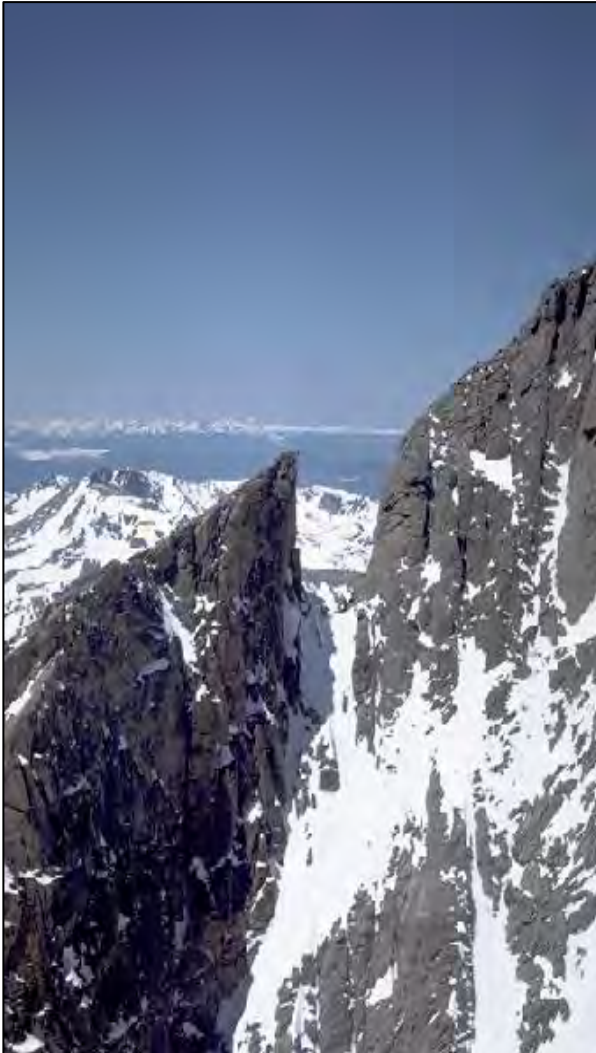




# Rocky Mountain Climate Protocol

## *Climate monitoring in the Greater Yellowstone and Rocky Mountain inventory and monitoring networks, Version 1.0*

Natural Resource Report NPS/IMRO/NRR—2010/222



**ON THE COVER**

Longs Peak at Rocky Mountain National Park (left panel) and aerial view of Bighorn Canyon at Bighorn Canyon National Recreation Area (right panel). Photographs courtesy of NPS and Friends of Bighorn Lake.

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# Rocky Mountain Climate Protocol

## *Climate monitoring in the Greater Yellowstone and Rocky Mountain inventory and monitoring networks, Version 1.0*

Natural Resource Report NPS/IMRO/NRR—2010/222

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U.S. Department of the Interior  
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## **Standard Operating Procedures (SOPs)**

Standard Operating Procedures (SOPs) are available in a separate document in the Rocky Mountain Climate Monitoring Protocol Toolbox:

*NPS\_Rocky\_Mtn\_Climate\_Monitoring\_Protocol\_PreRelease\_Draft\_Sept9\_2009\_SOPs.docx*

### *For Sample Design*

SOP: Defining Climate Zones

SOP: Station Selection

### *For Field Methods*

SOP: Weather Station Visits and Documentation

### *For Data Acquisition and Processing*

SOP: Data Acquisition

SOP: Data Formatting

### *For Data Management*

SOP: Database Schema

SOP: Quality Control

### *For Analysis and Reporting*

SOP: Status Reports

SOP: Web site

SOP: Trend Analysis and Reporting

### *Optional SOP*

Daily Park Index Calculation

## Acronyms

|        |   |
|--------|---|
| AMO    | Atlantic Multi-decadal Oscillation                          |
| COOP   | Cooperative Observer Network                                |
| ENSO   | El Niño-Southern Oscillation                                |
| ESRI   | Environmental Systems Research Institute, Inc.              |
| GIS    | Geographic Information System                               |
| GPS    | Geographic Positioning System                               |
| GRYN   | Greater Yellowstone Network                                 |
| I&M    | Inventory & Monitoring                                      |
| NAO    | North Atlantic Oscillation                                  |
| NCDC   | National Climatic Data Center                               |
| NOAA   | National Oceanic and Atmospheric Administration,            |
| NOHRSC | National Operational Hydrologic Remote Sensing Center       |
| NPS    | National Park Service                                       |
| NRCS   | Natural Resources Conservation Service                      |
| NWS    | National Weather Service                                    |
| PDO    | Pacific Decadal Oscillation                                 |
| PDSI   | Palmer Drought Severity Index                               |
| PRISM  | Parameter-Elevation Regressions on Independent Slopes Model |
| RMCP   | Rocky Mountain Climate Protocol                             |
| ROMN   | Rocky Mountain Network                                      |
| SNOTEL | Snowpack Telemetry  |
| SNODAS | Snow Data Assimilation System                               |
| SOP    | standard operating procedure                                |
| SPI    | Standardized Precipitation Index                            |
| SWE    | snow water equivalent                                       |
| USDA   | U.S. Department of Agriculture                              |
| USGS   | U.S. Geological Survey                                      |

## Executive Summary

Climate is one of the primary drivers of the physical and ecological processes that determine the distribution, structure, and function of ecosystems. Moreover, climate is critical to park management and visitor experience, is a driver of change in other vital signs and park resources, and there is evidence that climate has changed in the past century and will continue to change. For these reasons, the Greater Yellowstone and Rocky Mountain inventory and monitoring networks have identified climate as a high priority vital sign. Here, we present a collaboratively developed protocol to monitor and report on climate for nine national park units in Colorado, Wyoming, Montana, and Idaho. Parks within the two networks are: Bighorn Canyon National Recreation Area, Florissant Fossil Beds National Monument, Glacier National Park, Grand Teton National Park, Grant-Kohrs Ranch National Historic Site, Great Sand Dunes National Park and Preserve, John D. Rockefeller, Jr. Memorial Parkway, Little Bighorn Battlefield National Monument, Rocky Mountain National Park, and Yellowstone National Park. We have two overarching goals for our climate inventory and monitoring: (1) to determine variations and changes in key climate measures relative to an established baseline, and (2) to develop comprehensive and high-quality climate datasets for use in understanding how climate may affect other vital signs. Specifically, we have the following five objectives:

1. Determine the status, trends, and periodicity in daily, monthly, and annual **temperature**, including extremes, at the scale of points, climate zones, and parks
2. Determine the status, trends and periodicity in daily, monthly, and annual accumulated **precipitation**, including extremes, at the scale of points, climate zones, and parks
3. Determine the status, trends, and periodicity in monthly and annual **drought** at the scale of climate divisions, parks, or climate zones
4. Determine the status, trend, and periodicity in daily, monthly, and annual **snow** water equivalent at the scale of points, climate zones, and parks
5. Determine the status, trends, and periodicity in daily, monthly, and annual **streamflow** at the major watershed level

To monitor climate we will rely on data from existing climate monitoring programs. Rather than establishing new climate stations in park units, our approach is to rely on existing programs with climate stations in or near the parks that provide consistent, long-term, and high-quality climate records for our regions. We outline methods to acquire, quality control, archive, and process climate data from these national programs and report on climate at scales relevant to parks (parks or climate zones within parks). Climate status reports will be produced every 1–3 years and will provide a descriptive summary of the past year(s) climate to support yearly park science and management planning. Climate variability and trends reports will be produced on 5–10 year cycles and will present rigorous analyses of inter-annual variability and long-term historical trends. In the process of preparing these reports, we will create high-quality historical climate datasets that will be available to support research linking resource dynamics to climate, as well as to aid resource management and park interpretation programs. In addition, we will create and maintain a Web site that provides links to timely climate information, reports, and high-quality climate datasets that are relevant to the parks within the networks.

## **Acknowledgments**

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# Revision History Log

| Previous Version # | Revision date | Author | Changes made | Section and paragraph | Reason for change | New Version # |
|--------------------|---------------|--------|--------------|-----------------------|-------------------|---------------|
|                    |               |        |              |                       |                   |               |
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# Tools and SOPs of Rocky Mountain Climate Protocol

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## Content

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RMCP Narrative

Appendix A: Data Sources

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SOP Defining Climate Zones

SOP Station Selection

SOP Weather Station Visits and  
Documentation

SOP Data Acquisition

SOP Data Formatting

SOP Database Schema

SOP Quality Control

SOP Status Reports

SOP Trend Analysis and Reporting

SOP Web site

---

Field Methods Data Sheets

Python Batch Uncompress GZ

Raster Datasets

Python Batch Uncompress TAR

Raster Datasets

Python Climate Station Module

Python Geoprocess Batch PRISM

Point Generation

Python Geoprocess Batch Clip

Raster Datasets

Python Geoprocessing Raster Time  
Series

Python ReportingUnits File Join

Python ReportingUnits NDCD Data  
Parser

Python ReportingUnits NDCD First  
Pass Cleaner

Python ReportingUnits Remove  
Months with Missing Values

Python ReportingUnits USHCN Data  
Parser

R ReportingUnits Cluster Analysis

R Generating Status Report Content

R Reporting Units Principal  
Components Analysis

Reporting Units Example Data  
Format

---



# 1 Introduction

## 1.1 The National Park Service Inventory and Monitoring Program and the Rocky Mountain Climate Protocol

The purpose of the National Park Service (NPS) Inventory & Monitoring (I&M) Program is to develop and provide scientifically credible information on the current status and long-term trends of the composition, structure, and function of park ecosystems, and to determine how well current management practices are sustaining those ecosystems. As part of the NPS's effort to ~~im~~improve park management through greater reliance on scientific knowledge," a primary role of the I&M Program is to collect, organize, and make available natural resource data and to contribute to the NPS institutional knowledge by transforming data into information through analysis, synthesis, and modeling of specific key ~~v~~vital signs." The I&M Program defines ~~v~~vital signs" as ~~a~~a subset of physical, chemical, and biological elements and processes of park ecosystems that is selected to represent the overall health or condition of park resources, known or hypothesized effects of stressors, or elements that have important human values" (NPS 2008b).

The five goals of the I&M Program are to (Fancy et al. 2008):

1. Inventory the natural resources and park ecosystems under NPS stewardship to determine their nature and status
2. Monitor park ecosystems to better understand their dynamic nature and condition and to provide reference points for comparisons with other, altered environments
3. Establish natural resource inventory and monitoring as a standard practice throughout the NPS system that transcends traditional program, activity, and funding boundaries
4. Integrate natural resource inventory and monitoring information into NPS planning, management, and decision making
5. Share NPS accomplishments and information with other natural resource organizations and form partnerships for attaining common goals and objectives

These goals are accomplished through parkwide inventories and a long-term monitoring program. In establishing a Service-wide natural resources I&M Program, the NPS created networks of parks that are linked by geography and shared natural resource characteristics. Working within and across networks improves the efficiency of inventory and monitoring because parks are able to share budgets, staffing, and other resources to plan and implement an integrated program.

The Rocky Mountain Network (ROMN) and Greater Yellowstone Network (GRYN) are 2 of 32 vital signs monitoring networks across the NPS. The ROMN is comprised of six NPS units (fig. 1.1): Glacier National Park, Grant-Kohrs Ranch National Historic Site, and Little Bighorn Battlefield National Monument, Montana; and Florissant Fossil Beds National Monument, Great Sand Dunes National Park and Preserve, and Rocky Mountain National Park, Colorado. The GRYN is comprised of four NPS units (fig. 1.1): Yellowstone National Park, Wyoming, Montana, and Idaho; Grand Teton National Park, including the John D. Rockefeller, Jr. Memorial Parkway, Wyoming; and Bighorn Canyon National Recreation Area, Montana and

Wyoming. Nine parks within the ROMN and GRYN are located in the central and southern Rocky Mountain Cordillera, roughly along a NNW–SSE axis that follows the Continental Divide. Little Bighorn Battlefield National Monument is the exception; it is about 300 kilometers (186 mi) to the east of the Divide on the northern Great Plains.

The ROMN Vital Signs Monitoring Plan (Britten et al. 2007) and GRYN Vital Signs Monitoring Plan (Jean et al. 2005) provide the foundations for the long-term ecological monitoring programs of these networks and describe the rationale and basis for the programs. Each of the vital signs plans was developed over a three-year planning effort that included park staff and scientific partners from numerous organizations and each plan identifies climate as a high priority vital sign.

# Rocky Mountain Climate Protocol

National Park Service  
U.S. Department of the Interior

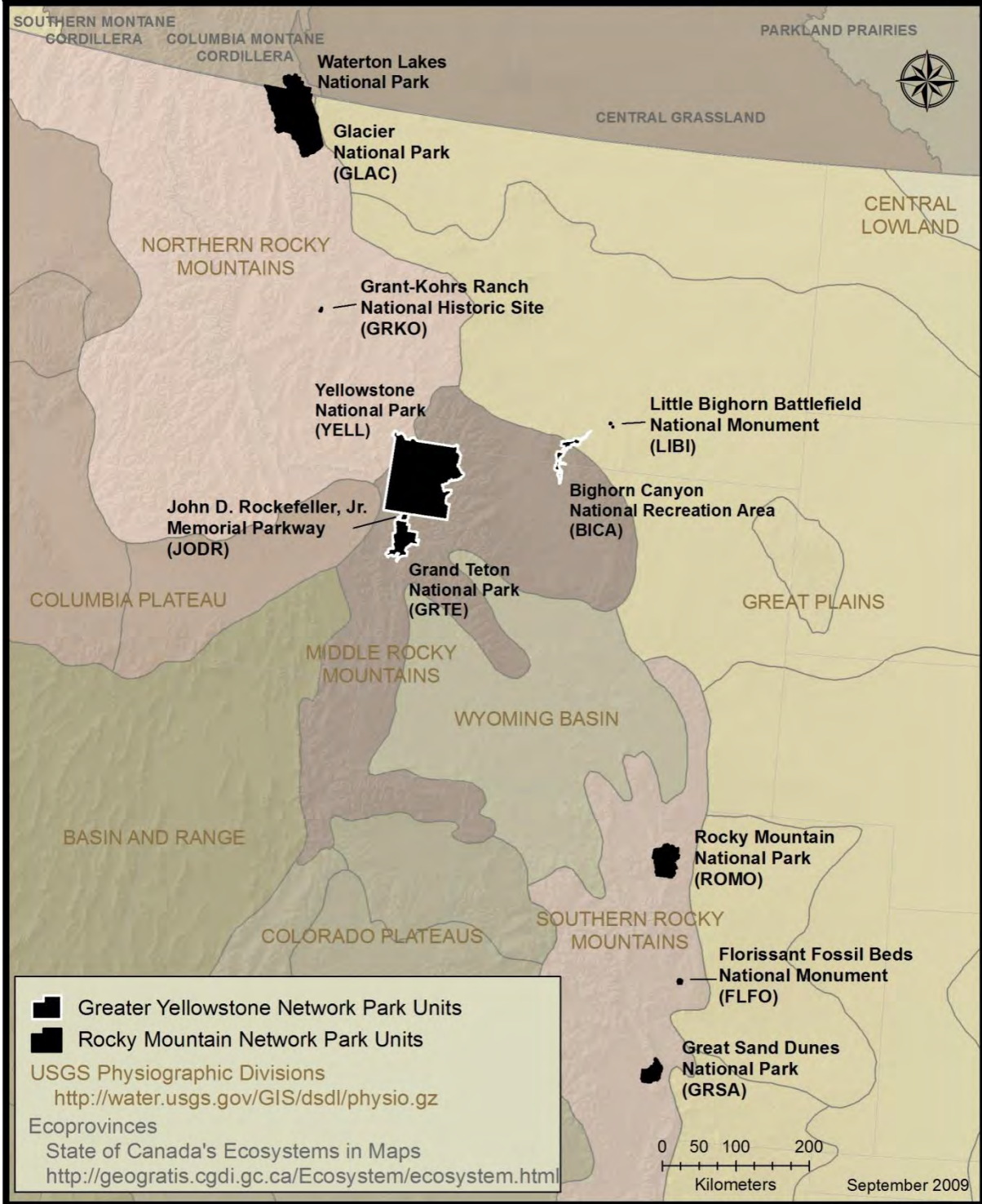


Figure 1.1. Map of ROMN and GRYN park units within the physiographic divisions of the United States and ecoprovinces of Canada.

## 1.2 Overview

Climate and weather describe the condition and variability of the atmosphere in a given place. The GRYN and ROMN identified climate as a high-priority vital sign and thus, will monitor status and trend in climate because it is critical to park management and visitor experience, it is a driver of change in other vital signs and park resources, and there is evidence that climate has changed in the past century and will continue to change.

The primary goal of the collaborative Rocky Mountain Climate Protocol (RMCP) is to explore and report on variations and changes in key climate measures and metrics (temperature, precipitation, snowpack, drought, and streamflow) relative to established baseline values. The second aim of this protocol is to assemble reliable climate data to be used for correlating trends in climate to trends in other vital signs. Ultimately, this should facilitate a better understanding of the role of climate as a driver of change in natural resources. Reports based on this protocol will provide NPS personnel and cooperators with an understanding of climate status, and variations in climate within and around the parks at spatial and temporal scales relevant to monitoring other systems and processes. This protocol may also help explain the dynamics of other vital signs or natural resources within parks. We will produce two types of reports, a climate status report and a climate inter-annual variability and trends report (trends report). The climate status report will be produced every 1–3 years for each park (in the case of ROMN) or for the network (in the case of GRYN) and it will provide a descriptive summary of the past year(s) climate to support yearly park science and management planning. The trends report will be produced on 5–10 year cycles and will present rigorous analyses of inter-annual variability, long-term historical trends, and correlate local trends with teleconnections (“recurring and persistent, large-scale pattern[s] of pressure and circulation anomalies that span vast geographical areas,” e.g., the North Atlantic Oscillation [NAO]; NOAA 2008) with hemispheric climate patterns. In addition to these reports, the RMCP will create and maintain a Web site that will provide links to timely climate information, reports, and data that are relevant to the parks. Understanding past and future climate may aid in the interpretation of current trends but both are beyond the scope of this protocol. Further information regarding paleoclimate and future climate scenarios for the region may be found in a report compiled by McWethy and colleagues (2010).

To monitor climate as a vital sign and as a critical driver of other vital signs, the RMCP will rely on currently existing climate monitoring programs. Rather than adding new climate stations throughout park units, our approach is to rely on existing programs that provide consistent, long-term, and high-quality climate records for our regions. The protocol will focus on two types of data: point data from weather stations distributed across the park units and the region that can provide daily measures of temperature and precipitation, and gridded data sets that provide modeled estimates of climate metrics for the continental United States. In addition to primary climate measures, such as temperature, precipitation, and snow water equivalent (SWE), the protocol will also explore and report on integrative metrics such as drought and streamflow. Again, we will rely on established monitoring programs, such as the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Geological Survey (USGS), to collect and provide the data. The RMCP describes the rationale and importance of our selected climate measures, methods to acquire climate data, and guidelines on how to analyze, report, and interpret climate data.

### 1.3 U.S. Rocky Mountains climate

The Rocky Mountains encompass a wide range of climatic settings, from relatively cold, dry continental settings to cool moist maritime settings and the warmer temperate setting of the American Southwest. The Rocky Mountains within the U.S have three broad physiographic regions: the northern, central, and southern Rockies (Kittel et al. 2002; fig. 1.1). The northern Rockies encompass northern Idaho and western Montana and include Glacier National Park and Grant-Kohrs Ranch National Historic Site. The central Rockies include western Wyoming and parts of Montana, Colorado, Utah, and Idaho. Bighorn Canyon National Recreation Area, Grand Teton National Park, John D. Rockefeller, Jr. Memorial Parkway, Yellowstone National Park, and Little Bighorn Battlefield National Monument are within this region. Finally the southern U.S. Rockies encompasses much of Colorado, southern Wyoming, and northern New Mexico. Florissant Fossil Beds National Monument, Great Sand Dunes National Park and Preserve, and Rocky Mountain National Park are in this region.

In general, moving south from the northern Rockies to the southern Rockies, the climate becomes warmer and dryer (fig. 1.2). Climate in all three regions is influenced by the Rocky Mountains that present a barrier to the westerly flow of the atmosphere carrying moisture from the Pacific Ocean. When the air masses collide with the mountains, the air moves upslope and precipitation is enhanced on the western edge and reduced on the eastern slopes. Winter storms approaching the northern Rockies are laden with moisture while those traveling farther south lose much of their moisture crossing the Sierra Nevada, southern Cascade Range, and intermountain West (Kittel et al. 2002). As a result, the total annual precipitation and the total precipitation in January are greater in the northern Rockies compared to the central and southern Rockies (fig. 1.2). January temperatures in the northern Rockies tend to remain slightly warmer than those of the central Rockies (fig. 1.2). On the eastern side of the Rockies, precipitation is generated in the springtime upsloping from polar continental air flows and warmer maritime air from the Gulf of Mexico colliding with the mountains. In the summer the southern and central Rockies receive dry continental air or monsoonal flows from the Gulf of Mexico and Gulf of California (Kittel et al. 2002). The Northern Rockies and Pacific Northwest are typically dominated by stable high pressure in the summer and moisture sources are variable. A more detailed overview of the climate in the parks within the GRYN and ROMN can be found in the weather and climate inventory reports produced for each network (Davey et al. 2006, 2007).

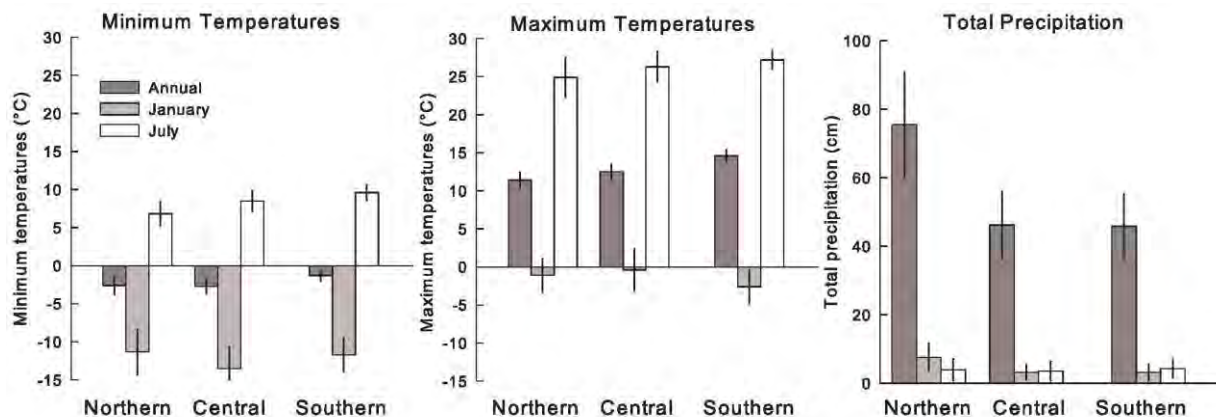


Figure 1.2. Average minimum temperature, maximum temperature, and total precipitation for the period of 1980–1997 in the northern, central, and southern Rockies. Bars indicate means  $\pm$  1 inter-annual standard deviation. Data from Kittel et al. 2002.

### 1.4 Conceptual framework and links between climate measures

While the goal of the RMCP is to monitor and report on the status and trends in temperature, precipitation, SWE, drought, and streamflow at scales relevant to the park units, these measures are inextricably linked to one another because they are all driven by larger-scale atmospheric processes.

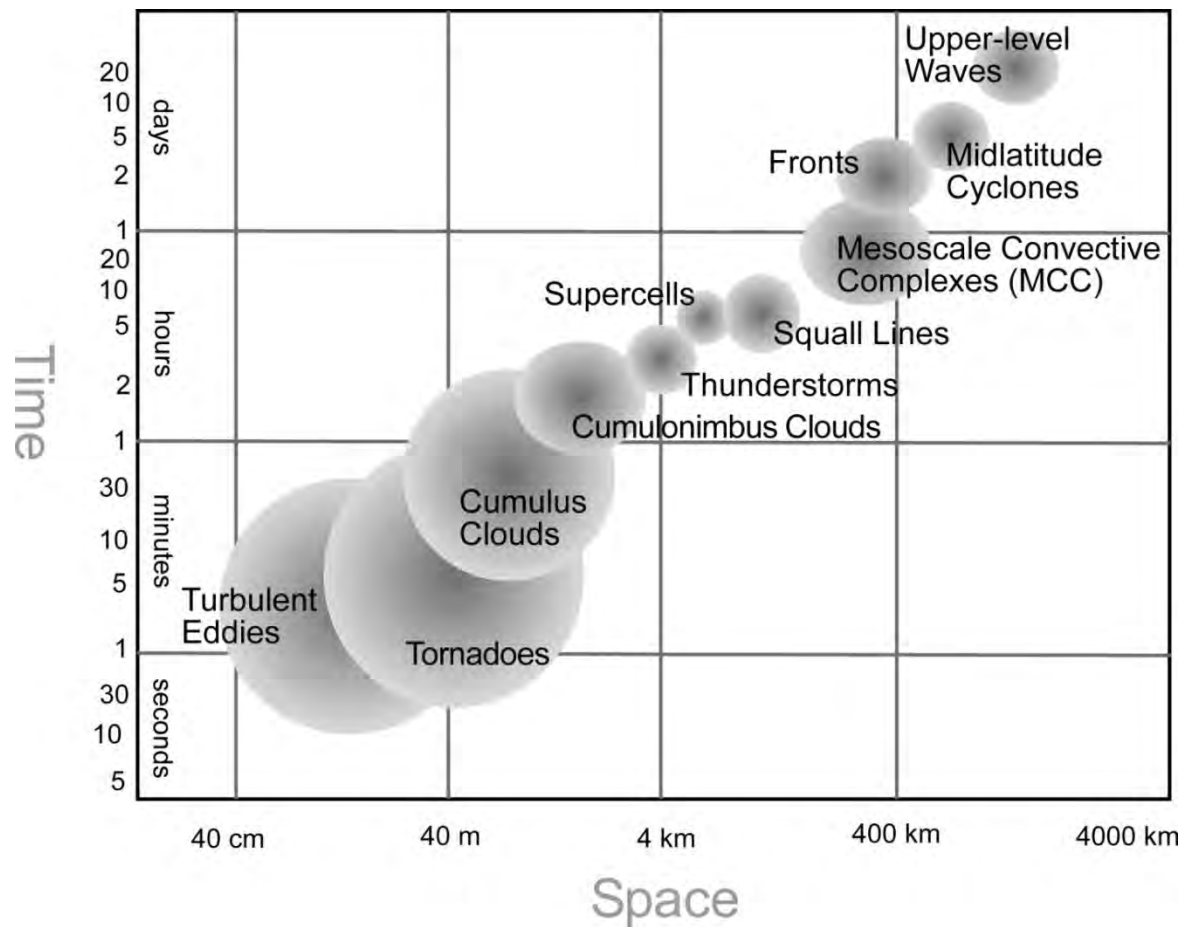


Figure 1.3. A continuum of atmospheric processes across space and time. This continuum is represented with a log scale and adapted from Frakes (1998).

The understanding and study of climate is often partitioned by scale, into four distinct categories: *planetary*-, *synoptic*-, *meso*-, and *micro-scale processes* (Barry and Chorley 1998). In general, there is a positive relationship between space- and time-scales in atmospheric processes, and planetary-scale processes occur over longer periods of time than micro-scale processes (fig. 1.3). Many of the smaller-scale processes are embedded within larger-scale processes. Planetary-scale processes, which occur at the scale of Earth, are driven by the atmospheric circulation and serve to redistribute energy, momentum and moisture imbalances across the planet. The general pattern of westerly winds and the polar jet-stream are examples of planetary-scale processes that influence climate in the Rocky Mountain region. Synoptic- and meso-scale refer to climate

processes at a scale of 1,000 kilometers (620 mi) or 5 kilometers (3 mi) to several hundred kilometers, respectively. Synoptic- and meso-scale systems are steered and influenced by planetary-scale circulation and are most often associated with the formation and movements of weather fronts, mid-latitude cyclones, surface high pressure systems, and orographic (mountain-related) precipitation. In the southern Rockies, the development of summer monsoons is an example of an atmospheric process at this scale. Finally, micro-scale processes are those that are confined to local areas, or points, and vary over short timescales (from seconds to hours). Examples of micro-scale factors affecting observations include aspect, elevation, land cover, and time of day.

The concept of varying scales in climate has a number of important implications for monitoring. First, it is critical to understand that many different processes operate concurrently in the atmosphere and climate monitoring efforts are likely to record signals from one or more of these processes. For instance, a surface weather station may record both the influence of its elevation (micro-scale) and the influence of a passing frontal system (synoptic-scale). Second, because surface monitoring of climate is confined to particular spatial- and temporal-scales, they will be well suited to capturing some variations and not others. For example, daily records of average temperature may miss short bursts of storm activity. Third, since larger-scale processes control smaller-scale processes, there is a need to understand the larger-scale processes to fully understand the smaller-scale processes. For instance, if frontal precipitation is a key source of precipitation, knowing why precipitation varies is ultimately tied to the larger processes that drive frontal activity. Finally, some scales are more predictable than others. Seasonal variations in temperature and precipitation can be predicted from global circulation patterns and the general trend for higher precipitation on the western edge of the Rocky Mountains is based on the effect of topography. Diurnal and elevational patterns in temperature are also fairly predictable on seasonal time frames, but not as much on a day-to-week scale. In contrast, many synoptic-scale patterns such as the day-to-week changes in the position of the jet stream and the formation of cyclones are less predictable than seasonal-scale variations, but can be reasonably well predicted with weather forecast models at a day-to-day scale.

Not only are atmospheric processes interacting concurrently at all scales, but the atmosphere is also interacting with Earth's surface. The interaction between the surface and the atmosphere is complex, with forcing and feedbacks occurring in both directions. It is well understood that the atmosphere directly affects surface conditions including the soil moisture, vegetation cover, and snow cover, however these surface characteristics also affect the atmosphere. Extensive snow cover can lower temperature through a higher surface albedo (fraction of incident solar radiation [solar radiation striking a surface] reflected by a surface) and can also influence long wave patterns that favor cooler conditions. Another example comes from fires that alter land cover and subsequently affect surface fluxes of moisture and energy. While it is beyond the scope of this protocol to monitor the strength of such surface to atmosphere feedbacks, we recognize the potential influence of these feedbacks on the status and trends in the climate of our parks.

### **1.5 Rationale for monitoring climate**

The GRYN and ROMN selected climate as a high-priority vital sign for several reasons. First, climate is one of the defining characters of NPS units, whether it is the hot days at Grand Teton National Park, the chilling temperatures in the alpine tundra of Yellowstone National Park, the long winters at Glacier National Park, or the winds at Rocky Mountain National Park. Second,

basic climate information is crucial data that park visitors and managers rely on for planning activities and to determine how and when to allocate resources within the parks. For instance, in the Rocky Mountain region, the timing of first and last snows can determine road closures and availability of access to large portions of the parks. Severe drought and a subsequent increase in fire danger may require parks to close areas or change policies regarding fires within the park. Third, climate is a forcing agent for all ecosystem properties and vital signs within the park. Climate can drive animal behavior, nutrient cycling and productivity, the invasion of exotic species, the structure of vegetation communities, and water quality (fig. 1.4). By understanding and isolating the effect of climate it becomes possible to discern the effects of other, possibly anthropogenic drivers of change. For instance, changes in the structure of willow communities may be caused by concurrent changes in climate, nutrient availability, and over-grazing by elk (Peinetti et al. 2002). To understand and mitigate for these changes, it becomes necessary to determine the relative effect of climate and other drivers.

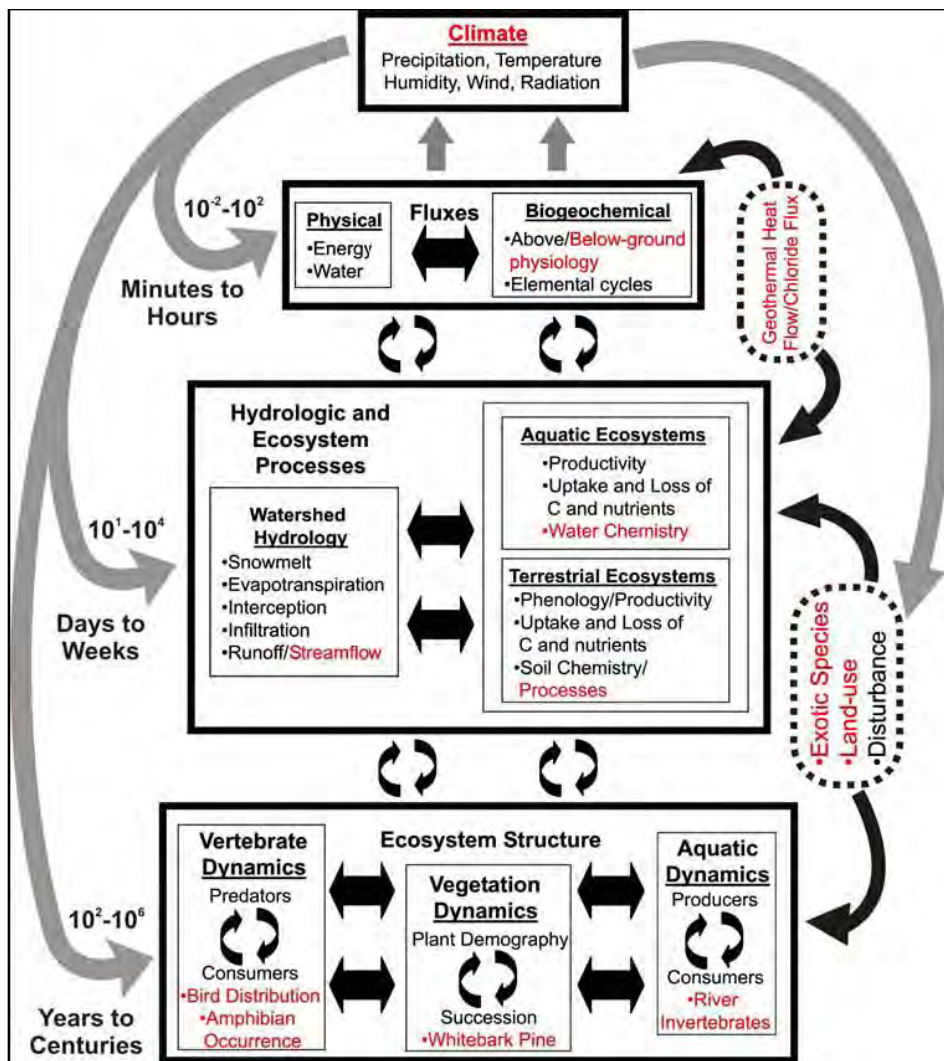


Figure 1.4. Conceptual model showing the relationship between climate and the structure and function of natural systems in the Rocky Mountain region. Numbers indicate a timescale of hours and red text indicates some of the other high priority vital signs in the GRYN and ROMN.



Finally, and perhaps most importantly, we will monitor climate because changes in climate of the western United States since the last century have been documented, and these changes are predicted to continue (Christensen et al. 2007). Documented climate changes in the western mountains and forests bioregion include increased seasonal, annual, minimum, and maximum temperatures, altered precipitation patterns, and a shift toward earlier timing of peak runoff (Loehman and Anderson 2009).

In western North America, winter and spring temperatures have increased during the 20th century (Mote et al. 2005). The rate of change varied with location, but the tendency was a warming of 1°C (1.8°F) per century from 1916 to 2003 (Hamlet et al. 2007). Pedersen et al. (2009) reported a 1.33°C (2.4°F) rise in annual average temperature for western Montana between 1900–2006, which is 1.8 times greater than the +0.74°C (1.3°F) rise in global temperatures between 1900–2005 (Lugina et al. 2006). Between 1950 and 1999 there was a shift in the character of mountain precipitation, with more winter precipitation falling as rain instead of snow, earlier snow melt, and associated changes in river flow that included relative increases in the spring and relative decreases in the summer months (Mote et al. 2005, Barnett et al. 2008). The vegetation growing season, as defined by continuous frost-free air temperatures, has increased by an average of about two days per decade since 1948 in the conterminous United States, with the largest changes occurring in the West (Ryan et al. 2008).

These climatic changes have resulted in widespread mortality in western forests, species range shifts, changes in the phenology, productivity, and distribution of species, and an increase in wildfire severity, intensity, and area burned (Loehman and Anderson 2009). A meta-analysis of climate change effects on range boundaries in northern hemisphere species of birds, butterflies, and alpine herbs shows an average shift of 6.1 kilometers (3.8 mi) per decade northward (or meters per decade upward), and a mean shift toward earlier onset of spring events (frog breeding, bird nesting, first flowering, tree budburst, and arrival of migrant butterflies and birds) of 2.3 days per decade (Parmesan and Yohe 2003). Tree mortality in the western United States has increased since 1955 and a likely cause is warmer and drier conditions (van Mantgem et al. 2009). Other observed trends include more frequent large wildfires (greater than 400 ha in size), longer duration wildfires, and longer wildfire seasons. The greatest increases in wildfire activity occurred in mid-elevation northern Rockies forests (Westerling et al. 2006). The forested area burned in the western United States from 1987 to 2003 was more than six and a half times the area burned from 1970 to 1986.

Climate models suggest that regional changes may include an increase in average temperature of around 0.3°C (0.54°F) per decade over the next 50 years, dramatically reduced snowpack accumulation in western mountains, and commensurate reductions in runoff and natural water storage. Ecological changes likely to result from these climatic changes include continued shifts in species phenology, productivity, distributions, species extinctions, increased frequency, size, and duration of wildfires, increased drought length and severity, and range expansion of forest pests and pathogens. Such changes in climate will also impact park visitation and management.

In one analysis, visitation to Canada's national parks system is projected to increase by 9%–25% (2050s) and 10%–40% (2080s) as a result of longer warm-weather tourism (Scott et al. 2007). Climate-induced environmental changes (e.g., loss of glaciers, altered biodiversity, fire or insect-impacted forests) will also affect park tourism, although uncertainty is higher regarding the

regional specifics and magnitude of these impacts (Richardson and Loomis 2004, Scott et al. 2007).

In summary, the GRYN and ROMN will monitor status and trend in climate because it is critical to park management and visitor experience, it is a driver of change in other vital signs and park resources, and there is evidence that climate has changed in the past century and will continue to change. While there are numerous aspects of climate that can be monitored, this protocol will focus on key measures and metrics: temperature, precipitation, snowpack, drought, and streamflow. Below, we provide our climate monitoring goals and objectives and then further define the measures of interest and provide rationale for choosing these by describing how they are linked to ecological processes. Last, we review the protocol development history and describe our monitoring approach and reporting products.

## **1.6 Monitoring goals and objectives**

### **1.6.1 Goals**

In the GRYN and ROMN, climate data have two roles:

1. As a vital sign, a key indicator of environmental change
2. As a factor that drives or responds to dynamics of network ecosystems

Corresponding network goals for climate inventory and monitoring are, briefly:

1. To determine variations and changes in key climate metrics relative to an established baseline
2. To develop climate datasets for use as a covariate in analyses of other vital signs

### **1.6.2 Objectives**

**Objective 1: Temperature.** Determine the status, trends, and periodicity in daily, monthly, and annual temperature, at the scale of points, climate regions, and parks. Required data include COOP temperature records. SNOTEL temperatures will be used in a limited capacity to describe conditions at higher elevations.

Proposed metrics and methodologies:

- Minimum, maximum, and mean monthly temperatures and departures from an established baseline
- Number of growing degree days per year, timing of first and last frosts, number of frost free days per year, number of days per year that exceed  $-17.8^{\circ}\text{C}$ ,  $-2.2^{\circ}\text{C}$ ,  $26.7^{\circ}\text{C}$ ,  $32.2^{\circ}\text{C}$ , ( $0^{\circ}\text{F}$ ,  $28^{\circ}\text{F}$ ,  $80^{\circ}\text{F}$ ,  $90^{\circ}\text{F}$ , respectively).
- Intra- and inter-annual variability and trend analyses and interpretation from the perspective of:
  - Regional coherence
  - Hemispheric teleconnections, including the El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), North Atlantic Oscillation, and Atlantic Multi-decadal Oscillation (AMO)

**Objective 2: Precipitation.** Determine the status, trends, and periodicity in daily, monthly, and annual accumulated precipitation, including extremes, at the scale of points, climate regions, and parks and where appropriate distinguishing between rainfall and snow. Required data include COOP precipitation.

Proposed metrics and methodologies:

- Total accumulated precipitation and departures from an established baseline
- Frequency of precipitation events that exceed an established threshold, number of days with precipitation, intervals between precipitation events
- Intra- and inter-annual variability and trend analyses and interpretation from the perspective of:
  - Regional coherence
  - Hemispheric teleconnections, including the ENSO, PDO, NAO, and AMO

**Objective 3: Drought.** Determine the status, trends, and periodicity in monthly and annual drought at the regional scales. Required data include COOP precipitation and temperatures, SNOTEL/snow course snowpack, and USGS streamflow.

Proposed metrics and methodologies:

- Frequency and duration of drought beyond established thresholds
- Intra- and inter-annual variability and trend analyses and interpretation from the perspective of:
  - Regional coherence
  - Hemispheric teleconnections, including the ENSO, PDO, NAO, and AMO

**Objective 4: Snowpack.** Determine the status, trend, and periodicity in daily, monthly and annual snow cover and SWE at the scale of points, climate zones, and parks. Required data include SNOTEL and snowcourse SWE.

Proposed metrics and methodologies:

- Amount and timing of peak SWE
- Number of days with snow cover and timing of snowmelt
- Frequency of extreme snowpack events beyond a defined threshold
- Intra- and inter-annual variability and trend analyses and interpretation from the perspective of:
  - Regional coherence

- Hemispheric teleconnections, including the ENSO, PDO, NAO, and AMO

**Objective 5: Surface Hydrology.** Determine the status, trends, and periodicity in daily, monthly, and annual streamflow at the major watershed level. Required data include USGS stream gage records.

Proposed metrics and methodologies:

- Timing and intensity of peak and average streamflow and departures from an established threshold, and other seasonal shifts in stream hydrographs
- Intra- and inter-annual variability and trend analyses and interpretation in light of SWE, drought, precipitation, seasonal temperatures, and hemispheric teleconnections including ENSO, PDO, NAO, and AMO

## **1.7 Rationale for choosing climate measures**

### **1.7.1 Temperature**

Air temperature is a measure of the average kinetic energy in a parcel of air, where the higher the temperature, the faster the molecules are moving. Temperature is measured using thermometers or thermistors most often shaded from direct sunlight and recorded hourly in degrees Celsius. With knowledge from atmospheric circulation patterns and the influence of topography on temperature, models can be used interpolate temperatures across space in areas where temperature is not directly recorded. The RMCP will monitor temperature because changes in temperatures are a key indicator of climate change, high-quality measurements are recorded from numerous locations in and around the parks, historic temperature records are available, and most importantly, temperature is a key driver of ecological processes.

Temperature is considered a key driver of ecological processes across numerous scales from organismal biology to ecosystem structure. Temperature determines the activation and efficiency of enzyme production, and therefore it regulates all aspects of life from microbial activity and plant growth rates to the body size of large predators. For instance, freezing temperatures can directly reduce the population size and number of breeding cycles in bark beetles and temperatures often determines foraging behaviors in birds. At an ecosystem scale, primary productivity and nutrient availability are driven by temperature via its effects on microbial activity (increasing temperatures increase microbial activity and the release of nutrients into the soil). Temperature is also one of the key determinants for tree line in the West because tree growth is limited by the low temperatures found at high elevations.

### **1.7.2 Precipitation**

Precipitation refers to any product of the condensation of atmospheric water vapor that is deposited on Earth's surface. It can come in many forms, including rain, drizzle, hail, and snow. Precipitation is measured using a rain gauge and most often recorded as daily total precipitation. Snow, which is a subset of precipitation, is included in rain gauge measures, but it also is described using a number of other metrics, primarily SWE. SWE is the amount of water contained within the snowpack and can be thought of as the depth of water that would theoretically result if the entire snowpack instantaneously melted. As with temperature measurements, precipitation is measured at point locations throughout the United States and models are used to determine the amount and variation in precipitation when and where it is not directly recorded. Unlike temperature, there is a greater degree of local variation in precipitation.

The RMCP will monitor precipitation for a similar set of reasons that temperature is monitored: changes in the total amount and seasonal variation in precipitation are key indicators of climate change, high-quality measurements are recorded from numerous locations in and around the parks, historic temperature records are available, and precipitation is a key driver of ecological processes.

Like temperature, precipitation can regulate processes on organismal and ecosystem scales. All organisms require water for growth and metabolism. At an ecosystem scale, precipitation determines nutrient availability via its effects on the weathering of rocks. Increased water availability also increases the rate of decomposition and the release of nutrients in the soil. As a result, wetter areas tend to have increased nutrient availability and productivity compared to drier areas. It is not only the amount of precipitation, but also the timing (e.g., winter vs. summer) and form of precipitation (e.g., snow, fog, and rain) that influences the type of vegetation present in an ecosystem. In the Rocky Mountains, the effect of precipitation on ecosystems is evident in the difference in communities on the west and east side of the continental divide (Peet 2000). Due to orographic (mountain-related) lifting and the rain shadow effect, the west side receives approximately twice the precipitation the east side receives, resulting in forests with different tree species and more dense and productive forests. One exception to this case is seen at Rocky Mountain National Park and the Colorado Front Range, which receives orographic precipitation from both the east and west.

### **1.7.3 Drought**

Drought is measured at a regional scale and is a function of many aspects of climate such as temperature, streamflow, wind, and soil moisture. Drought is difficult to define (see “What is drought?: Understanding and defining drought,” National Drought Mitigation Center, 2006, <http://drought.unl.edu/whatis/concept.htm>). In general, a drought is an extended period of time where an area has a deficiency of precipitation. Drought is a normal, recurrent feature of climate that occurs in virtually all climatic zones, although its effect differs by region. It is important to recognize that drought is a temporary aberration, different from aridity, which is a permanent feature of climate. Because there is no single, precise definition of drought, its onset and termination are difficult to determine and it is measured and described by a variety of metrics.

Many drought indices incorporate multiple data types into calculations that result in a single value ranging from negative (drought) to positive (wet). Drought indices can be reported at a variety of spatial scales, varying from climate regions to the globe, and at temporal scales ranging from weeks to decades. Below we briefly describe the three indices used by the RMCP; additional details on these indices can be found in —Appendix A: Data Sources.”

The first and probably best known drought index was the Palmer Drought Severity Index (PDSI; Palmer 1968). The PDSI is a soil moisture algorithm that is calibrated for relatively homogeneous regions and was developed specifically for agricultural areas. It has the advantage of integrating effects of temperature as well as precipitation on drought (Alley 1984) and is applied best to areas having uniform topography and where snow does not make up a large portion of the water supply (Alley 1984, Karl and Knight 1985). The PDSI values may lag emerging droughts by several months and may underestimate the effects of prolonged drought (Karl and Knight 1985).

The Standardized Precipitation Index (SPI) is an alternative metric that calculates the probability of recording a given amount of precipitation (McKee et al. 1993). The probabilities are standardized so that an index of zero indicates the median precipitation amount (half of the historical precipitation amounts are below the median, and half are above the median). The SPI was designed to quantify the precipitation deficit for multiple timescales. These timescales reflect the impact of drought on the availability of the different water resources. Soil moisture conditions respond to precipitation anomalies on a relatively short scale, whereas groundwater, streamflow, and reservoir storage reflect the longer-term precipitation anomalies. Two key distinguishing traits of the SPI are that it identifies emerging droughts months sooner than the PDSI and it is computed on various timescales, but it does not account for the role of heating on drought. SPI can be calculated for retrospective timescales from most immediate (proximate month and season) to sustained (multi-year).

The Drought Monitor (<http://drought.unl.edu/DM/MONITOR.html>) is a program that synthesizes multiple drought indices and impacts and represents a consensus of federal (U.S. Department of Agriculture [USDA] and NOAA) and academic scientists (National Drought Mitigation Center at University of Nebraska-Lincoln). Each week the Drought Monitor program produces a summary map of drought intensity for the nation and all states each week. Drought intensity is classified based on the PDSI, SPI, soil moisture, streamflow, and other indicators of drought such as vegetation health, groundwater levels, and SWE. It is on a scale ranging from abnormally dry (D0) to exceptional drought (D4). While the monitor provides excellent summary information on broad-scale conditions, local conditions (such as at the park scale) may vary.

The RMCP will monitor and report on drought because it is a key indicator of climate change, it has large implications for natural and cultural resource management, and it can strongly influence ecological processes within the parks. For instance, in the western United States, while short summer droughts are common, more intense or longer periods of drought can strongly increase the probability and severity of wildfires.

#### **1.7.4 Streamflow**

Streamflow is a measure of the volume of water over a unit of time that moves within rivers, streams, or water channels. It is most often measured as discharge using stream gauges which are placed at key locations within or at the base of watersheds. The record of flow over time, such as during a season or year, is referred to as a hydrograph. In the western United States, streamflow is primarily driven by the timing and quantity of snow melt, where the largest flows are typically in the late spring. Streamflow represents a spatial integration of precipitation (both solid and liquid) and evapotranspiration (which is affected by atmospheric factors such as temperature, solar radiation, and wind). Most stream gauges are maintained by the USGS. The RMCP will monitor and report on streamflow of unregulated streams and rivers within or adjacent to the park units because, like drought, it is a key indicator of climate change, it has large implications for natural and cultural resource management, and it can strongly influence ecological processes within the parks. Streamflow is directly related to the health of obligate organisms, such as fish, and is strongly correlated with water quality.

#### **1.7.5 Spatial climate data**

Spatial climate data are gridded data sets that typically include temperature and precipitation for a given period across a region. Most are created by statistically interpolating data values from

irregularly spaced station locations to a regular grid (Daly 2006). Because such data can be linked to GIS, incorporated in modeling exercises, and can be used to estimate climate for areas without nearby weather stations they provide an essential resource to park managers and scientists. An up-to-date gridded surface climate dataset can spatially represent the status of climate zones, provide details for important management areas, and put park climates in perspective of the surrounding region's climate. Daly (2006) reviews the strengths and weaknesses of the available gridded datasets. The RMCP will use data developed by PRISM (Parameter-elevation Regressions on Independent Slopes Model) as our primary gridded data set (Oregon State University 2007). PRISM is based on local regression that accounts for spatially varying elevation relationships, effectiveness of terrain as barriers, terrain-induced climate transitions, and cold air drainage and inversions (Daly 2006). Compared to other available datasets, it accounts for more spatial climate factors than other methods, has fine resolution (800 m), has near-real time availability, and is best suited for the complex terrain of the Rocky Mountains.

### **1.8 History of protocol development**

Early stages of protocol development included inventories of relevant data sources and preliminary climate reports. As part of the national level effort to inventory weather and climate information, reports for GRYN and ROMN (Davey et al. 2006, 2007) were produced by the Western Regional Climate Center. Each report provides a complete inventory of point-based monitoring within and around each park and provides a more detailed overview of climate within the regions. GRYN also produced prototype annual reports and documentation of procedures used in their creation in collaboration with the Wyoming State Climatology Office (Gray 2005, 2008a, 2008b, Gray et al. 2009a, 2009b).

Next, a framework for the RMCP was developed through a GRYN and ROMN climate data analysis workshop in Bozeman, Montana in April 2009 (Kittel et al. 2009). Participants from NPS and the climate science community outlined details of data requirements, data cleanup, analysis methods, and reporting timeframes for meeting networks' climate monitoring objectives. The resulting framework lays out monitoring products and guidelines for successful implementation of the protocol. These expert recommendations underpin much of the RMCP presented in this narrative and accompanying SOPs.

The RMCP has been developed to complement national-level climate monitoring efforts. Our approach is to acquire data from existing national climate monitoring programs that provide consistent, long-term, and high-quality climate records for our regions and provide the critical steps of summarizing, reporting, and interpreting status and trends in climate at the park scale. Specifically, we will rely on the following two programs for local point based observations: the National Weather Service (NWS) Cooperative Observer Program (COOP) and the USDA Natural Resources Conservation Service (NRCS) Snowpack Telemetry (SNOTEL) network and Snow Course program (table 1.1). We will rely on a number of programs for regional observations. These include the USGS stream gauging network, the National Operational Hydrologic Remote Sensing Center (NOHRSC) Snow Data Assimilation System (SNODAS), and PRISM. While some of these programs provide direct observations (e.g., COOP), others use observational data to produce models that provide sophisticated spatial interpolation across the entire domain (e.g., PRISM). Other programs that collect climate data, such as Remote Automated Weather Station (RAWS), will not be included unless necessary to infill remote

locations because of siting biases, instrumentation issues, poor quality control and metadata and the length of record. A discussion of our data selection process can be found in detail in Kittel et al. (2009). In appendix A, we describe the purpose, the type of data and the strengths and limitations of each of these national climate monitoring programs. The procedures for selecting specific stations of interest within the networks, the units of reporting, acquiring climate data, data quality assurance and control, and analyses are presented in subsequent chapters.

The national I&M office, in collaboration with the Western Regional Climate Center, developed the NPCLime–Climate Data for Parks project (found at <http://www1.nrintra.nps.gov/NPCLime>). NPCLime allows for station discovery, and data query, selection, and delivery for one or many stations in a single download. This program was developed as a tool to provide all NPS units with station-level data on temperature, precipitation, wind, and solar radiation. While we will acquire our data directly from the reporting agencies for each station type (e.g., COOP, SNOTEL) so that we can track the status of the data and the quality control process directly, we recognize the value and utility of NPCLime. We anticipate NPCLime to be particularly useful to park managers and staff in need of weather summaries and plots that are not included in the network climate database and the RMCP Web site.



**Table 1.1.** National climate monitoring programs used by the RMCP

| Program                          | Acronym     | Measures and metrics of interest            | Spatial scale                              | Temporal scale        | Approximate start dates |
|----------------------------------|-------------|---|--|-----------------------|-------------------------|
| <b>NWS COOP</b>                  | COOP        | Temperature, precipitation                  | Local stations                             | Daily                 | 1950s or earlier        |
| <b>USDA NRCS</b>                 | SNOTEL      | Temperature, precipitation, SWE, snow depth | Local stations                             | Hourly                | 1970s                   |
| <b>USDA NRCS</b>                 | Snow Course | Snow depth, SWE                             | Local stations                             | Monthly during winter | 1920s                   |
| <b>USGS stream gauging</b>       | —           | Streamflow                                  | Local stations                             | Hourly                | 1895                    |
| <b>SNODAS</b>                    | SNODAS      | Snow cover, SWE                             | 1 km grid                                  | Hourly                | 2003                    |
| <b>PRISM Climate Group</b>       | PRISM       | Temperature, precipitation                  | 800 m and 1 km grid                        | Monthly               | 1895                    |
| <b>Drought Monitor</b>           | —           | Drought                                     | National, state, county, climate divisions | Weekly                | —                       |
| <b>Climate Prediction Center</b> | —           | Teleconnections and atmospheric indices     | Global                                     | —                     | Most from 1950s         |

## 1.9 Monitoring approach

The RMCP will harvest and use existing climate information from established monitoring programs. We have chosen this approach for two reasons: it is inexpensive and more likely to be sustainable, and it will leverage the expertise of other federal agencies. Existing information is inexpensive to acquire. Acquisition of climate data is often as simple as going to a Web site and downloading the information. One of the key barriers to successfully using climate data is that it is from different agencies and in inconsistent formats.

Rather than investing time and expertise on installing weather stations, we will acquire pre-existing data sets and add value to them (fig. 1.5). The first value-added component will be maintaining all of the information from the disparate agencies in one central database and schema. Second, we will perform quality control procedures to produce datasets useful for summarizing, analyzing, and reporting on the climate data at scales relevant to the park units. Third, we will provide three reporting products to meet the RMCP monitoring goals:

1. *Climate Status Reports.* These reports provide a largely descriptive summary analysis of the climate of the past year or few years. Prepared and released on an annual (GRYN) or 2–3 year cycle (ROMN), climate status reports covers the previous calendar (January–December) year(s) for temperature, precipitation, and drought, and the previous water year(s) (October–September) for snowpack, SWE, and streamflow. When the process can become more automated, ROMN will produce reports for all parks annually. The purpose of these reports is to support park science and management planning on an annual to three-year scale. Additionally, status reports puts the year’s climate in context of longer-

term variability patterns and trends developed in the trends and inter-annual variability report.

2. *Climate Inter-annual Variability and Trends Reports*. These reports will be produced on 5–10 year cycles and will present rigorous analyses of inter-annual variability, long-term historical trends, and correlate local trends with teleconnections and hemispheric climate patterns (e.g., the PDO).
3. *RMCP Climate Web site*. This Web site will provide links to timely and relevant climate information, reports, and data, as well as access to the climate datasets processed by I&M networks for the status and trends reports.

In addition to the above products, when logistically possible, data will be provided at scales necessary for understanding changes in other vital signs (e.g., watershed scales). To provide a product useful for all vital signs and parks it is important to acquire, process, manage, and deliver climate information at a variety of different spatial and temporal scales. Spatial scales can range from local to global. Specifically, we will focus on points (stations), within-network climate zones, and larger regional variations. Temporal scales include daily, monthly, annual, and inter-annual variations.

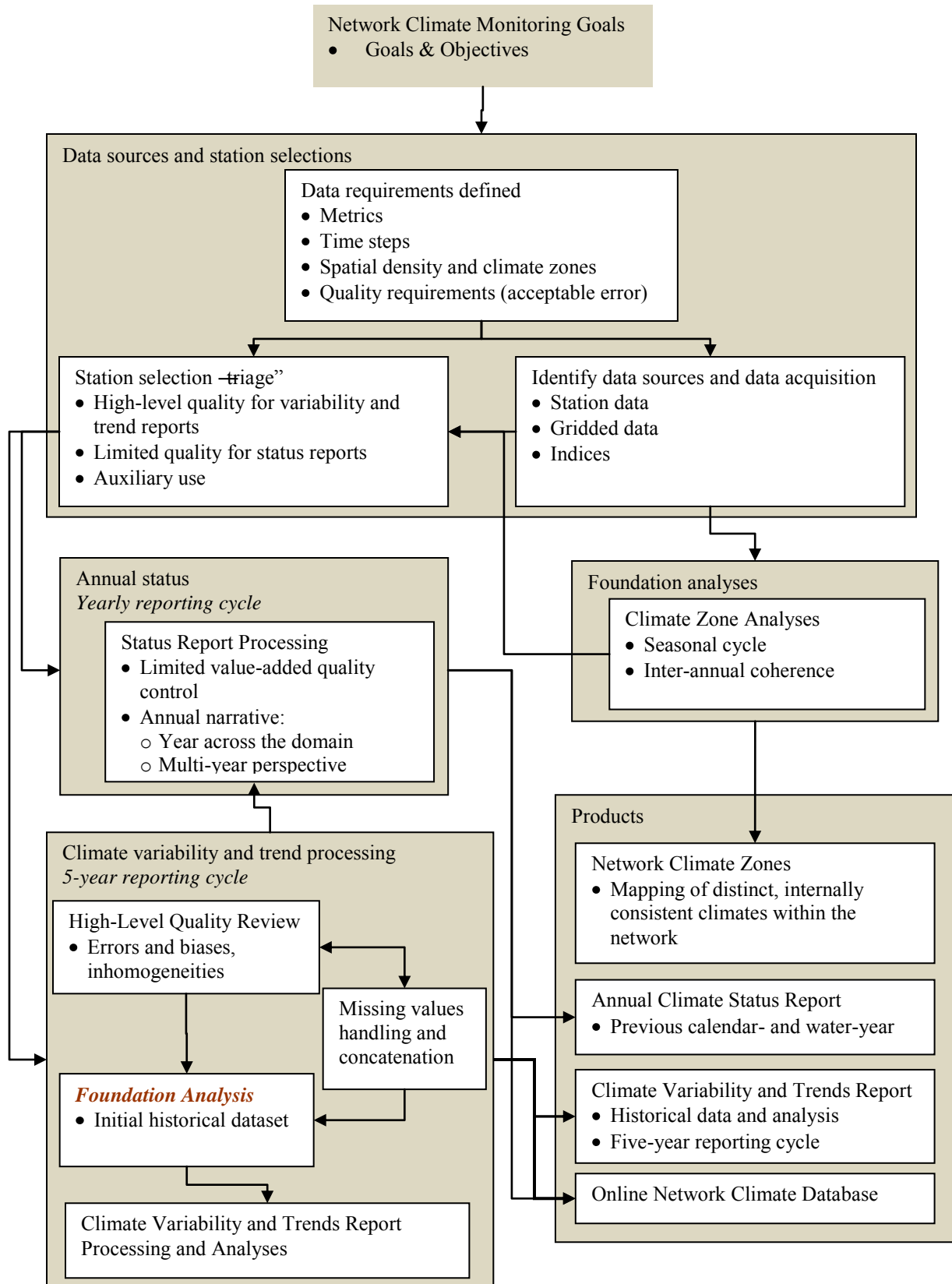


Figure 1.5. Overview of climate monitoring (after Kittel et al. 2009).

## 2 Sample Design

### Relevant SOPs:

- SOP: Defining Climate Zones
- SOP: Station Selection

### 2.1 Introduction

A sampling design indicates how data are to be collected over time and space. It ensures that data are representative of the target populations and sufficient to draw defensible conclusions about the resource of interest (EPA 2002). The sampling design for climate data collection uses stratification with specific sampling locations determined by judgement sampling. Because we are using existing weather stations to collect data for this protocol, we are limited in our ability to implement a formal sampling design and probabilistic sampling is not feasible. Still, we incorporated elements of sampling design to improve the representativeness of our samples and ensure we are using the highest quality data available. The select stations we use from the legacy network will be evaluated over time to determine their adequacy in representing spatial and temporal climatic variability. Provisions to improve sampling will be made over time, where necessary, and as funding allows.

### 2.2 Defining the target population

Defining the target population is a key step in developing a sampling plan. The target population is the set of all units that comprise the items of interest in a monitoring study, or the population about which inferences are to be made (EPA 2002). The target populations for this protocol are network-specific and are comprised of all national parks within the respective networks, along with the larger region of interest surrounding each park. The larger regions or ecoregions surrounding each park are included so that climate within a park can be placed in a regional context.

### 2.3 Stratification of climate zones

In large and dispersed networks like ROMN and GRYN, averaging weather observations across all parks would be of little value for understanding climate (Gray 2008a). Therefore, we stratify the target population into climate zones for use in analysis and reporting. Climate zones are identified using a combination of cluster analysis and principal components analysis to create strata with internally consistent climates. In stratified sampling, the target population is separated into non-overlapping strata that are more homogeneous than the the area as a whole, thereby reducing variation within strata. Stratification also improves the representativeness of sampling and the precision of state variable estimates (EPA 2002).

The stratification process involves three approaches to identify climate zones within a network. As recommended by Kittel et al. (2009), long-term weather data is used to delineate geographic regions that are associated with certain weather stations and have: (1) similar patterns of intra-annual (seasonal) variability in precipitation and temperature (mean temperature and diurnal temperature range), and (2) similar patterns of inter-annual (year to year) dynamics in precipitation and temperature. Snowcover timing is used to discriminate elevational zones by snowpack initial development and melt regime.

A detailed description of the entire process of identifying climate zones can be found in –SOP: Defining Climate Zones” and additional information is provided by Kittel et al. (2009). In brief, the analytical process begins with hierarchical cluster analysis of 1971–2000 monthly accumulated precipitation, average diurnal temperature range, and average temperature normals from all available weather stations within a network to identify stations having similar intra-annual variability in precipitation and temperature. Next, principal components analysis of monthly precipitation and temperature data is used to identify stations having similar long-term, inter-annual dynamics in precipitation and temperature. Correlation maps are used to explore the spatial extent of the clusters’ patterns, and correlate each cluster’s seasonal temperature and precipitation data with the PRSIM monthly temperature and precipitation normals for cells within the network domain (fig. 2.1). The final step in the process is to evaluate the analytical results in light of the ecological and climatological literature for that area (e.g., for GRYN, Whitlock and Bartlein 1993, National Research Council 2002, Eberhardt et al. 2007). This process will describe climate zones for each park that are defined as groups of similar weather stations. In the case of GRYN, preliminary results from this process defined three distinct climate zones.

#### 2.4 Selection of sampling locations (weather stations)

Ideally to describe climate within each network and have strong inference to the area of interest, probabilistic sampling would have been used to locate sampling locations (i.e., weather stations) within each climate zone. However, this protocol relies on extant climate monitoring programs. Weather monitoring agencies typically use judgement sampling to determine the type, number, and placement of stations. Most stations are located where they are accessible and thought to be representative of an area. Previous inventories for GRYN (Davey et al. 2006) and ROMN (Davey et al. 2007) identified all COOP and SNOTEL weather stations in or near network parks (table 2.1). Given that sampling locations were determined through judgement sampling, we developed specific criteria to select stations for inclusion in our reports.

**Table 2.1.** Number of active COOP and SNOTEL stations in or within 40km of GRYN and ROMN park units as reported by Davey et al. (2006) and Davey et al. (2007)

|        | GRYN           |                |                    | ROMN                      |            |                       |                            |                               |                   |
|--------|----------------|----------------|--------------------|---------------------------|------------|-----------------------|----------------------------|-------------------------------|-------------------|
|        | Yellowstone NP | Grand Teton NP | Bighorn Canyon NRA | Florissant Fossil Beds NM | Glacier NP | Grant-Kohrs Ranch NHS | Great Sand Dunes NP and Pr | Little Bighorn Battlefield NM | Rocky Mountain NP |
| COOP   | 28(12)         | 12(4)          | 10 (1)             | 9 (1)                     | 25(8)      | 5(0)                  | 8(1)                       | 3(0)                          | 28(1)             |
| SNOTEL | 31(10)         | 5(0)           | 1(0)               | 0(0)                      | 8(2)       | 2(0)                  | 2(1)                       | 0(0)                          | 13(5)             |

Note: Numbers in parentheses indicate the numbers of active stations within park boundaries.

Station selection is based on two objectives (Kittel et al. 2009):

1. To provide an extensive *spatial* picture of climate across the network domain, its constituent climate zones, and the region immediately around the network. This is a key part of describing the year in review in the climate status reports.
2. To provide for a rigorous *temporal* analysis of inter-annual variability, regime shifts, and longterm trends in key daily, monthly, seasonal, and annual climate metrics. These

stations can provide baseline data to provide context for status reports and are the foundation of the climate variability and trends reports.

To achieve these goals, selection entails both objective and subjective processes, which are described in —SOPStation Selection.” In selecting stations we distinguish two sets of stations for analysis and reporting: (1) a larger set of stations with histories of varying length for reporting a snapshot of the year(s) included in the climate status reports, and (2) a subset of these stations which have longer histories and high-quality data to allow analysis of temporal variability and trends. Remaining available stations that are not used directly in temporal or spatial analyses may yet have value during the infilling process if they span gaps in the otherwise higher quality stations (Kittel et al. 2009).

## **2.5 Periodic evaluation of the sampling design**

Our sampling design is limited because we are using a network of legacy stations that are operated by other agencies. However, we incorporated elements of sampling design to improve the representativeness of our samples and ensure we are using the highest quality data available. We expect that stations will be added and removed from within the sampling domain over time. Therefore, every 5–10 years or when the trend analyses and reporting occurs, it is essential to review the sampling design and evaluate the spatial and temporal coverage provided by the available datasets for each climate zone and park. If necessary, additional weather stations or data sources should be acquired to ensure the integrity of the sampling design and more specifically, inference from stations to climate zones.

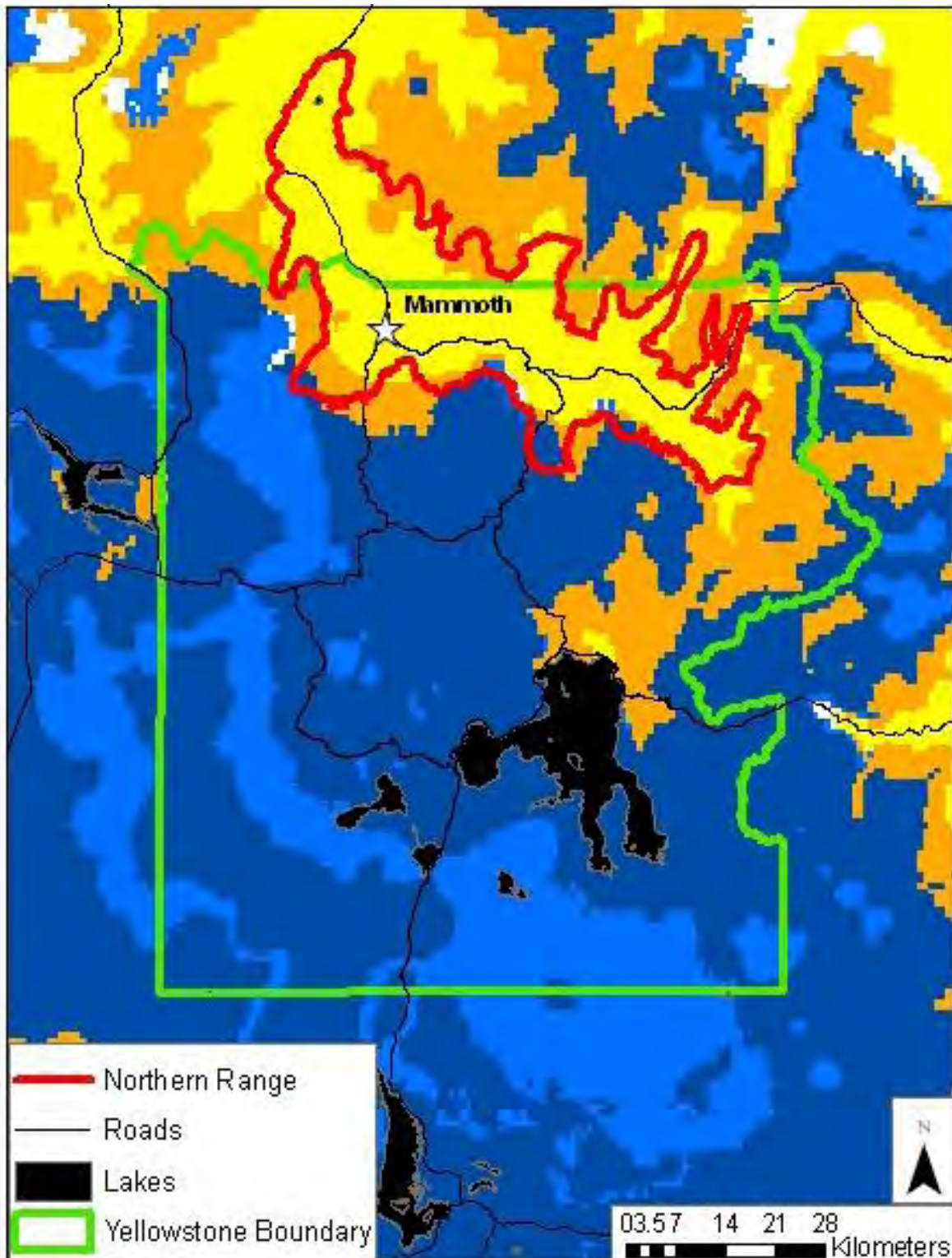


Figure 2.1. Three climate zones (blue, orange, yellow) for Yellowstone National Park as defined by a preliminary cluster analysis of 1971–2000 monthly precipitation normals from 58 weather stations. Darker colors within each zone indicate stronger correlation with weather station data used in the analysis. A description of methods appears in –SOP: Defining Climate Zones.”

## 3 Field Methods

### Relevant SOPs:

- SOP: Weather Station Visits and Documentation

### 3.1 Introduction

As previously described, the RMCP is a data-harvesting protocol that uses data collected by other agencies for the analysis of climate status and trends. “Chapter 4: Data Acquisition, Quality Control, and Processing,” describes how and where data are acquired from various sources, including NWS COOP stations and NRCS SNOTEL stations in and near the parks. Data collection and transmission for these programs is accomplished by the responsible agency and is briefly described in appendix A. Fieldwork associated with the RMCP is for the documentation and maintenance of stations operated by outside agencies, not to collect actual climate data. Seasonal field preparations will be minimal, but will include scheduling visits to remote or high-elevation stations during summer months when access is easiest and coordinating with park permitting offices to avoid area closures.

Because a principal goal of our climate monitoring protocol is to detect and characterize changes in climate through time, consistency in measurements is essential and at least as important as accuracy in measurements. Changes in instrumentation, site characteristics (e.g., vegetation growth or urbanization), or observation methods (e.g., personnel changes) can impose artificial patterns and trends on the observed data. Examples of problems that occur when stations are not regularly inspected and maintained can be found at Surfacestations.org ([http://www.surfacestations.org/odd\\_sites.htm](http://www.surfacestations.org/odd_sites.htm)). Regular maintenance and collection of station metadata are critical to long-term station operation and interpretation of the data. While specific requirements vary, all climate stations are scheduled for at least annual maintenance (NWS 1989; NRCS 2009). Although field maintenance and calibration of instrumentation is expected to be performed by the respective agencies, budgetary and staffing limitations may prevent routine inspections of weather stations. Consequently, inattention to maintenance has been identified as the greatest source of failure in weather stations and networks (Davey et al. 2006, 2007).

To ensure the integrity of climate data used in our reports, the RMCP includes an effort to regularly document station and site conditions. This process includes: (1) compiling and archiving a history for each station; (2) conducting site visits every 2–3 years and recording station and site conditions using Weather Station Documentation, Weather Station Site Visit, and Weather Station Photo Documentation data sheets (see the RMCP Toolbox); (3) communicating needs for station or site maintenance to the responsible agency (contacts listed in “SOP: Weather Station Visits and Documentation”), and (4) communicating with agencies to confirm maintenance activities were performed and reporting the outcome in the climate status reports. While park staff and/or staff from other agencies are responsible for conducting maintenance on many stations, the site visits described in this protocol will be conducted by network staff, accompanied by a climatologist or expert in the field. All stations used for status and/or trend reporting will be included in this effort, including those outside of park boundaries. We will attempt to document conditions at each station at least every two years.



### **3.2 Station documentation: The initial site visit**

Station documentation is completed during the initial site visit. Subsequent site visits are simply referred to as site visits. To begin the station documentation process, a database is needed to schedule and record the following events for each station used in status or trend reports: station documentation and site visits, station metadata, and requests and responses regarding maintenance needs. Prior to conducting field visits there is also a need to compile historical metadata for each station. Metadata include the type of station, equipment specifications, the types of data reported, repairs reported, site characteristics, station moves, and data completeness statistics. Paper or electronic versions of the station metadata are taken in the field on all site visits to provide a baseline for comparison to current site conditions.

During the first visit to a station, the equipment and surrounding area will be surveyed, and the station documentation and photo documentation forms will be completed according to –SOP: Weather Station Visits and Documentation.” Photographs of the stations are critical to determine how much of any potential change in observed air temperatures might be due to land-use or instrument changes at the site (Davey and Pielke 2005). Photo documentation of stations is required for the following reasons:

- To leave a permanent archive record of site conditions
- Photos can be transmitted and stored, mental images cannot
- To show relationships between instrumentation and the factors that affect what they observe and record
- To record the condition of instruments
- To record the setting at all scales
  - Within a few centimeters to a few meters of the sensors
  - Within a few tens of meters
  - Within a few hundreds of meters
  - Within a few kilometers to tens of kilometers

If maintenance issues are identified during the compilation of historic metadata, the site visit, or from photo documentation these will be noted and reported to the appropriate agency representatives (table 3.1). Follow-up communication with the appropriate agencies will be conducted and the outcome reported in the appropriate climate status report.

### **3.3 Station documentation: Subsequent site visits**

After the initial visit, network staff will attempt to visit climate stations once every two to three years, ideally accompanied by a climatologist. The purpose of completing frequent site visits to all stations used in status and trend reporting is two-fold: (1) to determine if any environmental factors have changed that may affect the validity of the collected data, and (2) to initiate repairs or maintenance through the appropriate agency, if necessary. During each visit, the station and surrounding area will be surveyed and a Weather Station Site Visit and Weather Station Photo Documentation datasheets (RMCP Toolbox, Field\_Methods\_Data\_Sheets.xls) will be completed. The station and site will be photo documented according to –SOP: Weather Station Visits and

Documentation.” Station histories should again be available in paper or electronic format to take in the field for comparison to current conditions.

## 4 Data Acquisition, Quality Control, and Processing

### Relevant SOPs:

- SOP: Station Selection
- SOP: Data Acquisition
- SOP: Quality Control
- SOP: Database Schema
- SOP: Data Formatting

### Relevant Tools from RMCP Toolbox:

- Python Batch Uncompress GZ Raster datasets
- Python Batch Uncompress TAR Raster Datasets
- Python Geoprocessing Batch Clip Raster Datasets
- Python Geoprocessing Raster Time Series
- Python Climate Station Module

The RMCP relies entirely on data acquired from established weather and climate monitoring systems operated by a number of federal and academic entities (see –Appendix A: Data Sources” and –SOP: Data Acquisition”). Criteria for using data from these providers are listed below. As providers improve data distribution systems over time, the most current instructions for acquiring data are normally found on the Web site of each provider. The workflow shown in figure 4.1 helps ensure consistent data collection, formatting, and quality control prior to uploading data to a project database for annual processing and reporting. Data processing includes those activities required to meet stated data quality objectives and formatting requirements for analyses and long term data storage and distribution. Refer to each standard operating procedure (SOP) for estimates of the time and skill sets required to complete each task. The SOPs will receive annual review and update based on what is learned and improved through the use of the procedures.

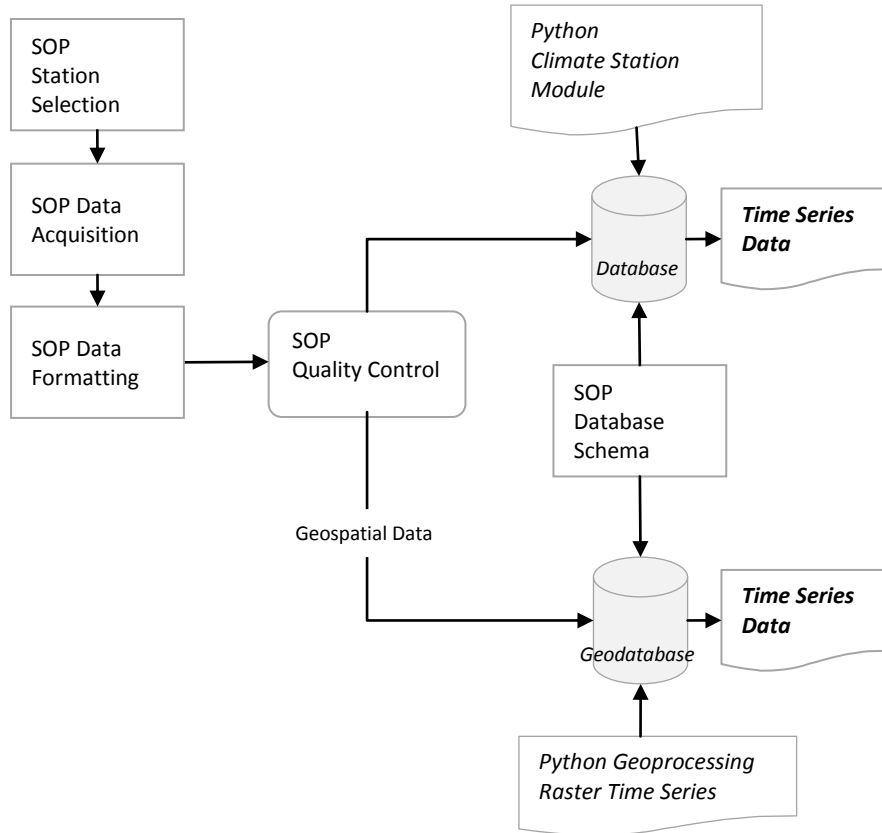


Figure 4.1. General workflow model for data acquisition and processing.

#### 4.1 Acquisition criteria

The following are minimum requirements for acquiring climate data. Additional criteria are detailed in “SOP: Station Selection,” which is based on guidance provided in Gray (2008b) and Kittel et al. (2009) to select data sources to support climate monitoring analyses:

1. Data are from an established program that has operated data collection stations for a minimum time period
2. Data represent measures observed within the area of interest, the park boundary, the climate zone, or where the professional literature supports a relationship between the park’s climate and the data (e.g., teleconnections) as stated in “Chapter 2: Sample Design.”
3. Data are certified for release as final (or provisional for use in climate status reports)
4. Data are in digital format with the exception of the B-91 weather recording forms (not a product of this protocol)
5. Data points are regular through space and time, and include a minimum of one observation per year

6. Literature supports that the measures (e.g., temperature, precipitation) has an effect on resources within and around the park
7. Data are freely available to the networks and park units

In addition, the following documentation must accompany and be stored with the data or be available and accessible at all times via an apparent link from the locally-stored data:

1. Collection/processing procedures
2. Quality assurance and control procedures, including all changes or additions to raw data values, such as data set normalization or extrapolation to populate missing values
3. Instrumentation specifications and changes to instrumentation
4. Station location, setting, and history
5. Purpose/goals of data collection/creation

#### **4.2 Data sources**

Sources for primary metrics and directly-measured integrative and timing metrics are readily available from government and academic agencies. Some datasets reflect point-based conditions or observations (e.g., COOP, SNOTEL, and USGS streamflow stations), while others represent an areal extent at a specified cell resolution (commonly known as “grid” or raster data (e.g., PRISM, SNODAS). –SOP: Data Acquisition” provides instructions on where and how to acquire these data sets.

Project staff normally acquire high-quality, well-documented data from each system once per year. However, if provisional data are available on a more frequent schedule and project staff can accommodate special requests, then recent climate and weather data for selected park sites could be acquired, processed, and made available more than once each year to support research, resource management, interpretation, and park operations. A Web site will likely be one of the best tools for supporting these real time needs.

Data providers, formats, and content are expected to change through time, and project staff should be prepared to watch for and adapt to changes in data availability and data acquisition and processing methods that may require more or less time and expertise in a given year or reporting cycle. The recommended strategy is to focus on data acquisition, processing, analysis, and reporting for those climate metrics and indices that directly support stated monitoring objectives. Optional data sources, climate measures, and analyses can be incorporated as resources allow. A description of which metrics are required versus optional can be found in –SOP: Trend Analysis and Reporting.”

#### **4.3 Quality control of data**

Kittel et al. (2009) outlines strategies and techniques for processing data to handle errors, inhomogeneities, and missing values. –SOP: Quality Control” specifies how project staff will review and process all newly acquired data prior to upload to the network climate database.

#### **4.4 Quality control for annual climate status reports**

The annual status updates build on data and analyses from the previous five-year cycle trends report, and are provisional and based on data available at the time status reports are being prepared and with limited quality control. At the time of data acquisition, the data will be categorized for tracking purposes as provisional or final. The guiding strategy for status report quality control is to:

- Implement an in-house protocol to catch and deal with most obvious and most readily corrected problems. Problems can be handled by correcting or removing values. Each corrective action requires documentation of the issues and solution.
- For certain datasets accept the standard quality control and corrections made by the originating data provider.
- Ignore complex issues based on documented rationale and explained in all reporting as qualifiers and caveats as to their possible presence affecting temporal and spatial analysis results.

These tasks are outlined in “SOP: Quality Control” by metric, objective, and analysis. This strategy generally encompasses levels of quality control implemented in other network protocols and analyses, such as for Northern Colorado Plateau Network (Garman et al. 2004) and Central Alaska Network (Keen 2008).

Because of the intermediate level of quality control, data and analyses presented in the status report and online should include caveats that data and results are provisional, subject to being updated in the trends report and subsequent releases of the network climate database.

#### **4.5 Quality control for climate variability and trends reports**

Quality control for Variability and Trends analyses is far more rigorous in handling complex data issues (see Kittel et al. 2009). Data checking and cleaning steps are outlined in “SOP: Quality Control” by analysis objective and metric and also in “SOP Trend Analysis and Reporting.” Additional information on creating useful climate datasets can be found in Kittel et al. (2009) and Kittel (2008).

Sophisticated quality control processes involve tailored treatment of station records that requires climatological expertise beyond that typically found within I&M networks. As described in “Chapter 7: Operational Requirements,” quality control procedures for trends reports will be conducted by or in close collaboration with a climatologist.

#### **4.6 Database schema**

Data will be stored in both a geodatabase for geospatial data and a Microsoft Access (or SQL Server) database for non-spatial data following quality control and initial processing, e.g., formatting the data for upload. The database schema will incorporate quality control techniques as outlined in the “SOP: Database Schema.”

#### **4.7 Data processing and geoprocessing**

Processing data includes all the steps and activities required to make the data useful for immediate and long term analysis, reporting, and distribution, as well as storage. This includes

documenting data sources, acquisition methods, structural, format, and content changes; quality assurance processes, and transformations, manipulations, or summarizations that prepare the data for use in the appropriate analysis applications, reporting systems, and data storage systems. All of the datasets will need to be reformatted either prior to quality control or prior to uploading into the database or geodatabase. Refer to “SOP: Data Formatting” for the specific steps and format required.

In general, the methods and instructions for data processing are specific to each data source, and are therefore incorporated into the “SOP: Data Formatting” and RMCP Toolbox and reflected in online guidance from data providers. For example, we may download Geographic Information System (GIS) raster PRISM data at the 1-kilometer scale, and after quality assurance and control procedures are completed, we may process the data in the following ways: change the climate zone, change the metric reported from temperature to temperature anomaly, or summarize the data into monthly, seasonal, or annual time series using scripts provided in the RMCP Toolbox.

Large climate raster datasets will require several geoprocessing steps conducted by the network data managers to uncompress and prepare the data for analytical techniques and storage as detailed in the following tools, found in the RMCP Toolbox:

- Python Batch Uncompress GZ Raster datasets
- Python Batch Uncompress TAR Raster Datasets
- Python Geoprocessing Batch Clip Raster Datasets

In addition to the data preparation, python scripts are also available to generate time series for the raster and climate station data, a step necessary for analyses and reporting. The scripts are “Python Geoprocessing Raster Time Series” and “Python Climate Station Module.” All of the above tools are provided as Python scripts with instructions for non-Python users.

## 5 Data Management

### Relevant SOPs:

- SOP: Quality Control
- SOP: Database Schema
- SOP: Web site

The data management system that supports the climate protocol is designed to ensure that analyses and reporting are based on standard and documented data sources from credible observation programs. Data management helps ensure that all data used in analysis and reporting are subject to quality control verification and validation processes to establish data integrity (fig. 5.1). A core database schema accommodates changes over time (versioning) and provides an archive for long-term data storage, as well as access to analytical and reporting products. A goal of the RMCP is to develop a high-quality historical network climate database.

### 5.1 Roles and responsibilities

Successful data management involves overlapping and shared responsibilities among all project staff over the entire life cycle of the data and products collected and generated as part of the project. Project personnel collectively develop, follow, and document standards for information needs, data quality, analytical inputs and outputs, data processing procedures, and reporting requirements to meet the stated objectives of the project.

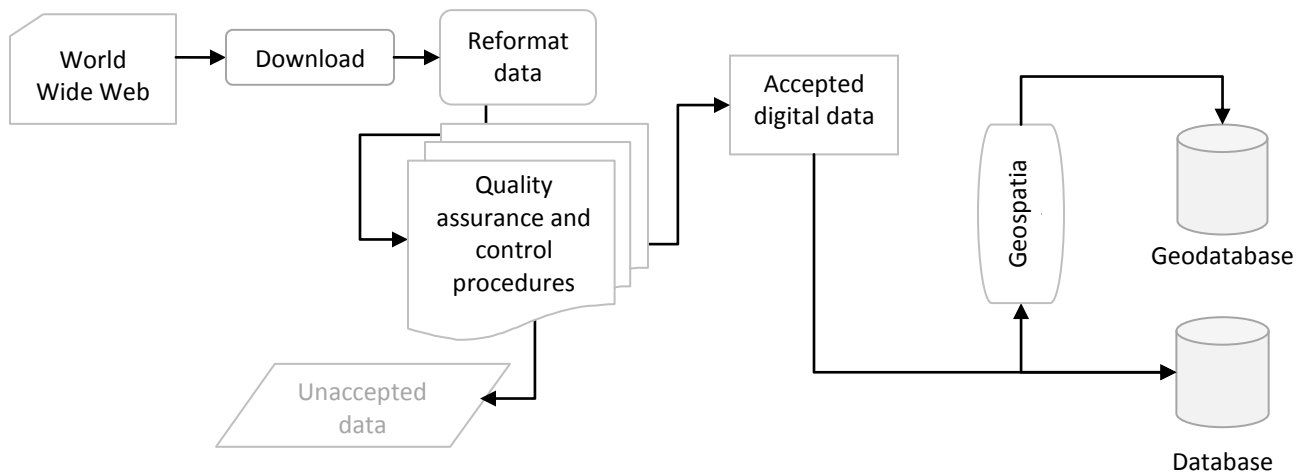


Figure 5.1. Data management workflow conceptual model.

### 5.2 Data standards

We intend to meet the following standards for climate data used in the RMCP as a basis for scientific credibility (US DOI 2007): (1) qualitative accuracy, (2) completeness, (3) consistency, (4) precision, (5) timeliness, (6) uniqueness, and (7) validity. To facilitate convergence with these standards, we will use established data providers whose data sources are documented relative to these listed standards, and which facilitate the local data management procedures (e.g., –SOP: Station Selection” and Kittel et al. 2009). Data qualifiers are normally reported with



results to inform readers of important restrictions or limitations to the data. By using the appropriate provisional or final source data and processing those data according to the given reporting requirements, situations in which climate data providers change source data after project staff have acquired and/or used the data will generally be avoided. If project staff or report readers identify questionable results or become aware of changes to source data after a report is made, then an assessment by project staff will determine for each case whether it is necessary to re-do all or a portion of the analysis and reporting.

All necessary non-spatial data are acquired in or converted to a format compatible with Microsoft Access. Geospatial data are formatted for use in Department of the Interior and NPS standard ESRI ArcGIS applications (ESRI 2009), including the file Geodatabase format to accommodate raster data. As the project matures data storage and analyses requirements may met by migrating to Microsoft SQL Server and ESRI ArcGIS Enterprise solutions (ESRI 2009).

Data management procedures and services accommodate raw or processed data acquired from established online sources. This includes resolving duplication and overlap of respective data sources required for analysis and reporting. –Appendix A: Data Sources” discusses data sources needed for status and trend reports.

Derived data are also managed, organized, documented, and distributed as part of the project. These information resources include spreadsheets, tabular and spatial databases and source files; ArcGIS map (.mxd) files, R and Python scripts, textual outputs from analytical procedures, images and graphics, and reports. Each derived and developed data set or product meets the standards for format, quality, organization, and maintenance as set forth in the applicable NPS data management plans (Daley 2005, Frakes et al. 2007, NPS 2008a).

### **5.3 Database standards and schema**

Developing a secure, useful, and flexible system to support long term data storage and ongoing accessibility to the required digital datasets is a critical aspect of this project. To meet this demand networks will maintain and analyze digital data in Microsoft Access and ESRI geodatabases that integrate established standards for long-term monitoring projects (Daley 2005, Frakes et al. 2007, NPS 2008a). The Microsoft Access database design developed from a common schema presented in –SOP: Database Schema” can be modified to meet the needs of an individual network. The common database schema will be refined as needed throughout the lifetime of the project and the changes will be documented and reflected in –SOP: Database Schema.” Software platforms may be upgraded to a more robust enterprise database system as the NPS I&M Program matures.

### **5.4 Quality assurance and quality control**

Following data acquisition, network data managers, ecologists, and climatologists assess the data for temporal and spatial completeness and potential data outliers, which may result in discarding the dataset if any criteria are deemed insufficient (Kittel 2008). –SOP: Quality Control” discusses the procedures applied to verify and validate each of the acquired dataset prior to accepting the data and uploading to the network database geodatabase.

The following data formats used for the RMCP require a specific set of quality assurance and processing standards for downloading, reformatting, verifying, validating, maintaining, and archiving as detailed in the appropriate SOP.

- Comma delimited (.csv) data file, e.g., SNODAS
- GIS raster data, e.g., PRISM.
- Geographic Positioning System (GPS) location data, e.g., COOP stations
- Microsoft Word documents
- XML metadata documents

All digital data will be converted to a common and consistent format for storage in the appropriate Microsoft Access database, ArcGIS geodatabase, or document software, e.g., Microsoft Word or Adobe Portable Document Format (PDF) (fig. 5.1).

### **5.5 Records management, data maintenance, and archiving**

The objective of RMCP records management, data maintenance, and archiving procedures is to ensure that protocol data, analyses, products, and reports are easily accessible, shared, and properly interpreted by a broad range of users in perpetuity (NPS 2008a).

Data and products for the project are expected to be digital in format, with the exception of manually-collected station data (i.e., station visit and site documentation forms as well as the copies of B-91 forms from COOP stations). Hard copy records from will be managed as directed in NPS Director's Order 19: Records Management and appendix, NPS Records Disposition Schedule (NPS 2001). All digital data acquired and derived are archived annually according to the procedures and standards in NPS Data Management Plans (Daley 2005, NPS 2008a, Frakes et al. 2007). Archived data and products are normally stored along with supporting documentation in a format such as ASCII text that is independent of an operating system platform and software to maintain data integrity and accessibility. The files are organized and maintained in a consistent folder structure for easy access.

### **5.6 Climate Web site**

I&M networks are responsible for developing and deploying Web site content specifically designed for a network's parks to provide informative products such as maps, graphs, climate measures, and hyperlinks to various climate resources of interest. Network data managers are normally responsible for the functionality of the Web site, and subject matter experts such as network ecologists or cooperating climatologists are responsible for maintaining current and useful content for Web sites. Network staff will be responsible for annually reviewing the Web site to ensure the content and applications are appropriate and up-to-date. Additional information, including potential hyperlinks, is provided in —Chapter 6: Climate Data Analysis and Reporting” and —SOP: Web site.” The climate Web site content also serves as a potential mechanism to support near real-time data requests from the park and researchers, eliminating a need to produce mid-cycle reports.

## 6 Data Analysis and Reporting

### Relevant SOPs:

- SOP: Status Reports
- SOP: Trend Analysis and Reporting
- SOP: Web site

### 6.1 Introduction

In preparation for writing this section of the protocol, GRYN sponsored a three-day climate data analysis workshop in April 2009 with Tim Kittel, Steve Gray, and Chris Daly along with ROMN and GRYN staff and representatives from Grand Teton and Yellowstone national parks (Kittel et al. 2009). Much of the content, format, and thought presented in this section were generated in preparation for or as a result of the workshop, as reported in Kittel et al. (2009). Past investigations (Gray 2008a) and prototype reports for GRYN (Gray et al. 2009a, 2009b), ROMN (Ashton et al. 2009, Frakes 2007), and the Northern Colorado Plateau Network (Garman 2009) were also instrumental in shaping the content of this section.

### 6.2 Overview of analysis and reporting objectives, products, and timeframes

Our monitoring goals and objectives and how we intend to report on these goals drives the data analysis portion of the protocol. For this reason, we begin the discussion of data analysis with an overview of our reporting products. The RMCP monitoring program will provide three reporting products to meet its monitoring goals:

1. *Climate Status Report.* This report provides a largely descriptive summary analysis of the climate of the past year or few years. Prepared and released on an annual (GRYN) or 2–3 year cycle (ROMN), the climate status report covers the previous calendar (January–December) year(s) for temperature, precipitation and drought, and the previous water year(s) (October–September) for snowpack, SWE, and streamflow. The purpose of the report is to support park science and management planning on an annual- to three-year scale. Additionally, the status report puts the year’s climate in context of longer-term variability patterns and trends developed in the trends and inter-annual variability report.
2. *Climate Trends and Inter-annual Variability Report.* This report will be produced on 5–10 year cycles and will present rigorous analyses of inter-annual variability, long-term historical trends, and correlate local trends with teleconnections and hemispheric climate patterns (e.g., the PDO). To describe the variability and trends of climate in a scientifically-defensible manner requires a substantial investment in quality control that is beyond the scope of what can be accomplished without climate science expertise (Kittel et al. 2009). Therefore, these reports will require contracting or collaboration with a climatologist. The 5–10 year cycle for these reports permits a high level of station data quality checks and correction since the previous report, and detailed analyses of long-term patterns in the annual, monthly, and daily climate record. These analyses will include comparison to an established baseline; Kittel et al. (2009) recommended that this be most recent 30-year “climate normal” period: 1971–2000 because it is currently the community standard and will give a conservative assessment of recent climate change, as

changes have been most marked since the middle of 20<sup>th</sup> century. The purpose of these reports is to provide park management, research, and public outreach with reliable, pertinent assessments of changes in park climates. Ideally, these reports will be turned into manuscripts and submitted to peer-reviewed journals. These assessments will be multi-faceted and will include:

- a. Evaluating a suite of ecologically-significant climate measures including temperature, precipitation, snowpack, drought, and surface hydrology
  - b. Assessing a spectrum of climate dynamics in terms of daily (e.g., occurrence of extremes), inter-annual, and long-term behavior
  - c. Testing connections to regional and hemispheric climatic processes
3. *RMCP Climate Web site.* This Web site will provide links to timely and relevant climate information, reports, and data, as well as access to the climate datasets processed by I&M networks for the status and trends reports. The high-quality network climate database will be developed and updated as the foundation for status and trends reports and can be readily used to support analyses of other vital signs, park science, management, and public programs. The database will be available upon request to I&M and park staff, with the final, vetted datasets available to the public. In addition to supporting the goals of the I&M networks, a network database will encourage the use of climate data in the analysis of other vital signs. Rather than data they would have to assemble and develop independently, NPS staff, cooperators, and other researchers are more likely to consistently use a central database that is of high quality and regularly updated, has pulled together climate data from multiple sources, and provides climate metrics at time steps that are key drivers of variability in park natural resources (Kittel et al. 2009). As an additional key benefit, open access permits critical review by outside users, giving another level of quality checking and assurance.

These three reporting products are interconnected, with the trends report providing the long-term context for the status report and data processing for both reports supplying periodic updates to the network climate database. The status and trends reports and the database rely on two initial analyses that we refer to as foundational analyses:

1. *Within-network climate zones.* A delineation of distinct, internally-consistent climate zones within the network domain will be used for reporting climate vital sign status and trends. –SOP: Defining Climate Zones” provides details regarding climate zones. This process is done at the start of protocol implementation, so that climate zones may be used as climate zones for the first status report.
2. *Baseline trends report and the associated high-quality historical network database.* Initial creation of a high-quality historical dataset is needed early to establish (1) the baseline for putting climate status in perspective and (2) the historical record as the basis for variability and trend analyses. This foundation dataset requires careful definition of data requirements matching planned analyses and careful implementation of data quality checking and correction procedures (Kittel et al. 2009).

Foundation tasks are initiated in the start-up year, with climate regionalization feeding into station selection for the historical dataset and status reports (table 6.1). A preliminary database for the first status report is also compiled at this stage. For the first five years, the annual status reports are based on and contribute to this preliminary dataset.

**Table 6.1.** Staging time line, showing timing of foundation, reporting, and database tasks and cross-task data flow (→) for the startup year (Yr 0) and initial and subsequent five-year cycles (see text for description of time line and information flow)

| Task                              | Start-up | First 5 years |      |      |      |             | Subsequent 5-year cycles |      |      |      |             |
|-----------------------------------|----------|---------------|------|------|------|-------------|--------------------------|------|------|------|-------------|
|                                   | Yr 0     | Yr 1          | Yr 2 | Yr 3 | Yr 4 | Yr 5        | Yr 1                     | Yr 2 | Yr 3 | Yr 4 | Yr 5        |
| Foundation I: Regionalization     | x        |               |      |      |      |             |                          |      |      |      |             |
| Foundation II: Historical Dataset | i        |               |      |      | c    |             |                          |      |      |      |             |
| Status Report                     |          | x             | x    | x    | x    | x           | x                        | x    | x    | x    | x           |
| Climate Database                  | i        | p             | p    | p    | p    | full update | p                        | p    | p    | p    | full update |
| Trends Report                     |          |               |      |      | i    | c           |                          |      |      | i    | c           |

i = initiate → c = complete, x = initiate & complete same timeframe, p = preliminary database updates,  
 → cross-task information flow.

Analyses associated with the RMCP can be divided into two categories: those for the status reports are primarily descriptive in nature, and those for the trends reports are statistical tests and require advanced quality control checks prior to being executed. The former can be completed by I&M staff, while the latter are expected to require input from a climatologist. Consequently, this protocol provides more detailed descriptions of analyses and reporting requirements for status reports (–SOP: Status Reports”) and a more general description of the content and quality control process for trend reports (–SOP: Trend Analysis and Reporting”). Both SOPs will be refined over time as the reporting process is repeated.

Analyses and reporting for both the status and trends reports will occur at the scale of points (stations), zones, parks, and an area of interest immediately surrounding parks. The grouping of analyses into status or trend reports will vary by network. Presently, GRYN intends to provide one annual report that covers three park unit and ROMN intends to sequentially generate park-specific climate status reports every 2–3 years for each of six parks. Report presentation and content are expected to change over time to improve efficiency and better meet the needs of park staff. Along this same line, it is expected to take multiple years to get the status reports to their desired level of detail and clarity of presentation. The data acquisition, processing, analysis, and reporting will become streamlined as the report-generating process is repeated, thereby allowing more time for network staff to focus on additional analyses and improving the format of the presentation.

### 6.3 Reporting audience and reporting philosophy

The goal of the RMCP is to produce scientifically sound, consistent, and comparable monitoring information that can be used to support park management and decision making. The NPS seeks to —improve park management through greater reliance on scientific knowledge” (NPS 2008b); the production of reports and effective communication of scientific results serves as the final link in transforming data into information. Our specific internal audiences include (1) park managers, (2) park resource professionals and other park staff, including interpretive staff, (3) the GRYN

and ROMN technical committees, the NPS Intermountain Region, and Service-wide I&M and resource stewardship programs. Our external audiences include: (1) the academic community, (2) other government agencies, (3) nonprofit or non-governmental organizations, and (4) the general public.

We anticipate providing quality assured RMCP data and information including data (non-sensitive), reports including annual reports, synthesis reports, and other products (such as project summaries) via the Internet.

The routine preparation of reports on a predictable and recurring basis of data summaries and basic interpretation can: (1) foster program support by establishing a client base, (2) motivate continued progress in program components, and (3) serve as the foundation for more comprehensive interpretive reports. We are committed to regular reporting of climate information to internal and external audiences to maximize the usefulness of our data. We are also committed to producing only high-quality reports that are based on data that has undergone appropriate quality control measures.

#### **6.4 Climate metrics used in reporting**

The status and trends reports utilize the same metrics that fall into four general categories:

- *Primary metrics.* Key climate metrics directly measured (minimum and maximum temperature, precipitation, and SWE).
- *Integrative metrics.* Variables expressing combined effects of primary metrics (e.g., streamflow, drought). These are either directly measured or derived from primary metrics.
- *Timing metrics.* Measures indicating the timing or length of a seasonal process (e.g., accumulated growing degree days, frosts, peak streamflow). These are calculated from primary or integrative metrics.
- *Secondary.* Other climate-related measures of interest, but currently not covered by the protocol (e.g., lake ice on/off, surface wind, solar radiation). Presently, SOPs for the acquisition, quality control, analysis, and reporting on these measures are not incorporated into the protocol. They may be added in the future as funding and staffing allow. GRYN and ROMN are not likely to find adequate wind or solar radiation data unless the networks establish their own means for collecting these (S. Gray, personal communication in Kittel et al. 2009). Lake ice off dates are collected at Jackson Lake in Grand Teton National Park by the Bureau of Reclamation and are discussed in —SOP Status Reports.”

#### **6.5 Status reports**

The procedures for creating status reports are in —SOP: Status Reports.” In brief, the status reports provide a general summary of climate metrics that are relevant to ecological processes (temperature, precipitation, snowpack, drought, and streamflow) for a specific water year (1 October–30 September) or calendar year (1 January–31 December) with a park-centric view. Results will be reported at multiple scales, from ecoregion down to the station level. In larger parks, reporting will be primarily based on more homogeneous within-network climate zones (discussed in chapter 2 and —SOP: Defining Climate Zones”).

Data acquisition and quality control procedures will be performed according to the methods outlined in the preceding chapters. A framework for processing the status reports is provided in figure 6.1. Data analysis for the status reports is largely descriptive and involves the creation of multiple graphics to aid with data comparisons and interpretation. Reports are expected to contain only essential data in the early years of reporting and to be expanded over time to include optional trend analysis or graphics. “SOP: Status Reports” describes the overall format of the report, as well as the descriptive statistics, graphics and analyses used to develop the narrative portion of the report. Program R code for generating summary statistics and graphics will be provided and maintained on the RMCP Toolbox.

For the most part, status reports only include graphs that pertain to the reporting year(s). Extended discussion, graphics, and tables which cover the full set of analyses, metrics, and zones prepared in each reporting cycle can be made available on the RMCP climate Web site as an online appendix to the report. This will save effort in preparation of physical reports and keep the narrative to the most important annual features and long-term dynamics, while still making more intensive and extension information available to users (as an example, see Western Water Assessment 2009).

The narrative of the status reports integrates information across climate measures. The intent is not to be all inclusive of the data available, but to provide a succinct interpretation of the year’s climate.

An important purpose of the report narrative is to aid with understanding the dynamics of other park resources and reveal areas for further analyses. By highlighting the departures from normal conditions, we may elucidate links between climate and other vital signs. For instance, our status reports may provide an impetus for park or I&M staff to investigate correlations among drought years and invasive cover. The annual report is not intended to provide a comprehensive analysis of climate, a physical understanding of why changes occur, or to determine long-term trends in climate. More detailed trend analysis and syntheses will be conducted every 5–10 years and included in trend reports.

The general content of the annual status report is outlined below. While results are presented by climate measure, the most useful and interesting narrative will integrate information from all measures.

- I.* Outline of status report content
- II.* Executive summary (not to exceed one page)
- III.* Introduction (not to exceed one page)
  - a. Data and analysis methods
  - b. Data sources used
  - c. Quality control measures used on data
  - d. Site documentation or visits completed during the reporting period
  - e. Brief description of and references for data analysis methods
- IV.* Results and discussion
  - a. Status of weather stations: list and map of stations used in short-term (spatial) and long-term (temporal) analyses and data completeness statistics for COOP stations.

Summary of station documentations and site visits. Summary of network dataset and how to obtain data from networks.

- b. Temperature
  - c. Precipitation
  - d. Snowpack
  - e. Drought
  - f. Streamflow
  - g. Correlation among atmospheric indices and climate metrics (*optional* and only included if there are existing long-term reports/baseline)
- V. Summary and conclusions (integrating information across climate measures)
- VI. Literature cited



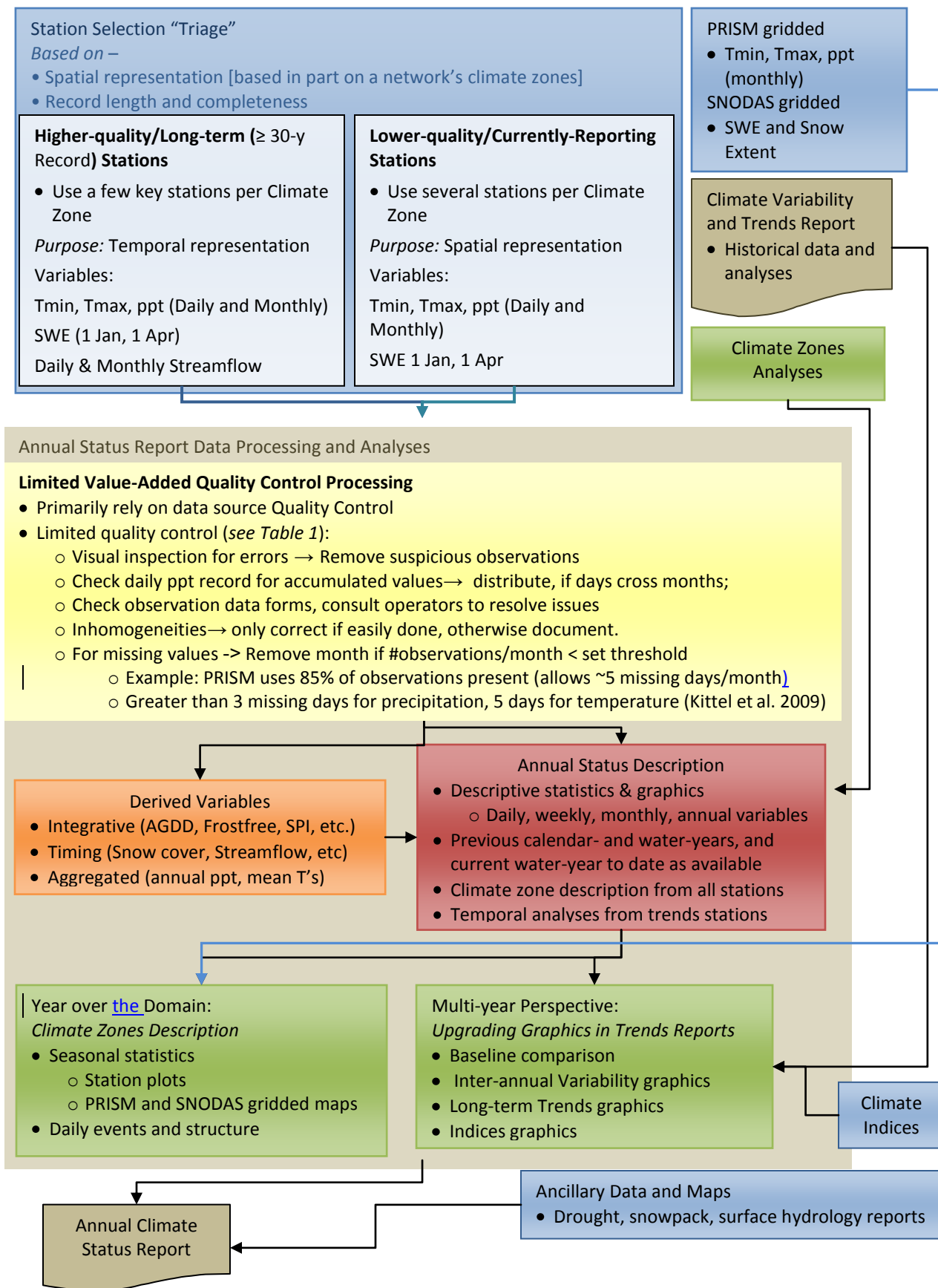


Figure 6.1. Overview of processing for climate status reports (after Kittel et al. 2009).

## **6.6 Inter-annual variability and trends report**

The general procedures for creating inter-annual variability and trends reports (trends reports) are in —SOP Trend Analysis and Reporting.” Trends reports contain a comprehensive and rigorous analysis of only the highest-quality, long-term records from stations relevant to the park or climate zone. The most important difference between the status and trend reports is the level of quality control procedures performed on the data. To avoid potentially reporting erroneous trends in climate variables, we are investing time and expertise in sophisticated quality control measures and rigorous trend analyses. The goal of trend reports will be to determine the status and trends in key climate measures at the park or regional scale. These reports will provide information similar to that provided by Pederson et al. (2010). Historic and current data for selected stations will be assessed for quality and completeness and corrected where necessary by or in consultation with a climatologist. The acquisition, quality control, and analyses will be performed according to the procedures outlined in the preceding chapters. A framework for the trends reports is provided in figure 1 in —SOP Trend Analysis and Reporting.”

Trend reports require a substantial investment in quality control and data management because the datasets used for these analyses require quality control measures and error processing specific to particular analyses (fig. 2 in —SOP Trend Analysis and Reporting”). This necessitates the management of multiple copies of very similar data, with each copy having different quality control depending on the intended analysis. As a result of the high level of quality control required prior to trend analysis, we expect these reports to require expertise beyond that currently held within the I&M Program. As explained in chapter 7, additional climatological expertise may be obtained through collaboration or contracts with climatologists.

Because of the need to develop a robust historic record of climate for each region or park, it is expected that the first synthesis report (the baseline report) will be the most time intensive and require significant time and expertise from a climatologist. All subsequent status reports and synthesis reports may refer to the climate record used in the initial report as the baseline and best record for that region. Where applicable, these comprehensive reports will be submitted for publication in peer-reviewed scientific journals. It is also expected that excerpts from these reports will be used to produce resource briefs highlighting climate change.

Additional information regarding the contents of the inter-annual variability and trends report is provided in —SOP: Trend Analysis and Reporting.”

## **6.7 RMCP climate Web site**

The GRYN and ROMN will develop and maintain online resources for the RMCP in conjunction with each network’s Web and SharePoint sites. These online resources will include all status and trends reports and information on how to access the data used in the creation of the reports, as well as current and archived protocols, standard operating procedures, tools for data processing, links to additional climate information, and data from selected weather stations in the Rocky Mountain region.

## **6.8 Protocol publication and review**

Methodological details of the RMCP protocol will be re-evaluated after 1–2 seasons of data collection and at the completion of a monitoring “cycle” (every 6–10 years). The purpose of the review is to evaluate the procedures and determine where procedures fall short of stated

objectives. These reviews may include suggested modifications to field methods, data analysis, and reporting based on either scientific considerations or budgetary constraints. An official programmatic review of the RMCP approach to vital signs, including the objectives, designs, methods, and results as well as the ability of the network to sustain these protocols, will be conducted after approximately five years. If changes to the protocol are made, these will be included as a new revision and made available in the manner described above.

## **7 Operational Requirements**

This chapter describes required personnel and funding resources, and roles and responsibilities for the RMCP. Staff from both the GRYN and ROMN will continue to collaborate and share resources to implement this protocol and report on climate status and trends.

### **7.1 Project management**

The assigned project leader develops an annual climate monitoring work plan in coordination with the GRYN and ROMN program and data managers as part of annual work planning. Annual planning will address the acquisition, management, analysis and reporting of climate data, and identify needs and projected costs not explicitly defined in this chapter. Depending on the scope and breadth of proposed work plan objectives, the project leader may also prepare proposals for alternative funding sources that can be leveraged with NPS vital signs monitoring funds.

### **7.2 Climate status reports**

Climate status reports are completed by network staff or cooperators. GRYN intends to produce a single climate status report every year for its parks, while ROMN expects to deliver status reports for individual parks on a 2–3 year cycle. At the point where status reports can become more automated, ROMN will provide them annually. The climate status reports cover the previous calendar (January–December) year(s) for temperature, precipitation and drought, and the previous water year(s) (October–September) for snowpack, SWE, and streamflow. A generalized schedule for completing the climate status report is given in table 7.1. Most report preparation takes place between February and May as data become available. For example, data from NWS COOP stations may not be accessible for download until four months after it was collected.

**Table 7.1.** Approximate schedule for completing the climate status report

| <b>Timing</b>          | <b>Activity</b>  | <b>Responsibility</b>                  |
|------------------------|--|--|
| <b>October–January</b> | • Determine annual budget  | Program manager and project leader     |
|                        | • If applicable, prepare task agreements with cooperators          | Program manager                        |
| <b>February–April</b>  | • Acquire data   | Data manager                           |
|                        | • Perform data quality control and documentation                   | Data manager (lead) and project leader |
|                        | • Analyze climate data   | Project leader                         |
|                        | • Prepare status report(s)   |  |
| <b>April–May</b>       | • Update project metadata records for previous year                | Data manager                           |
|                        | • Review draft reports   | Program manager                        |
|                        | • Publish annual reports   | Project leader                         |
|                        | • Prepare resource briefs  |  |
|                        | • Upload certified data and reports to NPS enterprise data systems | Data manager                           |
|                        | • Upload reports on network Web sites                              |  |
| <b>June</b>            | • Review and revise protocol narrative and appendices              | Project leader (lead)                  |
|                        | • Review and revise SOPs   | Project leader and data manager        |
|                        | • Review and revise project database                               | Data manager                           |
| <b>September</b>       | • Close out year-end budget and prepare administrative reports     | Program manager                        |

### 7.3 Climate trends and inter-annual variability reports

This report will be produced on a 5–10 year cycle to present rigorous analyses of inter-annual variability, long-term historical trends, and to describe connections between local climate trends with hemispheric climate patterns (e.g., the PDO). The first or baseline report establishes an initial understanding of inter-annual variability. Substantial time and expertise is required to process, analyze, and interpret data for trend reports, including the assessment and documentation of every weather station from which data is used for trend reports. Completing this work will require networks to collaborate and cost-share with climate experts and others who have a mutual interest in rigorously reporting long-term historical climate trends and inter-annual variability.

Defining climate zones and then selecting stations for use in trend reports are the first steps in preparing the initial trend reports. Documenting the history and status of each weather station and conducting station field visits are other important steps that can begin immediately. Complete and comprehensive station documentation is required (“SOP: Weather Station Visits and Documentation”) before data quality control or data analysis is started. The framework for

completing the prerequisites and production of reports are presented in table 7.2. While park staff or staff from other agencies are responsible for conducting maintenance on climate monitoring stations, the site visits described in this protocol will be conducted by network staff, accompanied by a climatologist or similar subject-matter expert. Only stations used for status and/or trend reporting will be included in this effort.

**Table 7.2.** Prerequisite and steps for completing the first trend and inter-annual variability reports

| Activity type                      | Activity description  | Schedule               |
|------------------------------------|---|------------------------|
| Defining climate zones             | <ul style="list-style-type: none"> <li>Conduct analysis to identify internally coherent, within-network climate zones to serve as meaningful climate zones. See —OP: Defining Climate Zones.”</li> </ul>  | Prior to data analysis |
| Station selection                  | <ul style="list-style-type: none"> <li>Select a few high-quality weather stations to represent each climate zone or park. See –SOP: Station Selection.”</li> </ul>  | Prior to data analysis |
| Climate station records            | <ul style="list-style-type: none"> <li>Compile and archive a history for each station from which data is used for trend reporting following –SOP: Weather Station Visits and Documentation.”</li> </ul>   | Prior to data analysis |
| Climate station records            | <ul style="list-style-type: none"> <li>Repeat site visit and update station history every two to three years following –SOP: Station Visits and Documentation.”</li> <li>Communicate needs for station or equipment maintenance to the responsible agency.</li> </ul>   | Biannual               |
| Data acquisition                   | <ul style="list-style-type: none"> <li>Acquire data required for trend reporting from stations selected for use in trend reporting following —SOP: Station Selection” and –SOP: Data Acquisition.”</li> </ul>   | Prior to data analysis |
| Quality control/ quality assurance | <ul style="list-style-type: none"> <li>Follow —SOPQuality Control” and maintain/document versions at each stage where data is modified.</li> <li>Acquire access to original or copied B-91 forms (original written weather observation values) to allow comparisons between original and electronic versions of data sets.</li> </ul> | Prior to data analysis |
| Data analysis and reporting        | <ul style="list-style-type: none"> <li>Analyze and report on climate data for inter-annual variability and long term trends following —SOP: Trend Analysis and Reporting.”</li> </ul>   | Periodic               |

## 7.4 Personnel requirements

An I&M network project leader is responsible for project planning and coordination and to perform or oversee data analysis and report preparation. General roles and responsibilities for this protocol are summarized in table 7.3. Each network assigns these responsibilities to network staff and/or cooperators. During annual work planning, the networks may choose to implement this protocol in coordination (sharing funding and staff to do the monitoring) or separately.

**Table 7.3.** Roles and responsibilities for climate monitoring

| RMCP role                  | Responsibilities   | Network position |
|----------------------------|--|------------------|
| <b>Administrative lead</b> | <ul style="list-style-type: none"> <li>• Provides program oversight and administration</li> <li>• Tracks and reports project budget, requirements, objectives, and progress toward meeting objectives</li> <li>• Serves as NPS key official, agreement technical representative, contracting officers technical representative on agreements or contracts for climate monitoring work</li> <li>• Facilitates communication between NPS climate project leader and collaborators</li> <li>• Reviews reports and other products for completeness and compliance with I&amp;M Program guidance and specifications</li> <li>• Liaison to WASO programs, offices, and other I&amp;M networks</li> </ul>                       | Program manager  |
| <b>Project leader</b>      | <ul style="list-style-type: none"> <li>• Plans and coordinates project operations, namely the acquisition, analysis and reporting of climate data</li> <li>• Performs or oversees maintenance and archiving of project records</li> <li>• Prepares data summaries and analytical results</li> <li>• Interprets data and prepares reports and other products (posters, Web site content, etc.)</li> <li>• Identifies need for advanced technical assistance in analysis and interpretation of data and prepares scope of work for agreements and/or contracts</li> <li>• Coordinates and ratifies changes to the protocol</li> </ul>  | Ecologist        |
| <b>Data manager</b>        | <ul style="list-style-type: none"> <li>• Advises on data and information management activities</li> <li>• Acquires, organizes, manages, and process data in preparation for analysis, distributions, and archiving</li> <li>• Post data, metadata, reports, and other products to NPS enterprise data storage and delivery systems and network Web sites</li> <li>• Maintains and updates database applications</li> <li>• Provides data management training as needed</li> <li>• Consults on spatial analysis techniques</li> <li>• Develops or oversees development of spatial data sets and maps</li> <li>• Prepares or oversees development of metadata for spatial and tabular data sources and products</li> </ul> | Data manager     |

## 7.5 Qualifications

Each position identified in table 7.3 requires minimum background knowledge, skills, and abilities. The project leader must be familiar with methods to provide climate data that is useful to national park managers. This includes sample design, data requirements, data processing, and quality assurance methods, analysis tools and approaches, and professional written and verbal communication of scientific results and ideas. The project leader and/or cooperators with subject-matter expertise will apply data preparation and computer analysis techniques that meet current standards of the climate science community. The administrative lead must be familiar with the standards and requirements for the NPS I&M Program and use of cooperative and interagency agreements. The data manager must work with the project lead to understand and provide for climate data input and processing requirements, related database applications, tools and procedures, basic Web site design and/or maintenance, and metadata production tools. Personnel in this position must have a working knowledge of Microsoft Access database and ESRI geodatabases.

The production of trend and inter-annual variability reports requires climate science expertise (Kittel et al. 2009). If the networks do not have a climate expert either on staff or available through a collaborator, creating these reports will require obtaining outside expertise.

### **7.6 Training**

If cooperative agreements are used, personnel in this position must have completed the NPS Agreement Technical Representative training. No additional explicit training requirements have been identified.

### **7.7 Facility and equipment needs**

This protocol requires no specialized equipment or facilities. Standard field equipment is required for station visits and documentation, including a modern digital camera and recreational-type GPS receiver capable of position averaging. The administrative lead ensures that office space and computer equipment and software are available for the project leader and data manager.

### **7.8 Budget**

Each network's annual fixed cost budget is expected to cover facilities, computer hardware and standard software, and travel expenses and salary for existing network positions with roles and responsibilities for climate monitoring (program manager, data manager, and ecologist). Due to the pre-analysis requirements and the need to meet the existing standards of the climate science community when preparing climate trend and variability reports, the portion of each network's annual budget available for climate monitoring is not expected to cover all costs associated with preparing trend reports. Networks will work with their park committees and partners to determine and program the funds required to complete initial and subsequent trend reports. Factors affecting the annual cost of implementing this protocol include paying for help from cooperators, hiring personnel to fill staffing requirements for the project, the number of stations included in the reports, and the schedule on which the initial trend and variability report is due.

### **7.9 Revising the protocol**

The protocol will be reviewed and improved in conjunction with preparing the climate summary report and the climate trend and inter-annual variability report. This may be on a one, two, or three year cycle depending on the network. The project leader and others will review the narrative, SOPs, associated database, and other products. Changes are logged according to procedures outlined in the following section.

The protocol narrative and each SOP contain a revision history log that is completed for each change to explain reasons for changes, and to assign a new version number to the revised SOP or narrative. Careful documentation of changes to the protocol and a library of previous protocol versions are essential for maintaining consistency in data acquisition and for appropriate treatment of the data during data summary and analysis.



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## Appendix A: Data Sources

### Acronyms

|        |   |
|--------|---|
| AMO    | Atlantic Multi-decadal Oscillation                          |
| COOP   | Cooperative Observer Network                                |
| ENSO   | El Niño-Southern Oscillation                                |
| NAO    | North Atlantic Oscillation                                  |
| NCDC   | National Climatic Data Center                               |
| NWS    | National Weather Service                                    |
| NOHRSC | National Operational Hydrologic Remote Sensing Center       |
| NRCS   | Natural Resources Conservation Service                      |
| NSIP   | National Streamflow Information Program                     |
| PDO    | Pacific Decadal Oscillation                                 |
| PDSI   | Palmer Drought Severity Index                               |
| PNA    | Pacific/North American pattern                              |
| PRISM  | Parameter-elevation Regressions on Independent Slopes Model |
| SNODAS | Snow Data Assimilation System                               |
| SNOTEL | Snowpack Telemetry  |
| SOI    | Southern Oscillation Index                                  |
| SWE    | snow water equivalent                                       |
| TNH    | Tropical-Northern Hemisphere                                |

### A.1.1 Introduction

The approach of the Rocky Mountain Climate Protocol is to acquire data from existing national climate monitoring programs that provide consistent, long-term, and high-quality climate records for our regions and provide the critical steps of summarizing, reporting, and interpreting status and trends in climate at the parkscale. Here, we describe the purpose, type of data, and strengths and limitations of each of these national climate monitoring programs including the National Weather Service Cooperative Observer Network, Natural Resource Conservation Service Snowpack Telemetry and Snow Course programs, U.S Geological Survey gauging stations, the Parameter-elevation Regressions on Independent Slopes Model, Snow Data Assimilation System, drought indices, and atmospheric and oceanic indices.

### A.1.2 Cooperative Observer Program

The National Weather Service (NWS) daily Cooperative Observer Network (COOP) Stations have been a foundation of the U.S. climate program for decades and has long served as the main climate observation network in the United States. COOP stations are established, supervised, and inspected by NWS personnel. Manual stations require recording of climate observations on a daily basis. 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 U.S. Historical Climatology Network (<http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn.html>) is a subset of the cooperative network but contains longer (80 years or more) and more complete records. The mission of the COOP, created in 1890, is: (1) to provide observational meteorological data required to define U.S. climate and help measure long-term climate changes; and (2) to provide observational meteorological data in near real-time to support forecasting and warning

mechanisms and other public service programs of the NWS (NWS 2009). Surface Airways Observation Network sites are also monitored within this network and are a subset of stations located at major airports and military bases.

The COOP provides national coverage with more than 11,000 volunteers, which in some cases include National Park Service employees. Observers record temperature and precipitation data daily. Data are reported daily or monthly (depending on the station) to the National Climatic Data Center (NCDC) or an NWS office. 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. Observations include: daily maximum and minimum temperature, daily observation-time temperature, daily liquid precipitation, snowfall and snow depth, and pan evaporation (at some stations). Additional measurements may include river stage and special phenomena, such as hail and damaging winds.

Although some COOP stations have electronic instrumentation, they lack automated transmission capability. Daily observations are obtained by personnel directly reading the instruments (e.g., min-max thermometers and rain gauges) or by reading digital displays connected to electronic sensors. Procedures for reading instrumentation as well as for the maintenance and calibration of equipment performed by the cooperative observer are described in "Observing handbook no.2: Cooperative station observations" (NWS 1989). Cooperative observers also report damaged or defective equipment and instruments to the NWS representative, who informs the observer about arrangement of repair or replacement.

Data from COOP stations are transmitted to designated regional offices of the NWS immediately after the 24-hour temperature and precipitation observations are recorded. Observations are transmitted by phone to a recording device where the observer is prompted by a machine for specific information. The NCDC receives all monthly reports from the observer or the NWS, transcribes the data from paper copies to electronic databases where necessary, archives the data, and distributes error-checked daily values to cooperating agencies (e.g., regional climate centers).

Strengths of the COOP data include: long-term records at most sites (i.e., decades to a century); a widespread national coverage with thousands of stations; excellent data quality when stations are well maintained; it is cost-effective, and manually-taken measurements (which can eliminate problems with equipment and remote communications). Limitations of the COOP include: daily rather than hourly observation, uneven exposures, many stations are not well-maintained, a dependence on schedules of volunteer observers, slow entry of data from many stations into national archives, data are subject to observational methodology, which is not always documented, and manual measurements (there is an increase in variation among stations caused by observers, as opposed to automated recorders).

### **A.1.3 Snowpack Telemetry (SNOTEL)**

The U.S. Department of Agriculture Natural Resources Conservation Service (NRCS) maintains a set of automated snow monitoring stations known as the Snowpack Telemetry (SNOTEL) network (NRCS 2009a). These stations, designed specifically for cold and snowy locations, measure daily precipitation and snow water content. Data are intended for hydrologic



applications and water-supply forecasting, so these measurements are recorded generally to within 2.5 millimeters (0.1 in), and snow depth is tracked to the nearest 25 millimeters (or 1 in). Most data records began during or after the mid-1970s. Many modern SNOTEL sites record hourly data. These stations function year around. The purpose of the network is to collect snowpack and related climate data to assist in forecasting water supply in the western United States, as well as supporting resource management activities of the NRCS and other agencies.

There are over 750 automated SNOTEL stations in 13 states in the West, including Alaska. The weather or climate elements measured are: air temperature (with daily maximums, minimums, and averages), precipitation, snow water equivalent (SWE), snow depth, relative humidity (enhanced sites only), wind speed and direction (enhanced sites only), solar radiation (enhanced sites only), and soil moisture and temperature (enhanced sites only). Stations record data at the following sampling frequencies: one minute for temperature, and one hour for precipitation, snow water content, and snow depth; and less than one minute for relative humidity, wind speed and direction, solar radiation, and soil moisture and temperature (the latter group at enhanced site configurations only). Data reporting intervals are user-selectable. Commonly used intervals are every one, two, three, or six hours. Data from SNOTEL can be found at: <http://www.wcc.nrcs.usda.gov/snow/>.

SNOTEL stations are fully automated and designed to operate unattended and without maintenance for a year or longer with batteries charged by solar cells. Access for maintenance can involve hiking, snowmobiles, skiing, snowshoes, or helicopters.

Data from SNOTEL stations are transmitted in real-time using meteor burst communications technology. This involves the use of VHF radio signals which are reflected at a steep angle off the ever-present band of ionized meteors existing from about 50–75 miles above earth. Three meteor burst master stations are the central collection points for all transmitted remote station data. These master stations are located near Boise, Idaho; Ogden, Utah; and Anchorage, Alaska. When the data are received, it is converted to engineering units and screened for errors, then stored in a database and made available to the public (NRCS 2009). Data reporting intervals are user-selectable. Commonly used intervals are every one, two, three, or six hours.

Strengths of the SNOTEL network are that sites are located in high-altitude areas that typically do not have other weather or climate stations. Also, data are of high quality and are largely complete, and the automated system is very reliable. Limitations include: historically, there are a limited number of metrics reported; sites are remote, so data gaps can be long; metadata are sparse and not high quality; the instrument error can be large; site histories are lacking; measurement and reporting frequencies vary; many hundreds of mountain ranges remain unsampled; and the period of record is relatively short (earliest stations were installed in the late 1970s and temperatures have been recorded since the 1980s).

#### **A.1.4 Snow Course**

The Snow Course program is managed by the U.S. Department of Agriculture NRCS. Sampling sites in this program (or courses, about 1,000 ft long) are manual sites, where trained observers measure only snow depth and snow water content (NRCS 2009b). Measurements are taken one to two times per month during the winter and spring. Data records for these sites often extend back to the 1920s or 1930s, and the data are generally of high quality. Data can be obtained at:

<http://www.wcc.nrcs.usda.gov/snowcourse/>. The purpose of the network is to collect snowpack and related climate data to assist in forecasting water supply in the western United States.

Snow Course data are available for 13 western states, including Alaska. The frequency of sampling is monthly or seasonally from January to June. Measurements include only snow depth and SWE. Advantages of this program are that the periods of record are generally long. Many of the sites have been in operation since the early part of the twentieth century. There are also a large number of high-altitude sites. The limitations include: measurements/reporting only occur on a monthly to seasonal basis, few weather/climate elements are measured, and the sampling sites are all manual sites.

### **A.1.5 U.S. Geological Survey (USGS) Gauging Stations**

The U.S. Geological Survey (USGS) has long operated a collaborative national network of stream gauging stations to meet federal, state, and local user needs for information on streamflows (USGS 2009). The network is currently funded in partnership with over 800 agencies. Approximately 7,500 stream gauges are used to provide long-term, accurate, and unbiased information on streamflow. Recently, the USGS announced a new program, the National Streamflow Information Program (NSIP), which includes improvements to the stream gauging infrastructure, a new funding mechanism, additional measurements of floods and droughts, and improved systems for monitoring and disseminating streamflow information. The NSIP plan provides for a stable, modernized stream gauging network that addresses core federal and cooperator needs, and it provides for: collecting vital information during droughts and floods, periodic assessments of streamflow characteristics to evaluate the effects of changes in climate and land-use, developing a highly reliable system for delivering data to users, and implementing a research and development program to produce better data-collection, delivery, and interpretation capabilities for the future.

Across the nation, there are approximately 25,000 sites with gauges that report a summary of daily values for streamflow and over 8,500 stations report real-time, time-series data on flow (recorded at fixed intervals) from automated equipment. These data represent the most current hydrologic conditions. Measurements are recorded at 5–60 minute intervals and transmitted to the National Water Information System (NWIS) database every 1–4 hours. Real-time data are available online for a period of 31 days. On an annual basis, USGS publishes daily streamflow data in a series of water-data reports. Time-series data describe: streamflow (discharge), stream levels, reservoir and lake levels, precipitation, and surface-water quality.

Strengths of the USGS Gauging Stations and NSIP include: long-term records at many sites, a widespread national coverage with thousands of stations, accurate and unbiased information, and real-time data that can be easily obtained online. If the NSIP meets its goals, it will address the current network weaknesses, which include instability in the network due to a heavy reliance on partner funds (which can result in year to year changes in stream gage operations including the discontinuation of gages). The NSIP, if adequately funded, would also upgrade additional stream gages to provide near real-time data delivery capabilities, and improve the overall delivery of information to users.

### **A.1.6 Parameter-elevation Regressions on Independent Slopes Model (PRISM)**

Parameter-elevation Regressions on Independent Slopes Model (PRISM; Oregon State University 2007) is a climate mapping system that uses point measurements of precipitation, temperature, and other climatic factors to produce continuous, digital grid estimates of monthly, yearly, and event-based climatic parameters. Data extends back to 1895. It is offered at numerous spatial scales with the 800-meter grid being both free and of reasonably high resolution. The greatest utility of PRISM is that it presents the spatial distribution of temperature and precipitation, which single point observations are unable to provide. The model was originally developed to provide climate information at scales matching available land-cover maps to assist in ecological modeling and 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 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 records. 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. Data include: precipitation, maximum temperatures, minimum temperatures, dew point temperatures, and percent of normal precipitation.

The maps produced through PRISM have undergone rigorous evaluation in the western U.S. and are recognized as being high-quality spatial climate data sets. PRISM incorporates point data, a digital elevation model, and expert knowledge of climate extremes. Although PRISM data sets were developed through projects funded, in part, by the federal government, there is not much funding for the maintenance and expansion of the data sets. Data may be available for a limited time only.

### **A.1.7 Snow Data Assimilation System (SNODAS)**

Snow Data Assimilation System (SNODAS) (National Operational Hydrologic Remote Sensing Center [NOHRSC]) integrates surface-based and remotely sensed observations to create a daily 1-kilometer gridded dataset that includes snow depth, SWE, and snow extent (Barrett 2003). The system serves to support hydrologic modeling and analysis, and data are available starting from 2003. SNODAS, while not useful for long-term analyses, provides a useful spatial representation of snow cover and SWE for each season. Thus, it complements the SNOTEL data. The intent of SNODAS is to provide a physically consistent framework to integrate snow data from satellites, airborne platforms, and ground stations with model estimates of snow cover (Carroll et al. 2001).

The snow model has high spatial (1 km) and temporal (1 hour) resolutions and is run for the conterminous United States. SNODAS is run each day. The National Snow and Ice Data Center archives the following metrics: (1) SWE or liquid and solid water in the pack, (2) snow depth, (3) snow melt runoff at the base of snowpack, (4) sublimation from the snowpack, (5)

sublimation of blowing snow, (6) solid precipitation, (7) liquid precipitation, and (8) snowpack average temperature.

The strengths of SNODAS include that it enables basin-scale analyses and it is spatially continuous. Limitations of SNODAS include: the system is intended more for research than as an operational dataset; it covers a short period of record; the combination of observations and model make verification difficult since observations are part of the output; there is uncertainty with satellite-derived snow cover maps where trees are present; the model is less accurate in complex terrains and locations are further away from SNOTEL stations.

### **A.1.8 Drought Indices**

There are a number of drought indices used to estimate the severity of drought in an area using algorithms that incorporate recent temperatures, rainfall, and soil moisture. The main indices we will report on are the Palmer Drought Severity Index (PDSI), the Standardized Precipitation Index (SPI), and Drought Monitor.

#### **A.1.8.1 Palmer Drought Severity Index (PDSI)**

PDSI is a soil moisture algorithm calibrated for relatively homogeneous regions and was the first comprehensive drought index developed in the United States (Palmer 1965). In 1989, a modified method to compute the PDSI was begun operationally (Heddinghaus and Sabol 1991). This modified PDSI differs from the PDSI during transition periods between dry and wet spells. The PDSI is calculated based on precipitation and temperature data, as well as the local available water content of the soil. The values vary between extremely wet ( $>4$ ) and severe drought ( $<-4$ ). Ideally, the Palmer Index is designed so that a  $-4.0$  in South Carolina has the same meaning in terms of the moisture departure from a climatological normal as a  $-4.0$  in Idaho (Alley 1984).

The PDSI has typically been calculated on a monthly basis, and a long-term archive of the monthly values for every climate division in the United States exists with the NCDC from 1895 through the present. There are considerable limitations to using PDSI because values may lag emerging droughts by several months; it is less well suited for mountainous land or areas of frequent climatic extremes; snowfall, snow cover, and frozen ground are not included in the index. and it is complex—has an unspecified, built-in timescale that can be misleading. However, despite these drawbacks it is widely reported and used to monitor drought and trigger relief programs.

#### **A.1.8.2 Standardized Precipitation Index (SPI)**

The SPI is an index based on the probability of precipitation for any timescale (McKee et al. 1993). The SPI calculation for any location is based on the long-term precipitation record for a desired period. This long-term record is fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero (Edwards and McKee, 1997). McKee et al. (1993) originally calculated the SPI for 3-, 6-, 12-, 24-, and 48-month timescales and it can provide early warning of drought and help assess drought severity. The values range from extremely wet ( $>2$ ) to extremely dry ( $<-2$ ) where positive SPI values indicate greater than median precipitation, and negative values indicate less than median precipitation. A drought event occurs any time the SPI is continuously negative and reaches an intensity of  $-1.0$  or less. The event ends when the SPI becomes positive. Each drought event, therefore, has a duration defined by its beginning and end, and an intensity for each month

that the event continues. The positive sum of the SPI for all the months within a drought event can be termed the drought's "magnitude." For Colorado, 2.3% of SPI values are within the "Extreme Drought" category which is a percentage that is typically expected for an "extreme" event (Wilhite 1995). In contrast, the PDSI reaches its "extreme" category more than 10% of the time across portions of the central Great Plains. For this reason and because of the limitations of PDSI in snowy environments, the SPI is the preferred metric for this protocol.

The SPI is being monitored at the climate division level for the contiguous United States by the National Drought Mitigation Center and the Western Regional Climate Center  
[http://drought.unl.edu/monitor/spi/program/spi\\_program.htm](http://drought.unl.edu/monitor/spi/program/spi_program.htm).

### **A.1.9 Atmospheric Indices**

Long-term and large-scale atmospheric and ocean variations play a key role in understanding and predicting intra-seasonal and inter-annual variations in climate (CPC 2005a). For instance, the Pacific Decadal Oscillation (PDO) which represents variation in sea surface temperature and atmospheric pressure in the northern Pacific Ocean correlates with the occurrence of drought induced fires in the Rocky Mountains (Schoennagel et. al 2005). Some of the key variations relevant to Greater Yellowstone and Rocky Mountain networks include the North Atlantic Oscillation (NAO; Wang et al. 2002), PDO (Gray et al. 2003, Westerling and Swetnam 2003), Pacific/North American pattern (PNA; Barnston and Livezey 1987), El Niño-Southern Oscillation (ENSO; described using the Southern Oscillation Index [SOI]; Gray et al. 2003; Schoennagel et al. 2005) and the Atlantic Multi-decadal Oscillation (AMO; Gray et al. 2003), and the Tropical-Northern Hemisphere (TNH). Below we describe the indices we may use to determine if there are correlations among them and long-term climate patterns in our parks. In all cases, the indices are calculated by another entity. We will acquire the monthly or annual data and correlate these global scale indices to other regional or local climate.

#### **A.1.9.1 Southern Oscillation Index (SOI)**

The SOI is calculated by the NWS Climate Prediction Center from the monthly or seasonal fluctuations in the air pressure difference between Tahiti and Darwin, Australia. The index is most commonly computed on a monthly basis and ranges from about -3 to +3. The anomaly is based on the period of 1951–1980 and calculated as the difference between a standardized Tahiti and Darwin pressure (for more details see:

<http://www.cpc.ncep.noaa.gov/data/indices/Readme.index.shtml#SOICALC>).

Prolonged periods of negative SOI values coincide with abnormally warm ocean waters across the eastern tropical Pacific typical of ENSO episodes. Prolonged periods of positive SOI values coincide with abnormally cold ocean waters across the eastern tropical Pacific typical of La Niña episodes (CPC 2005b). ENSO episodes are associated with wetter than normal conditions during June–August in the intermountain regions of the United States and most of regions experience abnormally warm conditions during December–February.

#### **A.1.9.2 Atlantic Multi-decadal Oscillation (AMO)**

The AMO is an index of the sea surface temperatures in the northern Atlantic Ocean that is calculated from the Kaplan sea-surface temperature anomalies (Kaplan et al. 1998) using a baseline of 1950–1981. It is reported on a monthly basis and varies between approximately -0.75 and +0.75 and runs on approximately a 70-year cycle with cool and warm phases. The warm

phase of the AMO corresponds with less than normal rainfall in the summer in the central and Southern Rockies (Enfield et al. 2001).

#### **A.1.9.3 Pacific Decadal Oscillation (PDO)**

The PDO is a pattern of climate variability based on sea surface temperatures in the North Pacific Ocean (Zhang et al. 1997, Mantua et al. 1997). The monthly mean global average SST anomalies are removed to separate this pattern of variability from any “global warming” signal that may be present in the data. The PDO shows 20–30 year phases of cool or warm sea temperatures. Positive PDO values, or warmer sea temperatures, are usually associated with wetter conditions in the southwestern United States, while negative PDO values are suggestive of persistent drought in the southwest (Webb et al. 2000).

#### **A.1.9.4 Pacific/North American Pattern (PNA)**

The Pacific/North American teleconnection pattern (PNA) describes the atmospheric circulation in the Pacific and North America (CPC 2005c). The PNA pattern is associated with strong fluctuations in the strength and location of the East Asian jet stream. The positive phase is associated with an enhanced East Asian jet stream and with an eastward shift in the jet exit region toward the western United States. The positive phase of the PNA pattern is associated with above-average temperatures over western Canada and the extreme western United States, and below-average temperatures across the south-central and southeastern U.S. The PNA tends to have little impact on surface temperature variability over North America during summer. The associated precipitation anomalies include above-average totals in the Gulf of Alaska extending into the Pacific northwestern United States, and below-average totals over the upper Midwestern United States.

Although the PNA pattern is a natural internal mode of climate variability, it is also strongly influenced by the ENSO phenomenon. The positive phase of the PNA pattern tends to be associated with Pacific warm episodes (El Niño-Southern Oscillation), and the negative phase tends to be associated with Pacific cold episodes (La Niña).

#### **A.1.9.5 Tropical-Northern Hemisphere (TNH)**

The TNH pattern reflects large-scale changes in both the location and eastward extent of the Pacific jet stream, and also in the strength and position of the climatological mean Hudson Bay Low (CPC 2005d). The TNH significantly modulates the flow of marine air into North America, as well as the southward transport of cold Canadian air into the north-central United States.

The positive phase of the TNH pattern is associated with below-average surface temperatures throughout the western and central United States, and across central and eastern Canada. It is also associated with above-average precipitation across the central and eastern subtropical North Pacific, and below-average precipitation in the western United States and across Cuba, the Bahama Islands, and much of the central North Atlantic Ocean.

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