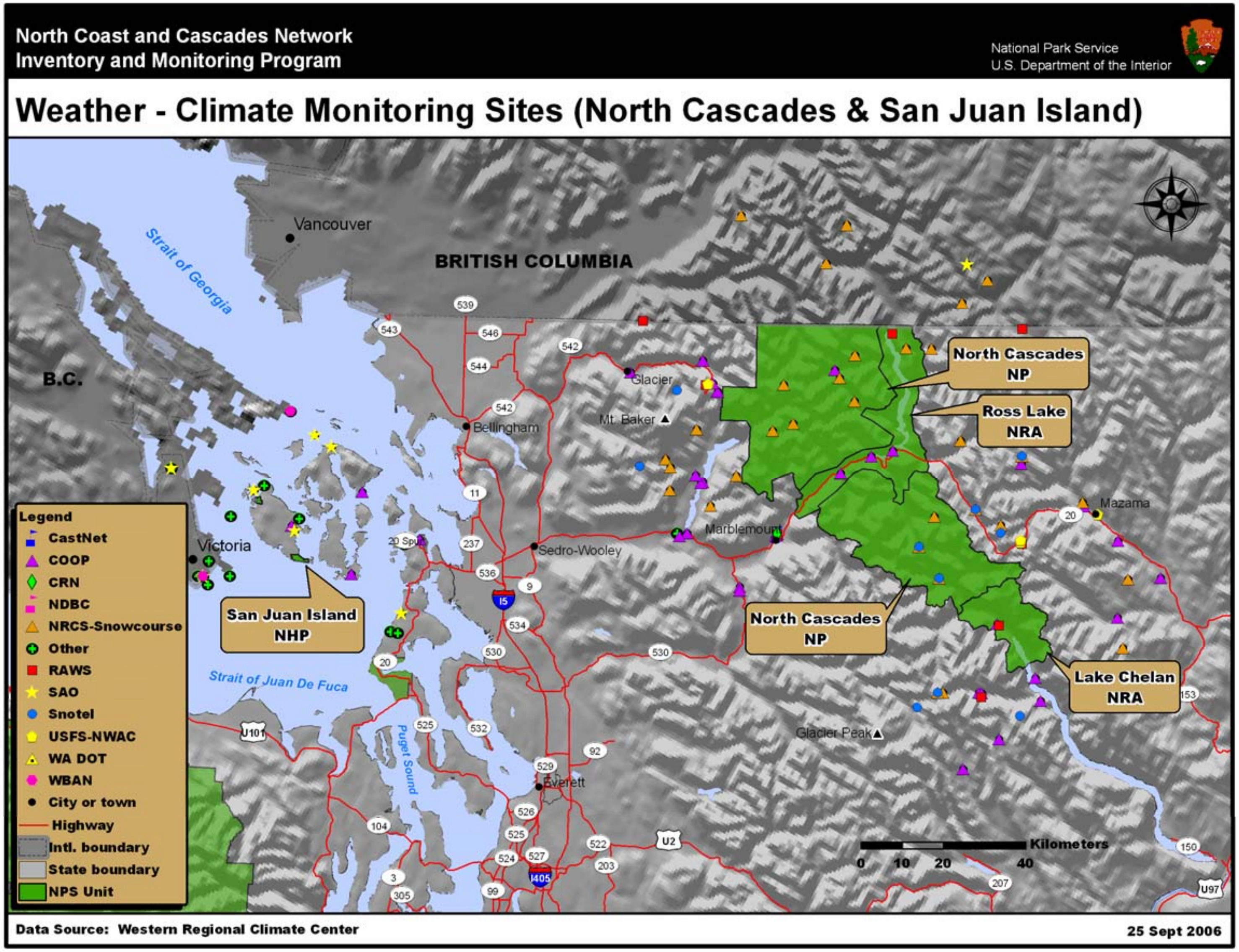


Figure 4.2. Station locations for NCCN park units in the North Cascades and San Juan Islands.

Table 4.4. Weather/climate stations for NCCN park units in the North Cascades and San Juan Islands. Stations inside park unit boundaries and within 30 km of the park unit boundaries are included. Listing includes station name, location, and elevation; weather/climate network associated with station; operational start/end dates for station, and flag to indicate if station is inside park boundaries. Missing entries are indicated by “M”.

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
North Cascades National Park Service Complex - NOCA							
Beaver Pass	48.900	-121.267	1122	COOP	6/1/1948	10/31/1971	Yes
Diablo Dam	48.714	-121.143	272	COOP	12/24/1914	Present	Yes
Newhalem	48.676	-121.242	160	COOP	4/11/1909	Present	Yes
Ross Dam	48.727	-121.072	377	COOP	2/1/1947	Present	Yes
Stehekin 4 NW	48.351	-120.727	387	COOP	1/20/1906	Present	No
Beaver Creek Trail	48.833	-121.200	671	NRCS-SC	1/1/1944	Present	Yes
Beaver Pass	48.883	-121.250	1122	NRCS-SC	1/1/1944	Present	Yes
Brown Top Ridge AM	48.933	-121.200	1829	NRCS-SC	1/1/1970	Present	Yes
Easy Pass AM	48.867	-121.433	1585	NRCS-SC	1/1/1959	Present	Yes
Jasper Pass AM	48.783	-121.400	1646	NRCS-SC	1/1/1959	Present	Yes
Meadow Cabins	48.583	-120.933	579	NRCS-SC	1/1/1945	Present	Yes
Mount Blum AM	48.767	-121.467	1768	NRCS-SC	1/1/1964	Present	Yes
New Lake Hozomeen	48.950	-121.033	853	NRCS-SC	1/1/1971	Present	Yes
Park Creek Ridge	48.450	-120.917	1402	NRCS-SC	1/1/1928	Present	Yes
Thunder Basin	48.517	-120.983	732	NRCS-SC	1/1/1948	Present	Yes
Hozomeen	48.981	-121.078	518	RAWS	10/1/2004	Present	Yes
Stehekin	48.347	-120.720	375	RAWS	6/1/2001	Present	Yes
Park Creek Ridge	48.450	-120.917	1402	SNOTEL	10/1/1978	Present	Yes
Thunder Basin	48.517	-120.983	1280	SNOTEL	10/1/1987	Present	Yes
Marblemount RS	48.540	-121.447	109	CASTNet	2/1/1996	Present	No
Austin Pass	48.850	-121.650	0	COOP	9/1/1963	Present	No
Austin Pass	48.850	-121.650	1443	COOP	8/1/1960	11/26/1973	No
Chiwawa River	48.033	-120.833	827	COOP	5/30/1925	12/31/1957	No
Concrete 12 NE	48.667	-121.583	1373	COOP	8/1/1963	9/30/1976	No
Concrete 12 NNW	48.700	-121.817	1037	COOP	M	8/31/1971	No
Concrete 2 SW	48.533	-121.767	40	COOP	6/1/1948	2/7/1985	No
Concrete Ppl Fish St.	48.540	-121.742	59	COOP	12/1/1905	Present	No
Darrington 21 NNE	48.541	-121.446	115	COOP	4/3/2003	Present	No
Domke Lake	48.183	-120.583	683	COOP	10/1/1926	12/31/1939	No
Glacier R S	48.888	-121.937	285	COOP	4/5/1914	Present	No
Harts Pass	48.700	-120.650	1967	COOP	M	9/30/1976	No
Holden	48.200	-120.783	1049	COOP	11/1/1930	6/30/1957	No
Holden Village	48.199	-120.774	981	COOP	6/1/1962	Present	No
Koma Kulshan	48.650	-121.700	259	COOP	1/1/1937	12/31/1944	No
Lucerne 1 N	48.233	-120.600	366	COOP	1/1/1906	1/1/1989	No
Marblemount R S	48.538	-121.450	106	COOP	6/1/1948	Present	No
Mazama	48.609	-120.445	661	COOP	6/1/1948	Present	No
Mazama 6 SE	48.533	-120.333	598	COOP	3/1/1936	9/30/1976	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Mount Baker Lodge	48.867	-121.667	1266	COOP	11/1/1926	1/14/1983	No
Sauk	48.417	-121.567	70	COOP	6/1/1948	4/30/1949	No
Sauk River	48.425	-121.567	81	COOP	8/1/1966	Present	No
Shuksan	48.917	-121.700	619	COOP	11/1/1954	8/31/1974	No
Snow Brushy Creek	48.100	-120.717	1193	COOP	10/1/1965	5/31/1975	No
Stockdill Ranch	48.367	-120.333	671	COOP	7/1/1909	4/1/1964	No
Upper Baker Dam	48.653	-121.693	210	COOP	1/1/1964	Present	No
Upper Baker River	48.667	-121.717	259	COOP	4/1/1960	9/1/1965	No
Winthrop 1 WSW	48.454	-120.194	535	COOP	3/1/1906	Present	No
Darrington 21 NNE	48.541	-121.446	124	CRN	M	M	No
CW1625 Oak Harbor	48.307	-122.677	48	CWOP	M	Present	No
CW2882 Anacortes	48.501	-122.664	70	CWOP	M	Present	No
CW2926 Concrete	48.539	-121.774	87	CWOP	M	Present	No
Whidbey Island	48.310	-122.700	36	GPS-MET	M	Present	No
Blackwall Peak	49.100	-120.767	-3048	NRCS-SC	M	M	No
Buttermilk Butte	48.300	-120.317	1600	NRCS-SC	M	M	No
Cloudy Pass AM	48.200	-120.917	1981	NRCS-SC	1/1/1927	Present	No
Devils Park	48.750	-120.850	1798	NRCS-SC	1/1/1950	Present	No
Dock Butte AM	48.633	-121.800	1158	NRCS-SC	1/1/1959	Present	No
Freezeout Cr. Tr.	48.950	-120.950	1067	NRCS-SC	1/1/1944	Present	No
Granite Creek	48.600	-120.800	1067	NRCS-SC	1/1/1971	Present	No
Harts Pass	48.717	-120.650	1981	NRCS-SC	1/1/1941	Present	No
Klesilkwa	49.133	-121.300	-3048	NRCS-SC	M	M	No
Lightning Lake	49.050	-120.850	-3048	NRCS-SC	M	M	No
Little Meadows AM	48.200	-120.900	1608	NRCS-SC	1/1/1927	Present	No
Lyman Lake	48.200	-120.917	1798	NRCS-SC	1/1/1928	Present	No
Marten Lake	48.767	-121.717	1097	NRCS-SC	1/1/1959	Present	No
Mazama	48.617	-120.450	664	NRCS-SC	M	M	No
Rainy Pass	48.567	-120.717	1457	NRCS-SC	1/1/1930	Present	No
Rocky Creek	48.683	-121.800	640	NRCS-SC	1/1/1959	Present	No
S.F. Thunder Creek	48.600	-121.667	671	NRCS-SC	1/1/1959	Present	No
Schreibers Meadow	48.700	-121.817	1036	NRCS-SC	1/1/1959	Present	No
Sumallo River (Disc)	49.217	-121.233	268	NRCS-SC	M	M	No
Thompson Ridge	48.450	-120.300	1280	NRCS-SC	M	M	No
Wahleach Lake	49.233	-121.583	-3048	NRCS-SC	M	M	No
Watson Lakes	48.667	-121.583	1372	NRCS-SC	1/1/1959	Present	No
Mazama	48.590	-120.400	671	NWAVAL	M	Present	No
Mount Baker	48.865	-121.678	1286	NWAVAL	M	Present	No
Mount Baker	48.865	-121.682	1286	NWAVAL	M	Present	No
Washington Pass	48.528	-120.650	1676	NWAVAL	M	Present	No
Washington Pass-Ridge to N	48.533	-120.650	2021	NWAVAL	M	Present	No
83 Monument	48.994	-120.650	1981	RAWS	7/1/1985	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Holden Mine	48.190	-120.776	975	RAWS	7/1/1994	10/31/1997	No
Kidney Creek	49.000	-121.900	914	RAWS	1/1/1985	Present	No
Marblemount	48.539	-121.446	109	RAWS	5/1/2003	Present	No
Mt. Baker	48.863	-121.689	1981	RAWS	5/1/1985	12/31/2004	No
Washington Pass	48.525	-120.647	1664	RAWS	1/1/1985	Present	No
Allison Pass	49.133	-120.833	1341	SAO	9/1/1958	Present	No
Elbow Lake	48.683	-121.900	975	SNOTEL	10/1/1995	Present	No
Harts Pass	48.717	-120.650	1981	SNOTEL	10/1/1981	Present	No
Lyman Lake	48.200	-120.917	1798	SNOTEL	10/1/1979	Present	No
Miners Ridge	48.167	-120.983	1890	SNOTEL	10/1/1988	Present	No
Mirror Lake	48.150	-120.650	1707	SNOTEL	10/1/1982	9/30/1988	No
Rainy Pass	48.550	-120.717	1457	SNOTEL	10/1/1981	Present	No
Swamp Creek	48.600	-120.800	1219	SNOTEL	M	M	No
Wells Creek	48.850	-121.783	1280	SNOTEL	10/1/1995	Present	No
Anacortes	48.508	-122.676	10	WA DOT	M	Present	No
San Juan Island National Historical Park - SAJH							
Discovery Island	48.420	-123.230	15	CANADA	M	Present	No
Esquimalt Harbour B. C.	48.433	-123.433	3	CANADA	M	Present	No
Kelp Reefs B. C.	48.550	-123.233	0	CANADA	M	Present	No
Saturna Island Meteorological	48.783	-123.050	24	CANADA	M	Present	No
Trial Island	48.400	-123.300	23	CANADA	M	Present	No
Vic. Hartland Automatic	48.533	-123.467	154	CANADA	M	Present	No
Victoria Automatic	48.417	-123.317	70	CANADA	M	Present	No
Victoria Harbour	48.417	-123.333	5	CANADA	M	Present	No
Victoria Int. Airport B. C.	48.650	-123.433	20	CANADA	M	Present	No
Victoria University	48.450	-123.300	60	CANADA	M	Present	No
Anacortes	48.512	-122.614	6	COOP	9/1/1892	Present	No
Friday Harbor	48.533	-123.033	31	COOP	6/1/1948	4/30/1952	No
Olga 2 SE	48.612	-122.806	24	COOP	7/1/1891	Present	No
Richardson 3 SE	48.433	-122.833	9	COOP	12/1/1948	8/31/1958	No
CW0870 Victoria	48.469	-123.390	18	CWOP	M	Present	No
CW1625 Oak Harbor	48.307	-122.677	48	CWOP	M	Present	No
CW2882 Anacortes	48.501	-122.664	70	CWOP	M	Present	No
CW3083 Friday Harbor	48.620	-123.128	33	CWOP	M	Present	No
VE7SDJ-1 Victoria	48.554	-123.448	62	CWOP	M	Present	No
Friday Harbor	48.550	-123.010	6	GPS-MET	M	Present	No
Whidbey Island	48.310	-122.700	36	GPS-MET	M	Present	No
Eastsound Orcas Island Airport	48.708	-122.911	9	SAO	4/1/2004	Present	No
Friday Harbor Airport	48.522	-123.023	33	SAO	1/1/1981	Present	No
Patos Island Anacort	48.733	-122.967	1	SAO	M	Present	No
Patricia Bay	48.650	-123.433	19	SAO	7/1/1940	Present	No
Roche Harbor SPB	48.608	-123.159	0	SAO	9/9/2002	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Smith Island	48.317	-122.850	21	SAO	1/1/1962	8/1/1984	No
Victoria Gonzales Heights	48.417	-123.317	69	SAO	1/1/1934	Present	No
Whidbey Island NAS	48.350	-122.667	10	SAO	1/1/1943	Present	No
Anacortes	48.508	-122.676	10	WA DOT	M	Present	No
Faturna Island Aut	48.783	-123.050	823	WBAN	M	Present	No
Victoria Gon	48.417	-123.317	70	WBAN	1/1/1971	Present	No

Several RAWS and SNOTEL stations provide near-real-time weather data within 30 km of NOCA (Table 4.4). Most of these stations have data records that are two decades or more in length. There are also a few active stations with the NWAVAL network that are within 30 km of NOCA and provide near-real-time data. These include sites at Mount Baker Lodge, near the Heather Meadows Visitor Center; Mazama, Washington; and the crest of State Highway 20, at Washington Pass. The only SAO station we have identified is about 20 km northeast of NOCA, at Allison Pass in Canada (Figure 4.2). This station has been operating since 1958.

We have identified no active or historical weather/climate stations within SAJH. However, there are two SAO stations on San Juan Island. One SAO station (Roche Harbor SPB) is located on the northwest tip of San Juan Island, about 2 km northwest of the American Camp unit of SAJH (Figure 4.2). This station has only been operating since 2002 (Table 4.4). The other SAO station (Friday Harbor Airport) has been operating since 1981 and is about five kilometers north of the English Camp unit of SAJH. Several Canadian weather/climate stations are located 10-20 km west of SAJH, on Vancouver Island, and provide near-real-time data for the area.

The only COOP station on San Juan Island (Friday Harbor) was only active during the late 1940s and early 1950s (Table 4.4). The closest long-term climate data records are found at the COOP station “Olga 2 SE”, which is located on Orcas Island about 20 km northeast of SAJH. This station has been operational since 1891, with a data record that is complete and of very high quality. Other long-term records are provided from the COOP station “Anacortes”, discussed previously.

4.2.3. Mount Rainier National Park (MORA)

Of the 17 weather/climate stations we have identified within MORA (Table 4.5; Figure 4.3), 15 are currently active. There are four active COOP stations inside MORA, each having long climate records. The longest record is at “Rainier Carbon River”, which has been operational since 1906. This station is located at the very northwest corner of MORA. Unfortunately, this station’s data record is unreliable. The next longest record is found at “Longmire Rainier NPS” (1909-present). Data from this site have been very reliable since 1978, with virtually no data gaps after this date. The most complete data record of these COOP stations is provided at “Rainier Paradise Rng.”, which has operated since 1916. There have been occasional one-month data gaps at this site, most notably in the 1990s. Data gaps occurred in April and June of 1994; January, July, and November of 1996; and April, August, and September of 2003. The final COOP station where a long climate record is indicated, “Rainier Ohanapecosh”, is an unreliable station with very intermittent data. Two NRCS-SC sites provide long-term records of snow depth.

At least nine weather stations provide near-real-time data for MORA. Six of these stations are associated with the NWAVAL network. The NWAVAL stations are concentrated at the primary visitor centers for MORA and at Chinook Pass, near the junction of State Highways 410 and 123 (Figure 4.3; Table 4.5). One RAWS station (Ohanapecosh) is located in southeastern MORA. This station has a short data record, however, as it started in 2003. A POMS station (Tahoma Vista) has been operating since 2004 in southwestern MORA, about eight kilometers northwest of Longmire. Finally, a SNOTEL station (Paradise) is situated on the southeast shoulder of Mount Rainier and has been in operation since 1980.

Outside of MORA, there are six active COOP stations located within 30 km of MORA (Table 4.5). All of these stations have longer data records, with the shortest data record occurring at Parkway Silver Spring, just outside the northeast entrance of MORA (Figure 4.4). The longest record from these COOP stations is found at "Buckley 1 NE", which has been active since 1913. This station has a very complete data record, with the exception of data gaps in January, September, and November of 2003. The COOP stations "Packwood" and "Randle 1 E" both started operating in 1924. Both of these stations are south of MORA. "Packwood" is located just over 10 km south of MORA, on U.S. Highway 12. "Randle 1 E" is located further west on U.S. Highway 12, about 20 km due south of the southwestern tip of MORA. The data record has been very complete since 1975 for "Packwood"; before 1975, there were no observations taken on weekends at this station. In contrast to "Packwood", the data record for "Randle 1 E" is very unreliable. "Mud Mountain Dam", about 15 km northwest of MORA, has provided a very reliable data record since 1939.

Near-real-time weather data are provided by at least seven NWAVAL stations within 30 km of MORA (Table 4.5). Three of these stations are at the Crystal Mountain Resort just outside the northeast boundary of MORA. Three more NWAVAL stations are located at White Pass, about 20 km southeast of MORA on U.S. Highway 12 (Figure 4.4). Four RAWS stations are located within 30 km of MORA, along with at least six SNOTEL stations. Some of these stations have data records that are up to three decades in length. A station with the WA DOT network is currently operated at White Pass and the WAAQ network has two stations near Enumclaw, Washington, about 25 km northwest of MORA. Additional near-real-time data are provided by several CWOP stations located mostly northwest of MORA in the outer suburbs of Tacoma and Seattle. A GPMP station operated in the early 1990s at Tahoma Woods, about 15 km west of MORA on State Highway 706, but it is no longer active

Table 4.5. Weather/climate stations for MORA. Stations inside MORA and within 30 km of MORA boundary are included. Listing includes station name, location, and elevation; weather/climate network associated with the station, operational start/end dates, and flag to indicate if station is inside park boundaries. Missing entries are indicated by "M".

Mount Rainier National Park (MORA)							
Name	**Lat.**	**Lon.**	**Elev. (m)**	**Network**	**Start**	**End**	**In Park?**
Longmire Rainier NPS	46.749	-121.812	842	COOP	1/1/1909	Present	Yes
Rainier Carbon River	46.994	-121.911	529	COOP	3/1/1906	Present	Yes
Rainier Ohanapecosh	46.732	-121.573	594	COOP	10/13/1926	Present	Yes
Rainier Paradise Rng.	46.786	-121.743	1654	COOP	12/1/1916	Present	Yes
White River Ranger Stn.	46.900	-121.550	1068	COOP	11/20/1943	3/12/1981	Yes

Mount Rainier National Park (MORA)							
Name	**Lat.**	**Lon.**	**Elev. (m)**	**Network**	**Start**	**End**	**In Park?**
Carbon River GPMP	46.996	-121.911	530	GPMP	7/29/1994	8/10/1994	Yes
Cayuse Pass	46.867	-121.533	1615	NRCS-SC	1/1/1940	Present	Yes
New Paradise Pk Disc	46.800	-121.733	1676	NRCS-SC	1/1/1961	Present	Yes
Chinook Pass	46.870	-121.520	1695	NWAVAL	M	Present	Yes
Chinook Pass	46.870	-121.520	1902	NWAVAL	M	Present	Yes
Paradise Mt. Rainier	46.790	-121.730	1676	NWAVAL	M	Present	Yes
Paradise-Mt. Rainier	46.780	-121.740	1676	NWAVAL	M	Present	Yes
Sunrise-Mt. Rainier	46.915	-121.642	1951	NWAVAL	M	Present	Yes
Sunrise-Mt. Rainier	46.920	-121.638	2103	NWAVAL	M	Present	Yes
Tahoma Vista	46.796	-121.884	1067	POMS	5/1/2004	Present	Yes
Ohanapecosh	46.731	-121.570	503	RAWS	10/1/2003	Present	Yes
Paradise	46.833	-121.717	1561	SNOTEL	10/1/1980	Present	Yes
Tahoma Woods	46.758	-122.124	415	CASTNet	7/1/1991	Present	No
Buckley	47.150	-121.950	250	COOP	6/1/1948	1/31/1977	No
Buckley 1 NE	47.169	-122.004	209	COOP	1/1/1913	Present	No
Bumping Lake	46.867	-121.300	1049	COOP	4/1/1910	9/6/1973	No
Carbonado 8 SSE	46.983	-121.967	500	COOP	12/1/1957	6/30/1962	No
Electron Headworks	46.900	-122.033	528	COOP	10/1/1943	4/30/1980	No
Fairfax	47.000	-122.000	433	COOP	3/1/1916	4/30/1950	No
Fairfax 1 NW	47.033	-122.033	0	COOP	7/1/1948	2/7/1985	No
Grass Mtn. 1	47.233	-121.750	854	COOP	9/1/1965	9/30/1976	No
Greenwater	47.133	-121.633	527	COOP	1/1/1939	11/1/1998	No
Lester	47.200	-121.483	497	COOP	3/1/1904	11/4/1974	No
Lester 2 E	47.217	-121.450	534	COOP	2/1/1934	6/30/1960	No
Mineral	46.717	-122.183	448	COOP	4/1/1930	12/13/1979	No
Mud Mtn. Dam	47.141	-121.936	399	COOP	1/1/1939	Present	No
Packwood	46.609	-121.674	323	COOP	10/1/1924	Present	No
Palmer 7 SE Charley	47.250	-121.783	488	COOP	6/1/1948	12/31/1955	No
Parkway	46.983	-121.533	805	COOP	1/1/1931	12/31/1944	No
Parkway Silver Spring	46.983	-121.533	793	COOP	9/1/1963	Present	No
Randle	46.533	-121.950	271	COOP	12/1/1951	Present	No
Randle 1 E	46.533	-121.933	274	COOP	12/13/1924	Present	No
Rimrock Tieton Dam	46.650	-121.133	833	COOP	7/1/1917	8/31/1977	No
Twin Camp Guard Stn.	47.150	-121.450	1251	COOP	9/1/1965	10/31/1976	No
CW1558 Orting	47.061	-122.183	197	CWOP	M	Present	No
CW5049 Enumclaw	47.206	-121.995	227	CWOP	M	Present	No
CW5101 Bonney Lake	47.157	-122.192	158	CWOP	M	Present	No
CW5490 Orting	47.131	-122.241	38	CWOP	M	Present	No
CW5958 Enumclaw	47.194	-121.987	210	CWOP	M	Present	No
Tahoma Woods	46.758	-122.123	423	GPMP	11/1/1992	7/31/1995	No
Airstrip	47.217	-121.450	549	NRCS-SC	1/1/1961	Present	No
Bumping Lake	46.867	-121.300	1052	NRCS-SC	1/1/1915	Present	No

Mount Rainier National Park (MORA)							
Name	**Lat.**	**Lon.**	**Elev. (m)**	**Network**	**Start**	**End**	**In Park?**
Bumping Lake New	46.883	-121.283	1036	NRCS-SC	1/1/1961	Present	No
Corral Pass	47.017	-121.467	1829	NRCS-SC	1/1/1940	Present	No
Grass Mtn. No. 2	47.217	-121.750	884	NRCS-SC	1/1/1961	Present	No
Lester Creek	47.183	-121.467	945	NRCS-SC	1/1/1961	Present	No
Lynn Lake	47.200	-121.783	1219	NRCS-SC	1/1/1970	Present	No
Sawmill Ridge	47.167	-121.433	1433	NRCS-SC	1/1/1961	Present	No
Twin Camp	47.133	-121.783	1250	NRCS-SC	1/1/1961	Present	No
White Pass (E. Side)	46.633	-121.383	1372	NRCS-SC	1/1/1953	Present	No
Chinook Pass 1km N	46.880	-121.520	1902	NWAVAL	M	Present	No
Crystal Mountain	46.940	-121.470	2094	NWAVAL	M	Present	No
Crystal Mtn-base	46.940	-121.470	1356	NWAVAL	M	Present	No
Crystal Mtn-top	46.940	-121.500	2094	NWAVAL	M	Present	No
White Pass	46.620	-121.420	1829	NWAVAL	M	Present	No
White Pass-base	46.640	-121.390	1372	NWAVAL	M	Present	No
White Pass-top	46.620	-121.390	1801	NWAVAL	M	Present	No
Enumclaw	47.198	-121.965	235	RAWS	1/1/2004	Present	No
Greenwater	47.156	-121.611	640	RAWS	5/1/1995	Present	No
Hager Creek	46.567	-121.631	1097	RAWS	1/1/1985	Present	No
Lester	47.208	-121.525	492	RAWS	5/1/1985	Present	No
State DNR - Ashford 5N	46.833	-122.000	1021	RAWS	6/1/1985	8/31/1985	No
Bumping Ridge	46.817	-121.333	1402	SNOTEL	10/1/1978	Present	No
Burnt Mountian	47.000	-121.917	1280	SNOTEL	M	M	No
Corral Pass	47.017	-121.467	1829	SNOTEL	10/1/1981	Present	No
Cougar Mtn.	47.250	-121.633	975	SNOTEL	M	M	No
Huckleberry Creek	47.067	-121.583	610	SNOTEL	11/5/1997	Present	No
Morse Lake	46.900	-121.483	1646	SNOTEL	10/1/1978	Present	No
Mowich	46.917	-121.950	960	SNOTEL	M	M	No
Pigtail Peak	46.617	-121.417	1798	SNOTEL	10/1/1981	Present	No
White Pass E.S.	46.633	-121.383	1372	SNOTEL	10/1/1980	Present	No
White Pass Summit	46.638	-121.390	1313	WA DOT	M	Present	No
Enumclaw 212th SE	47.210	-122.060	195	WAAQ	M	Present	No
Enumclaw Mud Mtn. Rd.	47.141	-121.933	304	WAAQ	M	Present	No

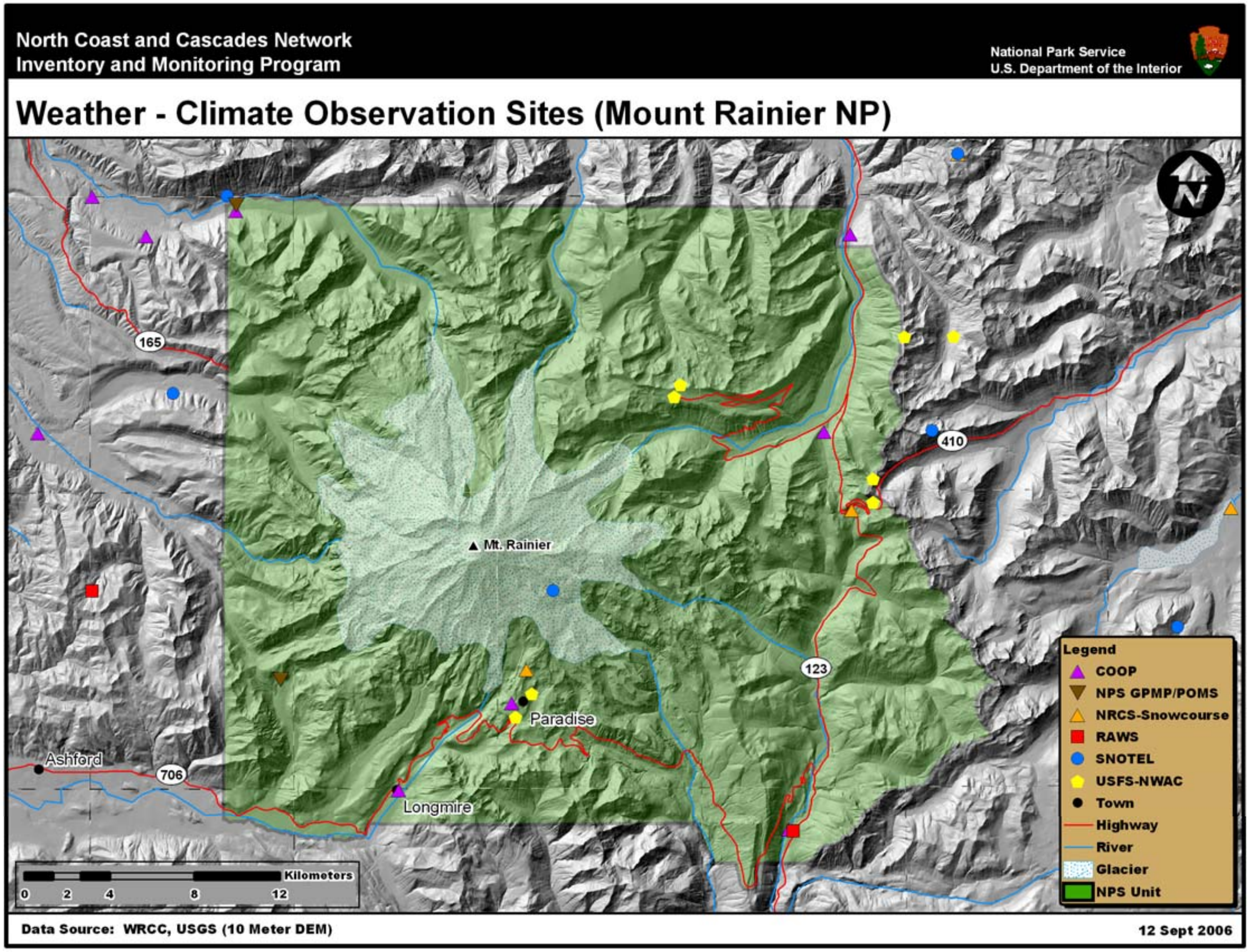


Figure 4.3. Station locations within MORA.

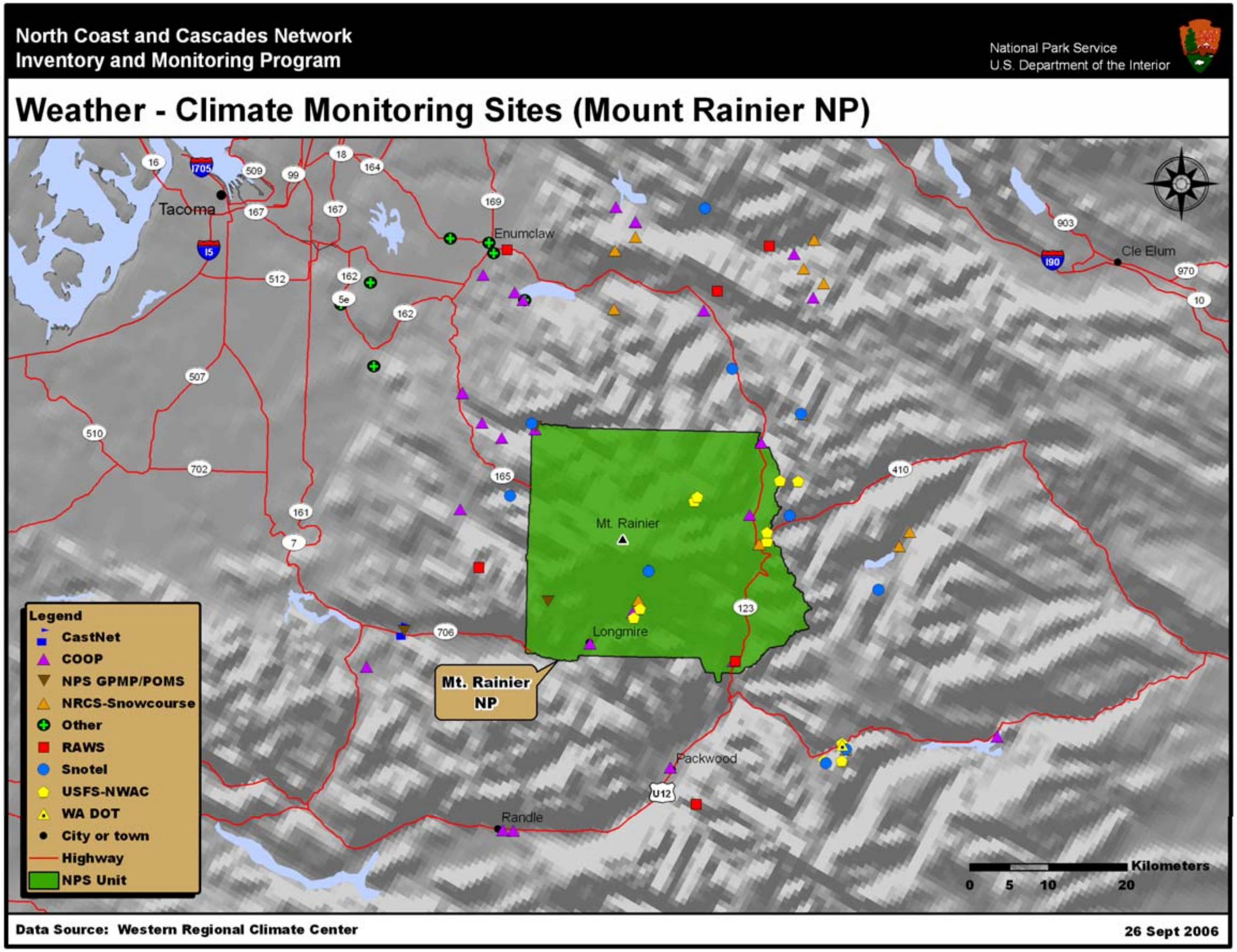


Figure 4.4. Station locations in and near MORA.

4.2.4. Columbia River Park Units

No weather/climate stations have been identified within FOVA (Table 4.6). However, due to its location in the urban areas of Portland, Oregon and Vancouver, Washington, FOVA has several stations that provide high-quality data within 10 km of the park unit. The COOP station “Vancouver 4 NNE” has the longest data record of the weather/climate stations we have identified for FOVA. This station is about 6 km north of FOVA (Figure 4.5) and has been operating since 1856. The data record for “Vancouver 4 NNE” is very complete, with virtually no data gaps. Another long-term record is provided at the COOP station “Vancouver Interstate Bridge”, immediately west of FOVA. This station has been operating since 1902.

Portland International Airport, about five kilometers southeast of FOVA, has a COOP station and a SAO station. Both of these sites have been operating since 1926 and provide data records that are of high quality. The SAO station has provided automated data for the last few decades. Besides the COOP station “Vancouver Interstate Bridge”, the closest weather/climate station to FOVA is the SAO station “Vancouver Pearson Airport”. This station is only a kilometer east of FOVA has operated since 1981. There are a few automated stations run by the ODOT and WAAQ networks within 10 km of FOVA (Table 4.6). Finally, there are a few weather stations located within 10 km of FOVA that are affiliated with volunteer networks (e.g., CWOP and WX4U).

Table 4.6. Weather/climate stations for NCCN park units on the Columbia River. Stations inside park unit boundaries and within 10 km of the park unit boundaries (30 km for LEWI) are included. Listing includes station name, location, and elevation; weather/climate network associated with station; operational start/end dates for station, and flag to indicate if station is inside park boundaries. Missing entries are indicated by “M”.

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Fort Vancouver National Historic Site – FOVA							
J D Ross Substation	45.667	-122.667	61	COOP	4/1/1960	5/31/1964	No
Portland Intl. Arpt.	45.591	-122.600	6	COOP	1/1/1926	Present	No
Portland WB City	45.533	-122.667	9	COOP	7/1/1888	7/1/1973	No
Vancouver 4 NNE	45.678	-122.652	64	COOP	1/1/1856	Present	No
Vancouver Interstate Bridge	45.621	-122.674	1	COOP	4/1/1902	Present	No
CW1222 Vancouver	45.626	-122.551	92	CWOP	M	Present	No
KA7CTT Vancouver	45.627	-122.563	91	CWOP	M	Present	No
KD7CTY Vancouver	45.660	-122.604	92	CWOP	M	Present	No
N7QXO-1 Vancouver	45.698	-122.688	71	CWOP	M	Present	No
Portland /Jefferson HS	45.561	-122.672	64	ODEQ	M	Present	No
Fremont Bridge E (I-405 MP 3)	45.539	-122.681	30	ODOT	M	Present	No
Fremont Bridge W (I-405 MP 3)	45.537	-122.684	30	ODOT	M	Present	No
Glen Jackson Bridge N Channel	45.591	-122.547	17	ODOT	M	Present	No
Interstate Bridge North Span	45.621	-122.673	23	ODOT	M	Present	No
Interstate Bridge South	45.617	-122.676	23	ODOT	M	Present	No

Name	Lat.	Lon.	Elev. (m)	Network	Start	End	In Park?
Span							
Portland AFB	45.617	-122.600	8	SAO	5/1/1936	12/31/1952	No
Portland Intl. Arpt.	45.591	-122.600	6	SAO	1/1/1926	Present	No
Vancouver Pearson Airport	45.621	-122.657	9	SAO	5/1/1981	Present	No
Vancouver Ross Substation	45.660	-122.650	61	WAAQ	M	Present	No
Portland Columbia Airport	45.600	-122.600	6	WBAN	5/1/1936	10/13/1940	No
Vancouver	45.650	-122.567	65	WBAN	4/2/1951	4/30/1952	No
Walnut Grove Vancouver	45.710	-122.620	98	WX4U	M	Present	No
Lewis and Clark National Historical Park – LEWI							
Fort Clatsop Natl. Mem.	46.136	-123.878	13	COOP	7/1/1998	Present	Yes
Astor Experiment Stn.	46.150	-123.817	15	COOP	1/1/1937	7/1/1973	No
Astoria	46.183	-123.833	61	COOP	4/1/1892	1/31/1961	No
Astoria Regional Airport	46.157	-123.882	3	COOP	1/1/1899	Present	No
Astoria Tongue Point	46.217	-123.767	0	COOP	3/1/1968	2/29/1988	No
Crossett	46.133	-123.533	128	COOP	7/1/1929	12/31/1942	No
Ilwaco	46.300	-124.033	3	COOP	9/1/1963	Present	No
Knappa 1 S	46.167	-123.567	40	COOP	7/1/1953	8/31/1954	No
Long Beach 3 NNE	46.383	-124.033	9	COOP	6/1/1922	5/31/1967	No
Long Beach Exp. Stn.	46.368	-124.038	8	COOP	11/1/1963	Present	No
Naselle 2 ENE	46.373	-123.753	15	COOP	8/2/1929	Present	No
Necanicum	45.900	-123.767	101	COOP	12/1/1952	8/31/1954	No
North Head	46.300	-124.083	64	COOP	8/1/1902	5/31/1953	No
Saddle Mountain Park	45.967	-123.700	473	COOP	9/1/1968	10/31/1976	No
Seaside	45.987	-123.924	3	COOP	1/17/1930	Present	No
AA7OA Astoria	46.181	-123.840	73	CWOP	M	Present	No
CW0260 Seaside	45.972	-123.937	50	CWOP	M	Present	No
CW0314 Gearhart	46.070	-123.929	13	CWOP	M	Present	No
CW0356 Seaside	46.011	-123.915	4	CWOP	M	Present	No
N7HAE Knappa	46.167	-123.583	32	CWOP	M	Present	No
Fort Stevens	46.200	-123.960	10	GPS-MET	M	Present	No
Hyack Ridge	45.883	-123.833	494	RAWS	1/1/1985	9/30/1989	No
Astoria Regional Airport	46.157	-123.882	3	SAO	1/1/1899	Present	No
Cape Disappointment	46.283	-124.050	55	SAO	8/1/1969	Present	No
Astoria	46.183	-123.833	6	WBAN	2/1/1897	1/1/1899	No
Astoria NAS	46.167	-123.883	4	WBAN	11/1/1943	5/31/1946	No
Astoria Tongue Point NAS	46.200	-123.767	22	WBAN	10/1/1941	1/31/1945	No
West Slope Astoria	46.180	-123.850	85	WX4U	M	Present	No

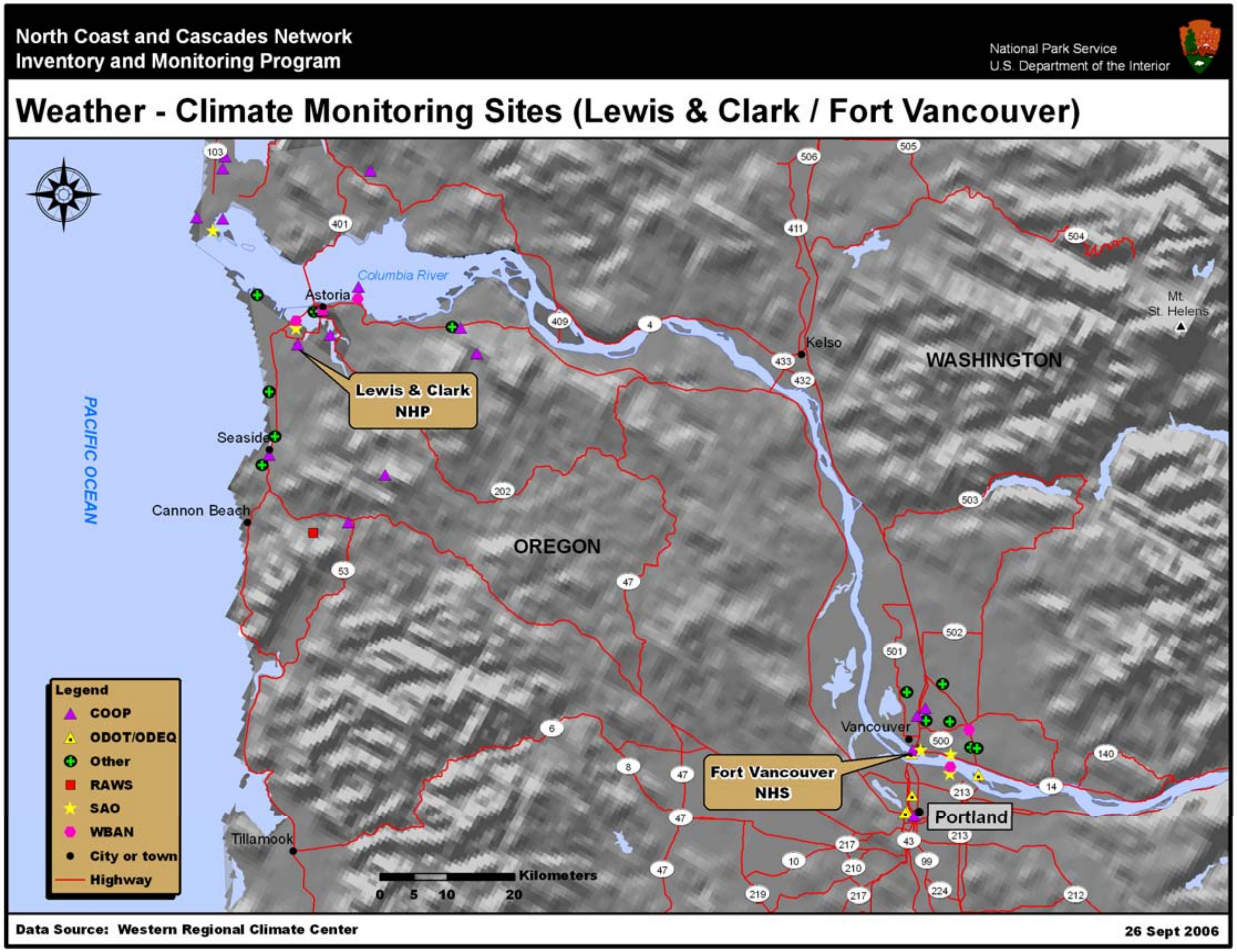


Figure 4.5. Station locations for NCCN park units on the Columbia River.

Lewis and Clark National Historical Park (LEWI) has one weather/climate station located within its boundaries. This is a COOP station (Fort Clatsop Natl. Mem.) and it has been operating since 1998. Five other COOP stations are currently operating within 30 km of LEWI. The COOP station "Astoria Regional Airport", about five kilometers north of LEWI (Figure 4.5), has been operating since 1899 (Table 4.6) and has a complete data record. A SAO station has been operating at this same location, with the same period of record. The COOP station "Naselle 2 ENE" is located about 25 km northeast of LEWI on the Washington side of the Columbia River and has been operating since 1929. However, the data from this station have been unreliable. The COOP station "Seaside", about 20 km southwest of LEWI, has operated since 1930 and has a reliable data record.

The best source of automated weather data for LEWI is the previously-discussed SAO station "Astoria Regional Airport". Besides this site, there is a SAO station at Cape Disappointment, about 20 km northwest of LEWI on the Washington side of the mouth of the Columbia River (Figure 4.5). This station has operated since 1963 (Table 4.6). Additional automated weather data within 30 km of LEWI are provided by a GPS-MET station "Fort Stevens", 10 km northwest of LEWI, and several volunteer stations associated with the CWOP and WX4U networks.

5.0. Conclusions and Recommendations

We have based our findings on an examination of the available records and the topography and climate within NCCN 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 NCCN. Much preliminary work has been accomplished by the NPS to identify weather/climate stations within NCCN park units. This report builds on these previous station inventories and suggestions for investigative climate protocols.

5.1. North Coast and Cascades Inventory and Monitoring Network

Metadata are complete sufficiently for most of the weather/climate stations within NCCN. Much of this is can be attributed to the extensive preliminary work done by the NCCN office to identify the weather/climate stations currently operating within their park units. Their work has been exemplary.

The NCCN park units located along the Columbia River (FOVA, LEWI) and the Puget Sound region (EBLA, SAJH) have satisfactory station coverage. Reliable real-time weather observations are provided by SAO stations at airports near each of these parks. It is important that the existing manual COOP sites with long data records that are near these park units be retained for the purpose of long-term climate monitoring. The NPS would likely benefit by working with the local National Weather Service offices (Portland, Seattle) to encourage the continued operation of these stations.

Of these four park units, SAJH has the least satisfactory coverage of weather/climate stations. There are no long-term climate records on San Juan Island, where SAJH is located. The longest data record on San Juan Island is at the SAO station at Friday Harbor Airport, providing about 25 years of data. The closest long-term records are from COOP stations that are almost 30 km away and are located either on different islands (e.g. Olga 2 SE) or on the mainland (e.g., Anacortes). Despite their not being located on San Juan Island, these two stations provide the best long-term records for the region around SAJH. Two SAO stations in Canada (Patricia Bay, Victoria Gonzales Heights) also provide long data records, although they are somewhat shorter in length than the COOP stations we just discussed. The SAO stations on San Juan Island (Friday Harbor Airport, Roche Harbor SPB) provide the most applicable weather observations for SAJH.

The NCCN park units host a large selection of montane and alpine environments and there is much interest in the characteristics of the NCCN montane and alpine ecosystem. Therefore, climate monitoring in these zones is useful despite higher maintenance costs due to remoteness and frequently inclement conditions. Climate monitoring has applications in hydrologic studies, as well as in alpine ecosystem studies where responses to climate change are investigated. The response of glaciers to climate changes is of particular importance for the NCCN due to the abundance of glaciers in many of the larger NCCN park units (MORA, NOCA, OLYM). At present, there are significant tracts of montane and alpine areas in the larger parks that have very little or no reliable weather/climate station coverage, including southeastern OLYM (Figure 4.1), the north unit of North Cascades National Park (Figure 4.2), and northern MORA (Figure 4.3; 4.4).

It must be noted that these areas in question are often adjacent to areas just outside of the park units that have at least one or two automated stations (both RAWS and SNOTEL). Despite this, the topographic complexity of the larger NCCN parks lowers the representativeness of any nearby stations, particularly for spatial precipitation patterns. Therefore, as resources allow, we recommend that the NPS partner with the USDA/NRCS to install one enhanced SNOTEL station in each of these areas, particularly in OLYM and NOCA. In OLYM, such an installation would help the characteristics of the sharp precipitation gradient that occurs between the very wet crest of the Olympic Mountains, and the much drier rainshadow regions on the west shore of Puget Sound. In NOCA, the northern unit of North Cascades National Park would likely benefit greatly from such an installation. The NRCS-SC sites currently located in this unit do not measure enough weather and climate elements to adequately describe the unit's local climate characteristics. Since the NRCS-SC sites only measure snowdepth a few times during the winter season, they also do not provide enough data to adequately monitor the unit's climate patterns and variability, especially at seasonal time scales and shorter. A small network of portable weather stations is operated by Jon Reidel, a staff member of NOCA, near selected major glaciers in NOCA. These stations report temperature and precipitation several times a day. However, temperature and precipitation are the only climate elements measured at these sites, these stations are only operational during the summer and fall seasons, and the data from these sites are not yet readily accessible. We suggest that one of the NRCS-SC sites in the northern unit of North Cascades National Park be enhanced with a full SNOTEL station, preferably at one of the more accessible locations such as Beaver Pass.

5.2. Spatial Variations in Mean Climate

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

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

5.3. Climate Change Detection

There is much interest in the characteristics of NCCN alpine ecosystems. Applications for climate monitoring include hydrologic studies and responses of high-altitude ecosystems to climate change, particularly the status of the region's abundant glaciers in response to climate changes. Despite the higher maintenance costs of these sites due to remoteness and frequently inclement conditions, climate monitoring in the high-elevation zones is quite useful.

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

5.4. Aesthetics

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

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

5.5. Information Access

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

Decisions about improvements in monitoring capacity are facilitated greatly by the ability to examine available climate information. Various methods are being created at WRCC to improve access to that information. Web pages providing historic and ongoing climate data, and information from NCCN 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 NCCN park units but also to climate-monitoring efforts for NCCN. These pages can be found through http://www.wrcc.dri.edu/nps.

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

5.6. Summarized Conclusions and Recommendations

- Much work already has been done by the NCCN office to locate weather/climate stations.
- Climate within NCCN is highly variable spatially due to regional topography
- Adequate resources exist for climate-monitoring activities at the NCCN park units in Puget Sound and along the Columbia River.
- Long-term records are not readily available for SAJH. The closest long-term stations are generally 20-30 km away from SAJH and are located in Canada, on other islands, or on the U.S. mainland.
- The more remote areas of the larger NCCN park units (MORA, NOCA, OLYM) have very limited weather/climate station coverage. These often contain montane and alpine environments that are very sensitive to climate change. Unfortunately, these areas are underrepresented in current weather/climate-monitoring efforts. There often are weather/climate stations located adjacent to these areas with limited station coverage; however, due to complex topography, these regions may not be able to rely as much on nearby stations as in flatter environments.
- Installing a SNOTEL station in southeastern OLYM would help to increase understanding of the characteristics of the sharp precipitation gradients between the Olympic Mountains and Puget Sound.
- In the northern unit of North Cascades National Park, converting one of the existing NRCS-SC sites to a full SNOTEL site would provide much needed climate data, allowing the NPS to better monitor climate characteristics in the region.

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Appendix A. Climate-monitoring principles

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

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

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

A.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.

A.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.

A.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.

A.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.

A.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.

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

A.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.

A.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.

A.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.

A.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.

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

A.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)

A.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)

A.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)

A.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)

A.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)

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

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

A.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)

A.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)

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

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

A.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)

A.3. Literature Cited

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Appendix B. Glossary

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

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

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

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

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

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

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

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

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

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

Rainshadow— A region of sharply reduced precipitation on the lee side of an orographic barrier, as compared with regions upwind of the barrier.

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

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

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

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

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

Appendix C. Factors in operating a climate network

C.1. Climate versus Weather

- Climate measurements require *consistency through time.*

C.2. Network Purpose

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

C.3. Site Identification and Selection

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

C.4. Station Hardware

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

C.5. Communications

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

C.6. Maintenance

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

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

C.7. Maintaining Programmatic Continuity and Corporate Knowledge

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

C.8. Data Flow

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

C.9. Products

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

C.10. Funding

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

C.11. Final Comments

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

Source: Western Regional Climate Center (WRCC)

Appendix D. Master metadata field list

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

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

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

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

E.1. Introduction

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

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

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

E.1.1. Network Purpose

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

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

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

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

E.1.2. Robustness

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

E.1.3. Weather versus Climate

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

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

E.1.4. Physical Setting

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

E.1.5. Measurement Intervals

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

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

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

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

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

E.1.6. Mixed Time Scales

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

E.1.7. Elements

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

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

E.1.8. Wind Standards

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

E.1.9. Wind Nomenclature

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

E.1.10. Frozen Precipitation

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

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

E.1.11. Save or Lose

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

E.1.12. Time

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

E.1.13. Automated versus Manual

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

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

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

E.1.14. Manual Conventions

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

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

E.2. Representativeness

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

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

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

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

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

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

E.2.1. Temporal Behavior

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

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

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

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

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

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

E.2.2. Spatial Behavior

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

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

E.2.3. Climate-Change Detection

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

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

E.2.4. Element-Specific Differences

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

E.2.5. Logistics and Practical Factors

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

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

E.2.6. Personnel Factors

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

E.3. Site Selection

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

E.3.1. Equipment and Exposure Factors

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

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

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

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

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

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

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

E.3.2. Element-Specific Factors

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

E.3.3. Long-Term Comparability and Consistency

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

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

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

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

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

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

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Appendix F. Descriptions of weather/climate monitoring networks

F.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, pressure, sky cover, ceiling, visibility, and current weather. Most of the data records are of high quality.

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

- Purpose of network: provide information for evaluating the effectiveness of national emission-control strategies.
- Primary management agency: EPA.
- Data website: http://epa.gov/castnet/.
- Measured weather/climate elements:
  - Air temperature.
  - Precipitation.

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

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

F.3. NWS Cooperative Observer Program (COOP)

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

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

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

F.4. NOAA Climate Reference Network (CRN)

- Purpose of network: provide long-term homogeneous measurements of temperature and precipitation that can be coupled with long-term historic observations to monitor present and future climate change.
- Primary management agency: NOAA.
- Data website: http://www.ncdc.noaa.gov/crn/.
- Measured weather/climate elements:
  - Air temperature (triply redundant, aspirated).
  - Precipitation (three-wire Geonor gauge).
  - Wind speed.
  - Solar radiation.
  - Ground surface temperature.
- Sampling frequency: precipitation can be sampled either 5 or 15 minutes. Temperature sampled every 5 minutes. All other elements sampled every 15 minutes.
- Reporting frequency: hourly or every three hours.
- Estimated station cost: $30K with maintenance costs around $2K/year.
- Network strengths:
  - Station siting is excellent (appropriate for long-term climate monitoring).
  - Data quality is excellent.
  - Site maintenance is excellent.
- Network weaknesses:
  - CRN network is still developing.
  - Period of record is short compared to other automated networks. Earliest sites date from 2004.
  - Station coverage is limited.
  - Not intended for snowy climates.

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

F.5. 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.

F.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. Earliest sites date from 2004.
  - 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.

F.7. NOAA Ground-Based GPS Meteorology (GPS-MET)

- 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.
  - Pressure.
- Reporting frequency: currently 30 min.
- Estimated station cost: $0-$10K, depending on approach. Data from dual frequency GPS receivers installed for conventional applications (e.g. high accuracy surveying) can be used without modification.
- Network strengths:
  - Frequent, high-quality measurements.
  - High reliability.

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

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

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

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

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

F.8. National Data Buoy Center network (NDBC)

- Purpose of network: support weather forecasting activities in marine environments along the U.S. coasts.
- Primary management agency: NWS.
- Data website: http://www.ndbc.noaa.gov.
- Measured weather/climate elements:
  - Air temperature.
  - Barometric pressure.
  - Wind speed and direction.
  - Wind gust and direction.
- Sampling frequency: hourly.
- Reporting frequency: hourly.
- Estimated station cost: unknown.
- Network strengths:
  - Data are of high quality.
  - Provides data in ocean locations.
- Network weaknesses:
  - A limited number of climate elements are measured.
  - Geographic extent: stations are located in oceans only.

This network is administered by NWS and provides hourly atmospheric and oceanic observations in marine environments in support of forecasting activities. All stations measure temperature, barometric pressure, wind speed and direction, and wind gust and direction.

F.9. The Northwest Weather and Avalanche Center network (NWAVAL)

- Purpose of network: support snow- and avalanche-monitoring efforts at NWAC.
- Primary management agency: NWAC.
- Data website: http://www.nwac.noaa.gov.
- Measured weather/climate elements:
  - Air temperature.
  - Relative humidity.
  - Precipitation.
  - Wind speed and direction.
  - Wind gust and direction.
- Sampling frequency: hourly.
- Reporting frequency: hourly.
- Estimated station cost: unknown.
- Network strengths:
  - Strategic location in montane and alpine environments, locations that traditionally have sparse weather/climate observations.
  - Data are readily available.

- Network weaknesses:
  - Geographic coverage – limited to mountain areas.
  - Data quality is sometimes questionable.

The Northwest Weather and Avalanche Center (NWAC) operates a network of weather stations in the mountainous areas of the Pacific Northwest, primarily in Washington. These stations are operated in support of NWAC's primary mission of monitoring avalanche conditions in the mountains of Washington and northern Oregon. Hourly weather and climate elements that are measured include temperature, humidity, wind, and precipitation. Daily measurements are made of snowfall and snowdepth.

F.10. Oregon Department of Environmental Quality (ODEQ)

- Purpose of network: support ODEQ's mission to protect air and water quality in Oregon.
- Primary management agency: ODEQ.
- Data websites: http://www.deq.state.or.us and http://www.met.utah.edu/jhorel/html/mesonet.
- Measured weather/climate elements:
  - Air temperature.
  - Relative humidity.
  - Pressure.
  - Wind speed and direction.
  - Wind gust and direction.
- Sampling frequency: unknown.
- Reporting frequency: unknown.
- Estimated station cost: unknown.
- Network strengths:
  - Real-time data.
- Network weaknesses:
  - Network coverage is limited to the state of Oregon

The primary mission of ODEQ is to protect and enhance Oregon's air and water quality. Weather and climate elements are measured by ODEQ stations in support of this primary mission. Measured meteorological elements include temperature, precipitation, wind, and relative humidity.

F.11. Oregon Department of Transportation (ODOT)

- Purpose of network: provide weather data to support management of Oregon's transportation network.
- Primary management agency: ODOT.
- Data websites: http://www.oregon.gov/ODOT and http://www.met.utah.edu/jhorel/html/mesonet.
- Measured weather/climate elements:
  - Air temperature.
  - Relative humidity.
  - Pressure.

  - Wind speed and direction.
  - Wind gust and direction.
- Sampling frequency: unknown.
- Reporting frequency: unknown.
- Estimated station cost: unknown.
- Network strengths:
  - Real-time data.
- Network weaknesses:
  - Coverage is limited to the state of Oregon.

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

F.12. Local networks – Olympic National Park (OLYM-MISC)

- Purpose of network: provide near-real-time (hourly or near hourly) measurements of meteorological variables for use in fire weather forecasts and climatology. Data from RAWS also are used for natural resource management, flood forecasting, natural hazard management, and air-quality monitoring.
- Primary management agencies: NCCN, OLYM.
- Data websites: http://www1.nature.nps.gov/im/units/nccn/index.htm and http://www.wrcc.dri.edu.
- Measured weather/climate elements:
  - Air temperature.
  - Precipitation.
  - Relative humidity.
  - Wind speed and direction.
  - Wind gust and direction.
- Sampling frequency: varies.
- Reporting frequency: varies.
- Estimated station cost: unknown.
- Network strengths:
  - Actively maintained by OLYM I&M staff.
- Network weaknesses:
  - Limited spatial coverage.
  - Data access.

Olympic National Park (OLYM) administers a collection of weather stations within its park boundaries that were previously administered by other agencies. Some of these stations were associated with the EPA Marine Biological Laboratory's General Ecosystem Model (GEM). Research projects with GEM have investigated the effects of atmospheric conditions on plant and soil processes. The University of Washington's College of Forest Resources has also operated a few stations in OLYM to monitor forest health. Meteorological elements measured at these stations generally include temperature, precipitation, wind, and humidity.

F.13. 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.

F.14. Remote Automated Weather Station network (RAWS)

- Purpose of network: provide near-real-time (hourly or near hourly) measurements of meteorological variables for use in fire weather forecasts and climatology. Data from RAWS also are used for natural resource management, flood forecasting, natural hazard management, and air-quality monitoring.
- Primary management 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 United States. Most gauges do not have heaters, so hydrologic measurements are of little value when temperatures dip below freezing or reach freezing after frozen precipitation events. There are approximately 1100 real-time sites in this network and about 1800 historic sites (some are decommissioned or moved). The sites can transmit data all winter but may be in deep snow in some locations. The WRCC is the archive for this network and receives station data and metadata through a special connection to the National Interagency Fire Center in Boise, Idaho.

F.15. 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: $100–$200K with maintenance costs approximately $10K/year.
- Network strengths:
  - Records generally extend over several decades.
  - Consistent maintenance and station operations.
  - Data record is reasonably complete and usually high quality.
  - Hourly or sub-hourly data.
- Network weaknesses:
  - Nearly all sites are located at airports.
  - Data quality can be related to size of airport—smaller airports tend to have poorer datasets.
  - Influences from urbanization and other land-use changes.

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

F.16. USDA/NRCS Snowfall Telemetry (SNOTEL) network

- Purpose of network: collect snowpack and related climate data to assist in forecasting water supply in the western United States.
- Primary management agency: NRCS.
- Data website: http://www.wcc.nrcs.usda.gov/snow/.
- Measured weather/climate elements:
  - Air temperature.
  - Precipitation.
  - Snow water content.
  - Snow depth.
  - Relative humidity (enhanced sites only).
  - Wind speed (enhanced sites only).
  - Wind direction (enhanced sites only).
  - Solar radiation (enhanced sites only).
  - Soil moisture and temperature (enhanced sites only).
- Sampling frequency: 1-minute temperature; 1-hour precipitation, snow water content, and snow depth. Less than one minute for relative humidity, wind speed and direction, solar radiation, and soil moisture and temperature (all at enhanced site configurations only).
- Reporting frequency: reporting intervals are user-selectable. Commonly used intervals are every one, two, three, or six hours.
- Estimated station cost: $20K with maintenance costs approximately $2K/year.
- Network strengths:
  - Sites are located in high-altitude areas that typically do not have other weather or climate stations.
  - Data are of high quality and are largely complete.
  - Very reliable automated system.
- Network weaknesses:

- Historically limited number of elements.
- Remote so data gaps can be long.
- Metadata sparse and not high quality; site histories are lacking.
- Measurement and reporting frequencies vary.
- Many hundreds of mountain ranges still not sampled.
- Earliest stations were installed in the late 1970s; temperatures have only been recorded since the 1980s.

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

F.17. USDA/NRCS Snowcourse Network (NRCS-SC)

- Purpose of network: collect snowpack and related climate data to assist in forecasting water supply in the western United States.
- Primary management agency: NRCS.
- Data website: http://www.wcc.nrcs.usda.gov/snowcourse/.
- Measured weather/climate elements:
  - Snow depth.
  - Snow water equivalent.
- Measurement, reporting frequency: monthly or seasonally.
- Estimated station cost: cost of man-hours needed to set up snowcourse and make measurements.
- Network strengths
  - Periods of record are generally long.
  - Large number of high-altitude sites.
- Network weaknesses
  - Measurement and reporting only occurs on monthly to seasonal basis.
  - Few weather/climate elements are measured.

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

F.18. Washington State Department of Transportation (WA DOT)

- Purpose of network: provide weather data to support management of the state of Washington’s transportation network.
- Primary management agency: Washington State Department of Transportation.
- Data websites: http://www.wsdot.wa.gov and http://www.met.utah.edu/jhorel/html/mesonet.
- Measured weather/climate elements:

- Air temperature.
  - Relative humidity.
  - Precipitation.
  - Wind speed and direction.
  - Wind gust and direction.
- Sampling frequency: unknown.
- Reporting frequency: unknown.
- Estimated station cost: unknown.
- Network strengths:
  - Real-time data.
- Network weaknesses:
  - Coverage is limited to the state of Washington.

These weather stations are operated by the Washington State Department of Transportation in support of management activities for the state of Washington's transportation network. Measured meteorological elements include temperature, precipitation, wind, and relative humidity.

F.19. Washington State Department of Ecology – Air Quality Program (WAAQ)

- Purpose of network: support efforts to monitor air quality in the state of Washington.
- Primary management agency: Washington State Department of Ecology.
- Data websites: http://www.ecy.wa.gov/programs/air/airhome.html and http://www.met.utah.edu/jhorel/html/mesonet.
- Measured weather/climate elements:
  - Air temperature.
  - Relative humidity.
  - Precipitation.
  - Wind speed and direction.
  - Wind gust and direction.
- Sampling frequency: unknown.
- Reporting frequency: unknown.
- Estimated station cost: unknown.
- Network strengths:
  - Real-time data.
- Network weaknesses:
  - Coverage is limited to the state of Washington.

The primary mission of this program is to protect and enhance air quality in the state of Washington. Weather and climate elements are measured by WAAQ stations in support of this primary mission. Measured meteorological elements include temperature, precipitation, wind, and relative humidity.

F.20. Weather For You (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.
  - Pressure.
- 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.

Appendix G. Electronic supplements

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

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

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