DRAFT

Climate Monitoring Protocols for the Greater Yellowstone Network:

Bighorn Canyon National Recreation Area, Grand Teton National Park (including J.D. Rockefeller, Jr. Memorial Parkway), and Yellowstone National Park

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SUMMARY

This document explains the rationale, motivations and procedures for monitoring climate within the Greater Yellowstone Network (GRYN). This document focuses on using a network of climate stations in the GRYN to determine:

1. How climate in the parks of the GRYN varies at different spatial and temporal scales relevant to the management of natural resources, natural hazards and the dynamics of other vital signs.
2. If the climate of the GRYN has changed significantly from that of past decades to centuries as a result of natural or anthropogenic forcing.
3. If significant changes in GRYN climate are detected, do these changes warrant specific research or management actions to monitor or predict their effects on natural resources and other vital signs?

The protocols consist of a narrative and appendices describing standards and operating procedures for the network. The narrative first defines objectives for the GRYN climate-monitoring program and the specific parameters to be monitored. This theme continues with a discussion of technical issues related to monitoring GRYN climate. The narrative then recounts the development of the existing climate-monitoring network within the GRYN, and explores the ability of this legacy network to meet the protocol objectives. Recommendations for updating and improving the legacy network follow. These recommendations include:

1. A policy calling for no loss of climate monitoring stations with long, continuous records from the parks of the GRYN and surrounding areas.
2. Adding stations in locations and strata of interest that area not adequately sampled by the current network (e.g. high elevations and whitebark pine communities).
3. Upgrading some existing stations to new NWS-COOP standards.
4. Designation of a climate program manager to oversee climate monitoring, reporting and data transfer in the GRYN.

The narrative also describes future research needed to improve climate monitoring in the GRYN and to better understand the links between climate and physical/biological processes in the region.

The technical specifications and procedures discussed in the narrative and appendices should be viewed as general guidelines rather than rigid standards for climate monitoring in the GRYN. Most of the climate monitoring stations within the GRYN are operated by agencies other than NPS (e.g. NRCS, NOAA, EPA), and each of these agencies has their own set of standards and procedures. Given the broad range of elevation and the extreme environmental conditions encountered at sites in GRYN, installation and equipment issues should be

considered on a case-by-case basis. Information on suitable climate monitoring equipment is also included in the appendix.

List of Key Acronyms Used in this Document:

BICA	Bighorn Canyon National Recreation Area
CAKN	Central Alaska Network
EPA	Environmental Protection Agency
GRYN	Greater Yellowstone Regional Network
GTNP	Grand Teton National Park
GYE	Greater Yellowstone Ecosystem
NCDC	National Climatic Data Center
NEON	National Ecological Observatory Network
NOAA	National Oceanic and Atmospheric Administration
NOAA-CRN	NOAA-Climate Reference Network
NPN	National Phenological Network
NRCS	Natural Resources Conservation Service
NWS	National Weather Service
NWS-COOP	NWS-Coopertive Observer Program
NWS-SOP	NWS-Surface Observer Program
RAWS	Remote Automated Weather Station
SNOTEL	Snowpack Telemetry Stations (Operated by NRCS)
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WRCC	Western Regional Climate Center
YNP	Yellowstone National Park

1. BACKGROUND AND OBJECTIVES

1.1 Issue Being Addressed

In its most basic sense, the term “weather” refers to the condition of the atmosphere at a specific point in time or during a short-lived (minutes to days in length) atmospheric event (Hartman, 1994; Burroughs, 2003). “Climate” is the aggregate of weather conditions for a location or region. Because the goals of the NPS Inventory and Monitoring Program are to develop baseline datasets for environmental conditions within each park unit and to look for changes in these conditions, the protocols described here are focused on climatic elements rather than weather. More specifically, these protocols center on providing data (e.g. average annual temperatures, average summer rainfall, etc.) that can be used to quantify and characterize the past, current and future climate of the parks encompassed by the Greater Yellowstone Network (GRYN; Fig. 1), and on supplying information related to regional climatic variability for applications in science and management. Persistent events such as droughts, heat waves, and severe winters are key features of the climate in a given area, so these protocols are designed to capture climatic extremes as well as representative features of seasonal to decadal variability. However, the in the current context, the study of weather cannot be reasonably separated from these objectives, so elements of short-term atmospheric variability are also briefly addressed.

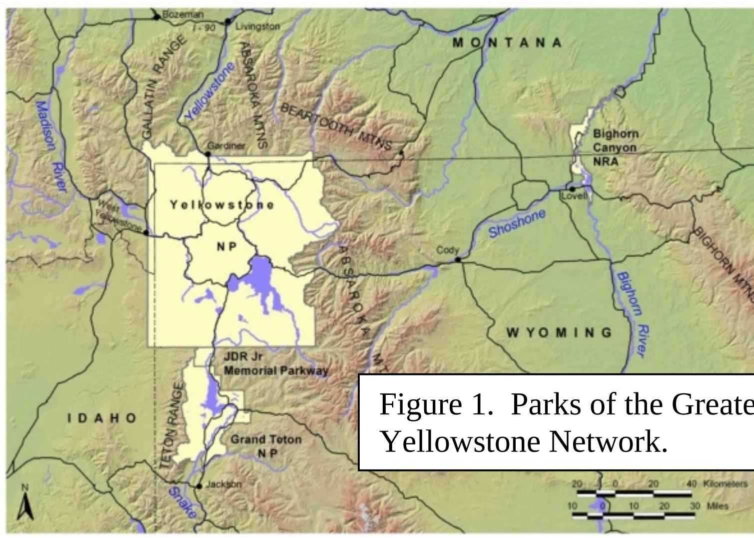

Figure 1. Parks of the Greater Yellowstone Network.

1.2 Overview: Climate of the GRYN

As a whole, the climate of the GRYN is marked by tremendous spatial and temporal variability. Areas within Yellowstone National Park, for example, experience significant differences in seasonal moisture-regimes related to topographic constraints (Whitlock and Bartlein, 1993). The Snake River meteorological station near the park’s south entrance experiences peak precipitation from December through February as Pacific moisture enters the area via winter storm tracks (Mock 1996). In combination, these three winter months account for nearly 40% of the station's total annual precipitation (http://www.wrcc.dri.edu/climsum.html). Though far from having a dry summer by most western U.S. standards, June, July and August provide only 17% of the total annual precipitation at the Snake River station. In contrast, the meteorological station at Mammoth (referred to as "Yellowstone National Park, WY" by the NWS) sees 40% of its total annual precipitation in May, June and July, and just 18% of the annual total from December through February. Orographic effects also account for large differences in total precipitation amounts- on average, Snake River station receives 811 mm/year (water equivalent) compared to 380 mm/year (water equivalent) at Mammoth.

Topographic complexity can also lead to a broad range of temperatures at different locations in Yellowstone National Park. Average maximum July temperatures at the Mammoth station (1901 m) reach 27º C, and temperatures above 32 º C are not uncommon (http://www.wrcc.dri.edu/climsum.html). With every 300 m gain in elevation, however, average maximum July temperatures decrease by 2-3 º C, so that at the 2800 m level the warmest daily temperatures may only reach 18-21 º C, on average (Curtis and Grimes 2004).

All of Yellowstone National Park experiences cold winters, but valley inversions and cold-air drainage can lead to remarkable cooling in some locations. Situated in the Madison River drainage, the west entrance to Yellowstone National Park (NWS station "West Yellowstone, MT") has seen January temperatures as low as –54 º C (-66 º F). The west entrance has also seen extreme low temperatures for December and February in the –50 º C range. Although the elevation at the Mammoth meteorological station is comparable to that of the west entrance (Mammoth is only 120 m lower), its location on the slopes above the Gardner River has kept extreme low temperatures from ever dropping below the – 37 º C mark.

The climate of Grand Teton National Park and the J.D. Rockefeller, Jr. Memorial Parkway is generally similar to portions of YNP dominated by wintertime precipitation. However, orographic effects again lead to extreme spatial heterogeneity in GTNP climate. The north-south trending Teton Range on the western end of GTNP receives massive amounts of Pacific moisture during the winter months. In fact, model-based annual precipitation estimates for upper elevation (> 3000 m) locations in the Teton Range can be as high as 2300 mm (water equivalent), and snow depths can reach 5 m (Curtis and Grimes, 2004). Parts of the Teton Range in GTNP can also receive precipitation on more than 200 days each year. Meteorological stations on the lee side of the Tetons such as Moose and Moran, Wyoming, on the other hand, receive only ~ 550 mm of precipitation each year, with average winter snow depths of ~ 0.28 m. As shown in the Moran, Wyoming meteorological record, valley temperatures in GTNP can be bitterly cold, sometimes reaching as low as –50 º C (http://www.wrcc.dri.edu/climsum.html), In comparison, summers in the Bighorn Canyon National Recreation Area (BICA) are much warmer, with average daily temperatures in July reaching ~ 24º C with occasional high temperatures over 35º C (Martner 1986). January is the coldest month with average maximum daily temperatures ranging between –2.8 º C (Lovell, WY) and 3.3º C (Yellowtail Dam, MT). Meteorological stations in BICA and in the surrounding Bighorn Basin receive an average of 257 mm precipitation each year. However, precipitation varies widely throughout the area, with stations such as Graybill, Wyoming (1155 m) receiving only 161 mm/yr, while Tensleep, Wyoming (1463 m) can receive > 330 mm average annual precipitation. BICA and surrounding areas experience peak precipitation in the months of April, May and June. Much of the rainfall during these months results from convective thunderstorm activity, thus producing a heterogeneous distribution of precipitation across the BICA region (Martner 1986, Mock 1996, Curtis and Grimes 2004). Lower elevations in the BICA region receive relatively little snow.

Another variable of interest for the development of these climate-monitoring protocols is wind. As shown in model results and observations, some of the higher mountain regions in and around YNP and GTNP are extremely windy, particularly during the winter months, with average wind speeds (at 50 m) between 8 to greater than 10 m/s (Martner, 1986; Curtis and Grimes, 2004). Portions of BICA can be quite windy with average wind speeds in the 6-8 m/s range. During summer thunderstorms, winds at BICA may regularly reach > 20 m/s.

1.3 Justification and Motivations for Monitoring Climate

Climate is a primary driver of almost all physical and ecological processes in the GRYN (Figure 2). Climate controls ecosystem fluxes of energy and matter as well as the geomorphic and biogeochemical processes underlying the distribution and structure these ecosystems (Jacobson et al., 1997; Schlesinger, 1997; Bonan, 2002). The effects of climate are especially visible in the strong zonation and steep elevational gradients displayed by vegetation types in the GRYN (Despain, 1990; Whitlock, 1993). Conceptual system models for the GRYN have also emphasized the influence of climate on other vital signs in the region (NPS, 2003). Because YNP and GTNP are major sources of runoff for the Columbia and Missouri River Basins, climatic variability in the GRYN has profound implications across large portions of North America.

Proxy records from archives such as glacial ice, lake sediments, tree rings and fossil corals show that, in both the recent and distant past, the earth's climate has varied significantly over timescales from months to millennia. Studies using combinations of instrumental records and paleo-proxies confirm, however, that global climate has changed rapidly over the 20th century and that the speed of

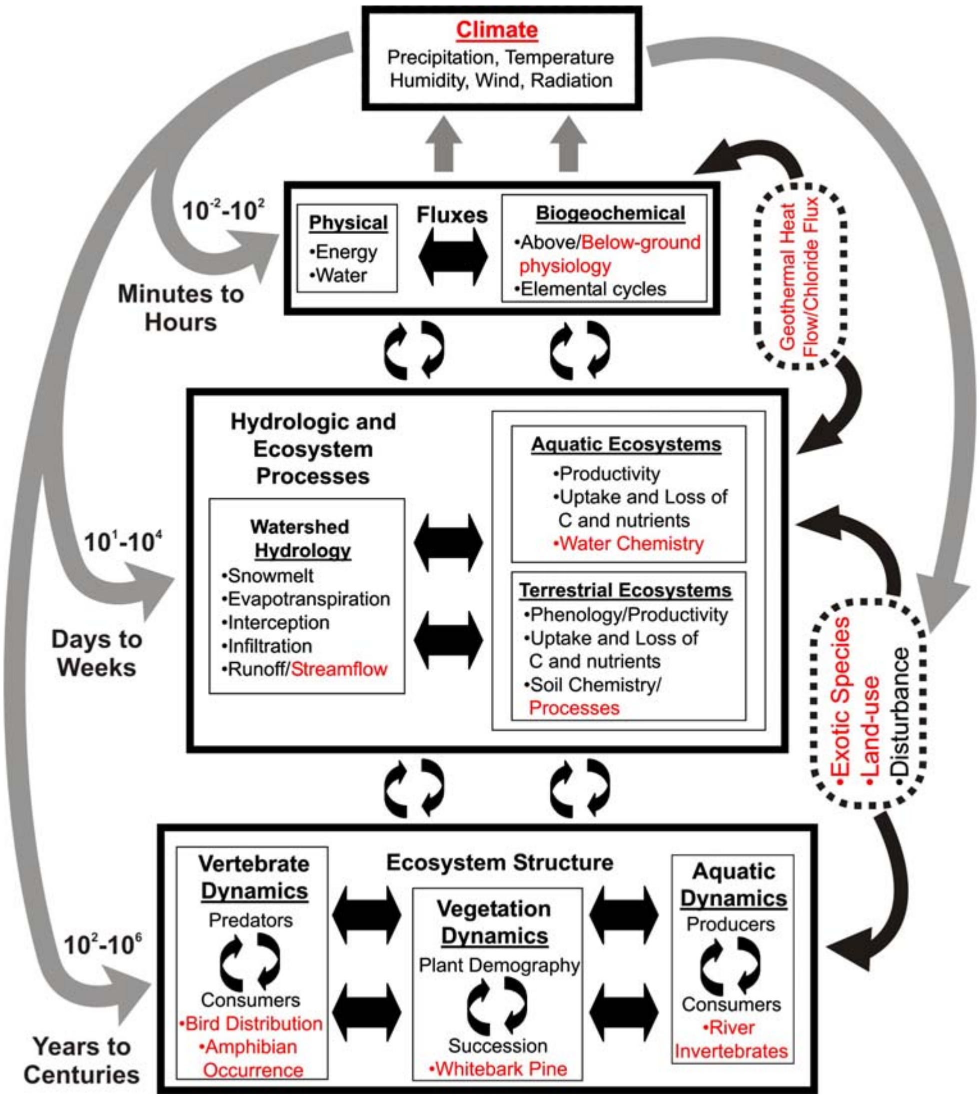

Figure 2. Conceptual model showing the relationship between climate and the structure and function of natural systems in the GRYN. Primary GRYN vital signs are shown in red.

these changes exceeds that of most previous fluctuations (Mann et al., 1999; IPCC, 2001; USGCRP, 2003). Global surface temperatures, in particular, have risen by 0.6 ºC ± 0.2 over the past century (IPCC, 2001). The bulk of scientific evidence indicates that this rise in global temperatures is related to human activities.

These global-scale changes will inevitably lead to significant alterations of Greater Yellowstone climate. Evidence suggests that increasing temperatures have already led to earlier snowmelt and peak runoff across the West (Cayan et al. 2001; Mote 2003). Additional small (1-2º C) temperature increases over the next 100 years could lead to 25-50% reductions in GRYN snowpack as well as a major shift from snow to rainfall precipitation events (Stewart et al. 2004).

Furthermore, ensemble studies incorporating output from the seven primary global climate-prediction models suggest that temperature changes over the next 100 yr will be greatest at elevations above 2800 m and in a zone from 40-55 º N (Bradley et al. 2004), making YNP and GTNP especially prone to future warming. Changing regional climate will, in turn, have a tremendous effect on natural systems in the GRYN (Bartlein et al., 1997; Baron, 2002; Wagner, 2003). It is imperative that the parks of the GRYN have a climate monitoring system in place that allows for the detection and characterization of GRYN climate-change and provides climate data for use in monitoring and predicting the dynamics of other vital signs.

Weather and climate are also among the primary drivers of floods, fires and avalanches (NRC, 1990; Singh, 1996; Casale and Margotini, 1999; Baker, 2003). Timely and accurate weather and climate information can aid in predicting their occurrence and behavior, thus improving human safety and reducing negative economic impacts. Development and maintenance of weather and climate monitoring networks will provide invaluable information for the scientific study of these events.

1.4 General Protocol Goals

The specific monitoring objectives proposed here are intended to address the following issues: How does the climate of the GRYN vary at different spatial and temporal scales relevant to the management of natural resources, natural hazards and the dynamics of other vital signs? Has the climate of the GRYN changed significantly from that of past decades to centuries as a result of natural or anthropogenic forcing? Do these changes in climate warrant specific research or management actions to monitor, predict or mitigate their effects on natural resources and other vital signs?

2. SPECIFIC MONITORING OBJECTIVES

2.1 OBJECTIVE I: Tracking Primary Climatic Elements

Objective: To reliably and efficiently sample precipitation and air temperature in the GRYN, thereby providing long-term data relevant to monitoring and predicting the dynamics of other vital signs and natural resources within the region. This objective will also provide baseline data and continuously updated datasets to facilitate the detection of regional climatic change (both natural and human-induced) and its effects on natural systems in the Greater Yellowstone Ecosystem (GYE) as a whole.

Justification/Rational for this Objective: Precipitation and temperature exert strong controls over almost all physical and ecological processes in the GRYN. Temperature and precipitation control ecosystem fluxes of energy and matter as well as the geomorphic and biogeochemical processes underlying the distribution and structure these ecosystems (Jacobson et al., 1997; Schlesinger, 1997; Bonan, 2002). In the GRYN the effects of temperature and precipitation variability are especially visible in the strong zonation and steep elevational gradients displayed by different vegetation types (Despain, 1990; Whitlock, 1993). Because YNP and GTNP are major sources of runoff for downstream areas throughout North America, precipitation and temperature variability in the GRYN have profound implications outside the region as well.

Applications: This objective should provide information that contributes to the detection of regional climatic variability/change and generates data for use in predicting the dynamics of other vital signs. High-quality, long duration records are also essential for the detection and characterization of natural, lower-frequency variability in the climate system (Cayan et al., 1998).

2.2 OBJECTIVE II: Tracking Secondary Climatic Elements

Objective: To reliably and efficiently sample secondary climatic elements such as wind speed/direction, relative humidity, soil temperatures and incoming solar radiation. These data will complement information on temperature and precipitation gathered under Objective I, and further the general GRYN program goals of monitoring and predicting the dynamics of other vital signs and natural resources.

Justification/Rational for this Objective: Like the primary climatic elements (precipitation and temperature), wind, humidity, soil temperature and solar radiation exert strong controls over physical and ecological processes in the GRYN. These data are also tied to a large number of key GRYN vital signs. In the case of whitebark pine, for example, relative humidity and wind/speed direction are both key factors in controlling the spread of white pine blister rust (Kendall and Keane 2001). Wind and humidity influence fire behavior while soil temperatures and incoming solar radiation help control plant species distributions and ecosystem productivity.

Applications: This objective should provide information on climatic variability that contributes our understanding other vital signs and general physical and ecological processes in the GRYN as well as the GYE as a whole.

3. STANDARDS AND PROCEEDURES

Note: Most of the climate stations within the GRYN are operated by agencies other than NPS (e.g. NRCS, NOAA, EPA), and each of these agencies has their own set of standards and procedures. However, when the GRYN Inventory and Monitoring program requires specific sampling standards or procedures, the NPS should work with the controlling agencies to ensure that these needs are met. Standards and procedures may also be altered on a case-by-case basis to account for the extreme conditions sometimes encountered in this region.

3.1 Scope of the Network

Primary Climatic Elements: The measurements of temperature and precipitation provided by this network should be applicable to the major ecological zones, elevation zones and geographic features (i.e. high-order watersheds, mountain ranges, etc.) within each park. The network of stations should also provide a comprehensive picture of precipitation and temperature variability within and among the park units.

Secondary Climatic Elements: Given the harsh environments encountered in some locations within YNP/GTNP it may be difficult or cost-prohibitive to install and operate sensors for all of the secondary climatic elements at every station. Anemometers (measure wind speed/direction) suited to icy conditions and high winds, for example, may cost over $5,000 each and have relatively short life spans (Kelly Redmond, WRCC, personal comm.). On the other hand, most modern, automated climate stations now collect data on these secondary elements as a matter of standard operating procedure. In many cases, the capacity to measure these secondary elements is built into commercial units (see www.campbellsci.com for examples) or the necessary sensors can be added to commercial sensor packages. Many existing stations can be easily and cheaply upgraded to accommodate these measurements.

Whenever technically and economically feasible, relative humidity, wind speed/direction, soil temperatures and incoming solar radiation should be monitored along with temperature and precipitation. At BICA there should be few (if any) limitations on the ability to monitor all of these elements. In YNP/GTNP, installation of these secondary sensors should be considered on a case-by-case basis.

3.2 Minimum Sampling and Reporting Rates

Primary Climatic Elements: In keeping with National Inventory and Monitoring Program standards for climate monitoring, precipitation amounts must be recorded on at least a daily basis. Daily minimum and maximum temperatures must also be recorded. These measurements, in turn, can be used to calculate all of the basic reporting parameters outlined by the National I&M Program protocols (Table 1).

Table 1. Minimum reporting standards for primary climatic elements (temperature and precipitation).

Minimum Reporting Parameters for Primary Climatic Elements	
Daily Data	**Units**
Daily Precipitation	mm
Daily minimum and maximum temperature	° C
Monthly Data	
Mean monthly precipitation intensity	mm
Mean monthly minimum and maximum temperature	° C
Number of wet and dry days	days
Number of days with temperature below 0° C	days
Number of days with temperature above 35° C	days
Annual Data	
Mean annual precipitation intensity	mm
Mean annual minimum and maximum temperature	° C
Number of wet and dry days	days
Number of days with temperatures below 0° C	days
Number of days with temperatures above 35° C	days

http://science.nature.nps.gov/im/inventory/climate/index.htm

Observations at 24-hour intervals are usually associated with NWS-Coop stations where park staff or other personnel must visit the station, reset instruments (e.g. reset min/max thermometers, empty precipitation gage) and manually record each day's data. When technically and financially feasible, increased sampling rates are desirable. Most modern automated data-logging or data-transmission systems can accommodate hourly recording/reporting, and recording/reporting intervals of up to 10 min. are common.

Secondary Climatic Elements: While relative humidity and wind speed/direction can be indicators of long-term climate, many GRYN vital signs, as well as general ecosystem processes, can have important short-term (hours to days) responses to these elements (see Figure 2; Bonan 2002). Moreover, the study and prediction of events like fires, floods and avalanches often requires rapid, nearly continuous recording and reporting of these elements (NRC, 1990; Singh, 1996; Casale and Margotini, 1999; Baker, 2003). As a result, 15-minute averages (or better) should be computed for humidity and wind speed/direction, whenever technically and financially feasible (Table 2). For similar reasons, the

National Interagency Fire Center's Fire Weather Working Team (FWWT) and the Fire Danger Working Team (FDWT) recommend providing hourly averages for incoming solar radiation (NWGC 2005). Soil temperature in the upper surface layers (top few cm) may respond very quickly to changes in air temperature, incoming solar radiation, etc. (Bonan 2002). As depth in the soil profile increases the rate and magnitude of responses to aboveground variability decreases. Surface or near surface soil temperatures should be measured at 15-min to hourly intervals while temperatures deeper (~ 1 m or more) in the soil profile can be taken over daily intervals.

Table 2. Suggested recording and reporting standards for secondary climatic elements.

Suggested Minimum Reporting Parameters for Secondary Climatic Elements	
15-minute intervals	**Units**
Wind Speed	m/s
Wind Direction	degrees
Relative Humidity	percentage
Soil Surface/Near Surface Temperatures (~10 cm)	° C
Hourly	
Incoming Solar Radiation	W/m^2
Daily	
Soil Temperatures at Depth (~ 1 m) Daily mean, minimum and maximum	° C

3.3 Accuracy and Operating Ranges

Primary Elements: Levels of sensor accuracy and operating ranges will vary with instrumentation, environmental setting (e.g. valley vs. mountaintop) and the established procedures employed by the responsible agency. The NWS Surface Observing Program (NWS-SOP), NOAA Climate Reference Network (CRN) and Remote Automated Weather System (RAWS) program provide general guidelines for acceptable tolerances relating to air temperature measurements (Table 3). Depending on which agency is responsible for the operation and maintenance of a station, any of these standards would likely be acceptable for applications within BICA. Based on information summarized in Section 1.2, however, these parameters will not be appropriate for all locations in YNP/GTNP. In particular, locations such as the West Entrance to YNP (West Yellowstone, MT) and Moran, Wyoming in GTNP may experience temperatures lower than the defined operating ranges in Table 3. Based on model estimates, many high elevation areas (> 2500 m) in YNP and GTNP are likely to experience conditions outside these tolerances (Curtis and Grimes, 2004). To accommodate such extreme conditions, guidelines for sensor accuracy and operating ranges at sites within YNP and GTNP should be flexible, and sensor needs reviewed on a case-by-case basis.

Table 3. Tolerances for air temperature sensors used in the NWS-Surface Observing Program, RAWS stations and NOAA Climate Reference Network.

Program	**Range**	**Accuracy**
NWS-SOP	-62 to +132º F	+/- 2.0º F at –62 to -50º F +/- 1.0º F at –50 to +122º F +/- 2.0º F at +122 to +132º F
RAWS	-50 to +50º C	+/- .06º C
CRN	-50 to +150º C	+/- 0.04% of observed value

http://www.fs.fed.us/raws/standards/NFDRS_final_revfeb05v2.pdf
http://www.ncdc.noaa.gov/crn/instrdoc
http://www.nws.noaa.gov/directives/010/pd01013002b.pdf
As used here, "accuracy" is defined as the agreement between the actual or true value and the measurement result (http://www.epa.gov/castnet/library/qaannual02/2002qaar-a.pdf).

The NWS-SOP, NOAA-CRN and RAWS programs provide general guidelines for acceptable levels of sensor accuracy when measuring liquid precipitation (Table 4). Additional guidelines for measuring snowfall, snow pack and frozen precipitation are offered by the NWS-SOP and NRCS-SNOTEL programs (Table 5). In the case of stations operating in snow-dominated areas (e.g. SNOTEL), sampling range can be adjusted to fit the location (e.g. raise the height of a sensor to accommodate large snow pack) or sensor designs can accommodate a very wide ranges of conditions (e.g. snow pillows).

Table 4. Same as Table 2, but for sensor tolerances when measuring liquid precipitation.

Program	**Range**	**Accuracy**
NWS-SOP	≤ 10 in/hour	+/- 0.02 in or 4% of hourly amount
RAWS	0-99.9 in	0.01 in
CRN	Instrument dependent	+/- 0.25 mm

http://www.fs.fed.us/raws/standards/NFDRS_final_revfeb05v2.pdf
http://www.ncdc.noaa.gov/crn/instrdoc
http://www.nws.noaa.gov/directives/010/pd01013002b.pdf

Table 5. Acceptable tolerances for measuring snow and frozen precipitation as defined by the NWS-Surface Observing Program and NRCS SNOTEL program.

Program	**Range**	**Accuracy**
NWS-SOP		
Snow depth	0-99 in	0-5 in +/- 0.5 in > 5 to 99 in +/- 1 in
Freezing Precipitation	0-40 in	Detects at 0.01 in
Frozen Precipitation	0-40 in	1% of total accumulation
NRCS-SNOTEL		
Snow Depth	Varies	+/- 0.5 in
Snow water equivalent	Varies	+/- 0.5 in

http://www.nws.noaa.gov/directives/010/pd01013002b.pdf
http://www.wcc.nrcs.usda.gov/factpub/sntlfct1.html

Secondary Elements: As with temperature and precipitation, these standards may not be appropriate for all of sampling environments encountered in the GRYN. Adjustments to these standards should be considered on a case-by-case basis.

Wind
Suggested standards for sampling wind speed and direction are offered by the NWS-SOP and RAWS programs (Table 6). Some locations in the GRYN may regularly experience conditions outside the ranges listed below. Because wind is generally an indicator of local climate or short-lived weather events (Hartman, 1994) and the purposes of these protocols are to provide information on larger-scale climatic variability in the GRYN, the benefits of installing and maintaining instruments that can operate under a wider range of conditions may not justify the costs.

Table 6. Tolerances for wind speed and wind direction used in the NWS-SOP and RAWS programs.

Program	**Range**	**Accuracy**
NWS-SOP		
Wind Speed	2-90 knots	+/- 1 knot to 10 knots +/- 10% of measured value above 10 knots
Wind Direction	1-360º	+/- 5º
RAWS		
Wind Speed	0-100 mph	+/- 5% of measured value
Wind Direction	1-360º	+/- 5º

http://www.fs.fed.us/raws/standards/NFDRS_final_revfeb05v2.pdf
http://www.nws.noaa.gov/directives/010/pd01013002b.pdf

Relative Humidity
Suggested standards for sampling relative humidity are taken from the NWS-SOP and RAWS programs (Table 7).

Table 7. Tolerances for measuring relative humidity used in the NWS-SOP and RAWS programs.

Program	Range	Accuracy
NWS-SOP *(Reported as Dew Point)*	-34 to –24º C -24 to -1º C -1 to +30	+/- 2.2º C +/- 1.7º C +/- 1.1º C
RAWS	0-100%	+/- 2.00% at 0-80% and 25º C +/- 5% at 80-100% and 25º C

http://www.fs.fed.us/raws/standards/NFDRS_final_revfeb05v2.pdf
http://www.nws.noaa.gov/directives/010/pd01013002b.pdf

Soil Temperatures
Suggested standards for sampling soil temperatures are taken from the NOAA-CRN and NWS-SOP programs (parameters not specified for RAWS; Table 8).

Table 8. Tolerances for measuring soil temperatures used in the NOAA-CRN and NWS-SOP programs.

Program	Range	Accuracy
NWS-SOP	Not specified	+/- 2º C
CRN	0-50º C	+/- 0.3º at 0 to 15º C +/- 0.2º at 15 to 35º C +/- 0.3º at 35 to 50º C

http://www.ncdc.noaa.gov/crn/instrdoc
http://www.nws.noaa.gov/directives/010/pd01013002b.pdf

Incoming Solar Radiation
Suggested standards for sampling incoming solar radiation are taken from the NWS-SOP, RAWS and NOAA-CRN programs (Table 9).

Table 9. Tolerances for measuring incoming solar radiation used in the NOAA-CRN, RAWS and NWS-SOP programs.

Program	Range	Accuracy
NWS-SOP *(Reported as Direct Insolation)*	Not specified	+/- 10%
RAWS *(Reported as W/m^2)*	Not specified	+/- 5%
CRN	0-1000 W/m^2	+/- 100 micro Volts per W/m^2

http://www.ncdc.noaa.gov/crn/instrdoc
http://www.nws.noaa.gov/directives/010/pd01013002b.pdf
http://www.fs.fed.us/raws/standards/NFDRS_final_revfeb05v2.pdf

Other Acceptable Standards: Because of the extreme conditions (e.g. low temperatures, high winds, deep snow pack) that may be encountered at some locations in YNP/GTNP, alternative standards for sensor tolerance may be considered. The World Meteorological Organization (WMO, 1971) and the National Science Foundation (NSF) Long-term Ecological Research Program (Greenland, 1986) both offer options for sensor accuracy and operating ranges that are suited to the difficult operating environments that may be encountered in YNP/GTNP. NSF and WMO standards have been adopted by the Central Alaska Network (Sousanes 2004).

3.4 Sensor Deployment and Equipment

Standards for sensor deployment and the siting of climate stations will vary by responsible agency. Standards must also be adapted to different environmental setting (e.g. valley vs. mountaintop). Three examples of sensor deployment and siting protocols from the NWS-SOP, RAWS and NOAA-CRN programs are found in Appendices 1a-c. While the specifics of these protocols vary by controlling agency, they share several common elements that apply to climate stations in the GRYN:

1. Stations should be sited in regionally representative locations. Surrounding vegetation, topography, elevation and local weather patterns should be considered when determining the representative nature of a site. The ideal site is not heavily influenced by unique local topography or microscale features/factors.
2. Sites should provide for long-term operation (50-100 yr) with relatively unchanged exposure. Locations that may be altered by construction or changes in vegetation should be avoided.
3. High-risk areas (e.g. floodplains or locations prone to vandalism) should be avoided.

Redmond et al. (2005) provide a more detailed discussion of these issues as they relate to the selection of new climate monitoring sites in national parks (Appendix 2).

Monitoring equipment will vary widely depending on responsible agency, desired applications and local environment. However, the CAKN offers a general model for climate stations that might be adapted for use in the GRYN. The CAKN sensor package/platform is relatively economical and well suited to use in cold snow-dominated areas. The CAKN stations are also designed to withstand the same severe conditions (i.e. high winds, icing) that are likely to be encountered in parts of the GRYN. The CAKN station design is described in Appendix 3.

3.5 Site Documentation

Collection of proper documentation and metadata for a station is critical to the long-term operation of the station and, more importantly, the interpretation of data from a station.   At a minimum the site/sensor information in Appendix 4 should be recorded for each station. Photographs of the site and instrumentation can also be an invaluable source of information, particularly when changes in the surrounding environment affect readings from a station.   At a minimum, the photographs listed in Table 10 should be taken for each station in the GRYN. Examples of a more thorough photo-documentation scheme developed by Kelly Redmond of the WRCC are given in Appendix 5. It is also suggested that these photographs be retaken on a yearly basis. Establishment of photo-points (permanent markers that denote the location each photograph should be taken from) is recommended.

Table 10. Minimum photographic documentation for climate monitoring stations in the GRYN.

Shot Taken From:	**Aspects Covered**	**Subjects**
Station	North, South, East and West	Vegetation/surroundings within the footprint of all sensors (suggest photographs showing surroundings within 3, 30 and 100 m of station)
Surrounding area	N, S, E and W	Entire station and tower
Vicinity of station (~ 3 m from station)	N, S, E and W	Deployment of key sensors and any sensor plots (e.g. areas used for soil or fuel moisture monitoring)

3.6 Maintenance of Climate Stations

Maintenance and, in some cases, downloading of data, will be governed by the equipment used and the protocols of the controlling agency. While more specific requirements vary, all climate stations must be visited at least once a year (NOAA 2003; NWS 2003; NWCG 2005). These site visits allow for calibration and repair of instruments, as well as an opportunity to document any changes to a site's surrounding environment (see section 3.5, above). A sample maintenance report for a standard climate station (here a RAWS station) is included in Appendix 6.

3.7 Data Management and Transfer

The exact flow of data from a climate station in the GRYN to the user community will depend on whether or not the station has automated telemetry (data transfer via telephone line, cellular phone link or satellite communications). Second, data flow will depend on the controlling agency. For most types of climate stations in the GYE, and all stations within the boundaries of the GRYN parks, the generalized flow of data is depicted in Figure 3.

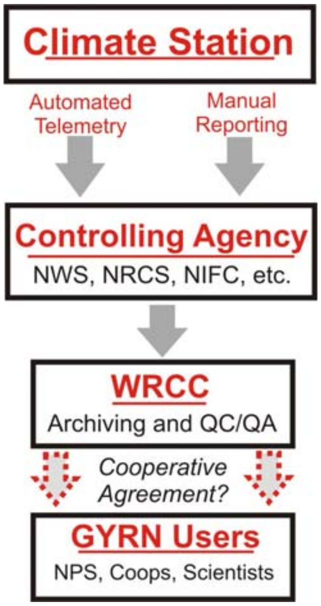

Figure 3. Generalized model for the flow of climate data from stations to GRYN users (NPS personnel, cooperators and scientist working in the GYE). Notice that the transfer of data from the Western Regional Climate Center (WRCC) to the end users must still be resolved.

In the case of a satellite telemetered RAWS unit, for example readings from the station are first uploaded to the GOES satellite and then sent to a receiving station in Wallops, Virginia (http://www.fs.fed.us/raws/book/24hrindex.shtml). The data are then transferred to the National Interagency Fire Center in Boise, Idaho where they are submitted to the Automated Sorting, Conversion and Distribution System (ASCADS). ASCADS performs a first order Quality Control/Quality Assurance (QC/QA) operation that identifies anomalous data and alerts the controlling agency/operator when potential problems arise. ASCADS then delivers the data to the National Weather Service where it is used in weather forecasting, and to the Western Regional Climate Center (WRCC) in Reno, Nevada where the data are archived and undergo additional QC/QA. NWS also archives station data at the National Climate Data Center (NCDC).

The last step in this data transfer process, namely the access of station data by users in the GRYN, must still be resolved. Summaries of the data and some short-term records are openly available through the WRCC and NCDC. Most historic records and raw data sets, on the other hand, are not readily accessible. Entry to these archives requires special passwords or payment for services. These special-access policies were put in place to avoid strain on the WRCC and NCDC data networks and to help pay for archiving and QC/QA services (Kelly Redmond, WRCC, personal comm.). It is strongly recommended that the GRYN pursue cooperative agreements that allow NPS personnel and network cooperators full access to the WRCC/NCDC archives. One possible arrangement might be the NPS providing start-up funds for new climate stations or climate station upgrades in exchange for access to WRCC/NCDC data and QC/QA services (see section 4.5).

3.8 Analysis and Reporting Products

The data and climate histories provided by this network will have wide applications among park personnel, scientists and stakeholders in the region. In turn, needs for data products and summaries are difficult to anticipate, and requirements may vary over time. However, climate-monitoring protocols for other NPS I&M Networks have recognized the need for standard reporting formats and procedures that provide general information on seasonal to interannual climate variability (Garman et al. 2004; Sousanes 2004). Standardizing these reports will also facilitate comparisons of climatic elements among the NPS I&M Networks.

Ideally the core of these reporting products would be developed at the level of the National I&M Program. More specialized products (specific to this network) could be developed with input from NPS scientists, managers and administrators in the GRYN; GRYN cooperators; the scientific community working in the GYE; and relevant stakeholders. In their climate monitoring protocols for the Northern Colorado Plateau Network, Garman et al. (2004) provide a particularly useful model for summarizing core elements of climate variability within a network. The elements in these reports include:

1) A monthly summary of primary and secondary climatic elements
2) An annual summary of primary and secondary climatic elements
3) Assessments of annual, monthly, and daily measures in the context of historical trends (i.e., climatic extreme assessments)
4) A comparison of climatic conditions among the units in a network
5) Comparison of climatic conditions in the GRYN with that of surrounding networks (e.g. ROMN, NGPN, NCPN, UCBN).

Components #1-3 are produced for each climate station in a park unit. The assessment of climatic extremes (#3) involves a comparison between the previous year's conditions and conditions over the historical period of record (both length of record and 30 yr normals). All climate stations in the network are employed in components #4-5. The NCPN protocols also call for an annual status report every year, and comprehensive analyses and synthesis reports every 3-5 yrs. (Additional detailed information on climate reporting and analysis from the NCPN are included in Appendix 7).

These reporting products should be produced and distributed by experts in the climate community. The WRCC is the logical choice for performing these duties because of their extensive expertise in data/information distribution and archiving. The WRCC could also handle summary products, QC/QA issues, and web-based data distribution simultaneously. The State Climatologists for Montana, Wyoming and Idaho may also have unique perspectives and capabilities for summarizing data on GRYN/GYE climate. In any case, the GRYN is strongly encouraged to develop cooperative agreements and other arrangements that allow for expert production and handling of climate-related products. Development of reporting and analysis products also offers opportunities for closer coordination with other I&M networks (e.g. element #5).

Creation and dissemination of these climate-related products would be further aided if the NPS-GRYN were to designate a “Climate Program Manager” (CPM) to liaison between the WRCC and park personnel/cooperators. Using a modification of the Central Alaska Network’s (CAKN) model for this position (i.e. Sousanes 2004), the CPM would ensure that NPS and GRYN requirements for reporting products are met, as well as overseeing data management, archiving and QC/QA efforts performed under cooperative agreements. The CPM might also ensure that siting of new stations and station upgrades performed by agencies other than NPS are in line with GRYN data needs. Under this model existing NPS or GRYN staff such as those already involved in data management/dissemination could perform the duties of the CPM. Alternatively, the CPM might be housed under a program such as the USGS’s National Biological Information Infrastructure Mountain Prairie Node (http://mpin.nbii.org) that is co-located with the GRYN offices in Bozeman, Montana. One further option might be the creation of a CPM at the multi-regional or national I&M Program level.

4. CURRENT GRYN CLIMATE MONITORING

Maps and geographic information systems analyses for this section were developed by Andra Toivola, Big Sky Institute, Montana State University. Datasets for the analyses in section 4.2 were updated and expanded from earlier work by Dave Selkowitz (i.e. Selkowitz 2003).

4.1 Development of the Legacy Network

The observation and monitoring of GYE climate began in the late 19th century as forts and military outposts became established in the area. In these days before the creation of the U.S. Weather Bureau (later the National Weather Service), the U.S. Army Signal Corps performed most weather observations (Hughes 1980, Guttman and Quayle 1996). The Army Signal Corps and park superintendents also took limited meteorological observations within YNP beginning in the 1870s and 1880s. Of particular note is the record from the Lamar Ranger Station that begins in 1881 (WRCC 2005). Formal, systematic monitoring of GYE climate began in 1892 with the establishment of a weather station on the grounds of what became the Montana State College of Agriculture and Mechanical Arts in Bozeman, Montana, later renamed Montana State University (Figure 4a). Additional stations were soon established in towns like Billings and Dillon, Montana. The first permanent “modern” station within the parks of the GRYN was established in 1894 at YNP headquarters in Mammoth. Additional YNP stations were established in the years 1904-05 (Old Faithful, Snake River, Lake

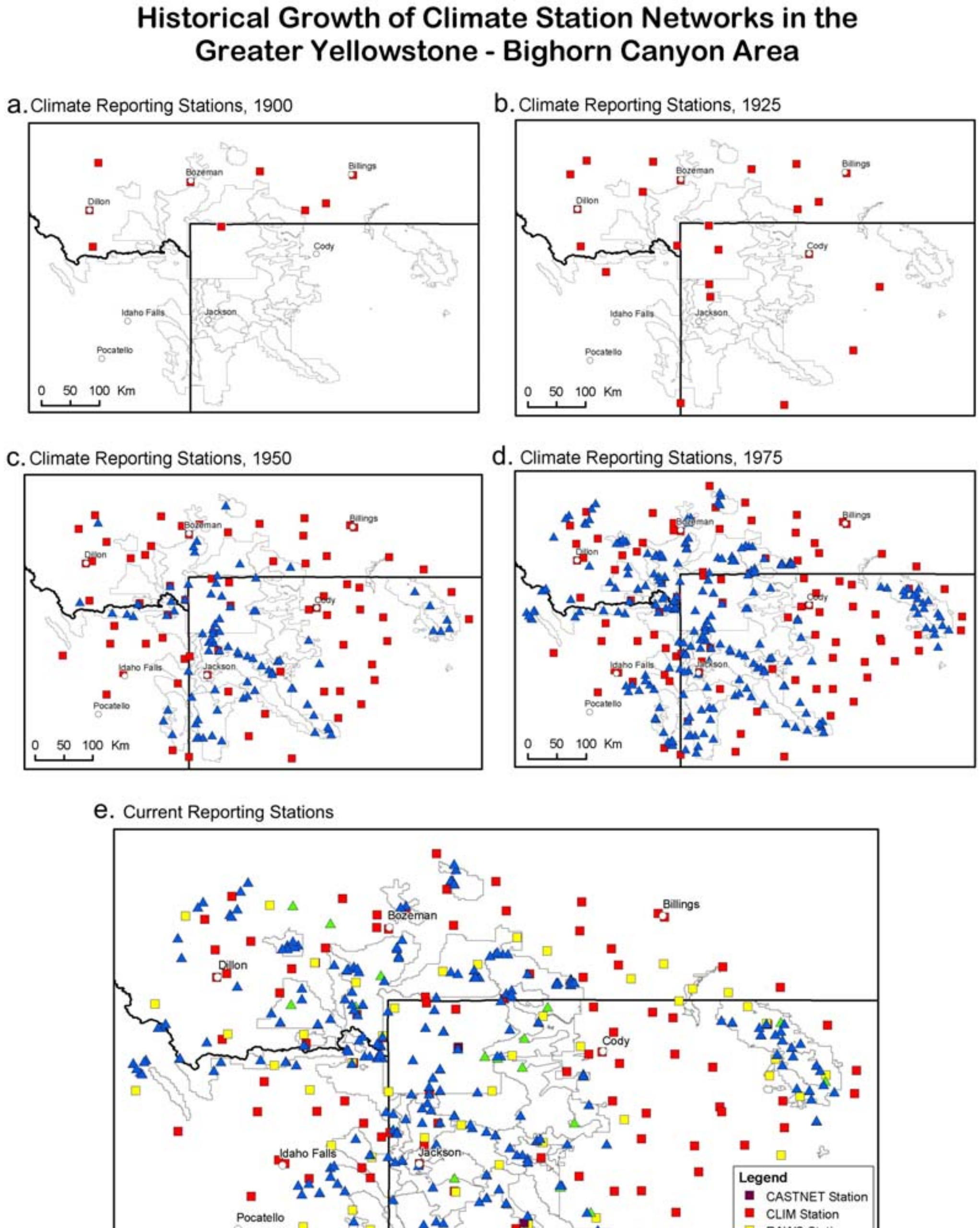

Figure 4. Historical development of climate monitoring in the Greater Yellowstone region.

Yellowstone) (Figure 4b). The West Yellowstone station began recording in 1924.

The development of stations to the south and east of YNP was somewhat slower. The first full station in GTNP was erected in 1911 near Moran, Wyoming. The Cody, Wyoming station (east of YNP) did not come into operation until 1915. The BICA area had no station until 1948 (Yellowtail Dam, Montana), and GTNP did not receive another NWS-COOP type station until 1958 (Moose, Wyoming). Like much of the western US, in the aftermath of the 1930s Dustbowl the GYE saw a massive increase in the number of reporting stations (Figure 4c). While additional NWS-COOP stations contributed to this growth, many of these post-1925 observer sites were developed as snow courses by the Soil Conservation Service (Now the NRCS). The number of observing stations grew again in the 1980s with the establishment of the NRCS SNOTEL (Automated Snow Telemetry) network. Driven by the need for more fire-weather related information, a number of Remote Automated Weather Stations have also been installed in recent years (Figure 4d).

Hidden in these statistics is a more complex history of GYE and GRYN climate monitoring. In the case of the Lamar Ranger Station record, for example, formal climate monitoring at this site was discontinued in 1977 (http://www.wrcc.dri .edu/). Likewise long-term recording stations such as those at Bechler Ranger Station (YNP) and Crandall Creek (border between YNP and Shoshone NF) were also discontinued in the 1950s, '60s and '70s. Many stations have been moved a number of times. Stations at Old Faithful and Mammoth changed locations four times since the 1970s, while the station at Lake Yellowstone has moved at least eight times in its 100-year history. Many seasons or even years of observations may be missing from these records. The station at Snake River, Wyoming, for example, was out of service for the entire period from 1958 to 1968. In addition, the responsibility for monitoring and maintaining most stations has changed many times. Procedures, equipment and the level of observer training have varied widely over the years.

Data gaps can greatly reduce the usefulness of a record for detecting trends or changes in the climate system. Station moves may also contaminate a record (Karl et al. 1990). Moving a station between vegetation or cover types, for example, can dramatically alter observations of any climatic element. Changes in instrumentation- or even the timing of observations- can alter measurements (Karl et al. 1986, Quayle et al. 1991). Station alterations and moves often produce a step-like change in the long-term record that can be misinterpreted as actual climatic change. A more subtle, but equally important problem, is that contaminated records may mask real trends or changes in regional climate. These anomalies or "inhomogeneities" can be addressed using statistical techniques (e.g. Karl and Williams 1987), but these corrections rely on having a large network of climate stations in the surrounding area.

Despite these problems- problems inherent to any climate monitoring effort- the legacy network of climate stations in the GRYN provides one of the longest and highest quality records of regional climate anywhere in the Rocky Mountain West (Figure 4e). Forty-four monitoring stations are currently located within the boundaries of the three GRYN parks alone. For comparison, by the mid 1990s the NPS units of the Central Alaska Network had only 3 NWS-COOP type climate stations to cover an area of 21.7 million acres (Sousanes 2004). However, if this legacy network is to meet the needs of the NPS Inventory and Monitoring Program, as well as the requirements of general science and natural resource management in the GRYN, some improvements to the system should be made. More importantly, the continuity of long-term records must be maintained. Toward these goals an analysis of the strengths and weaknesses of the existing network is described in sections 4.2-4.3 and recommendations for maintaining and upgrading the network are given in section 4.4.

4.2 Methods: Analysis of the Legacy Network

The analyses described here were designed to determine if the network of legacy stations in the GRYN/GYE can adequately address the monitoring objectives in this protocol. The legacy network was also analyzed to determine if it can provide data to address the general needs of agencies, scientists and stakeholders in the GRYN. These analyses were limited to stations in one of the five major climate-station categories (e.g. CASTNET, NWS-COOP, RAWS, SNOTEL or snowcourse). To *be included in this study stations must also provide data that can be accessed by NPS personnel and cooperators (on either an open access or fee for service basis). Temporary stations, field data loggers and informal seasonal observations were excluded from the study.*

Approach: The existing network of climate monitoring stations in the GYE was examined to determine if:

1. Current stations in the GYE can adequately capture key spatial and temporal components of regional climate variability.
2. Strata of management interest or scientific importance in the GRYN are being adequately sampled.
3. The array of stations provides data needed to understand and predict the dynamics of other vital signs in the GRYN.

Item #1 was addressed using literature reviews and an examination of existing instrumental- and paleo-climate records for the GYE. Item #2 involves a series of geographic information systems (GIS) analyses that compare the locations of existing GYE climate stations (*updated from* Selkowitz 2003) against the vegetation and topography of the region.

A full evaluation of Item #3 cannot be completed until protocols for other vital signs become available. Instead, potential climate-data requirements related to whitebark pine inventory and monitoring were examined as a test case. Whitebark pine is a key GRYN vital sign whose dynamics are closely linked to climate variability. In the future Item #3 must be continuously evaluated through consultations with other cooperators and NPS personnel familiar with GRYN vital signs. Because climate and climate-related processes span the entire GYE region, the needs of other cooperator agencies should also be considered. Toward this end a workshop bringing agency personnel (NPS, USDA Forest Service) and scientists together for a discussion of GYE climate was held in March 2005. Recommendations from this workshop are included below.

4.3 Results: Analysis of the Legacy Network

Temporal Variabilty: To be useful as a baseline for understanding future variability and change, climate records for the GRYN must provide a reasonable representation of natural variability (Carter and La Rovere 2001, Karl et al. 1990, Peterson and Easterling 1994, Hulme et al. 1999, Hulme and New 1997). Depending on the application, it may also be necessary to capture the range of extreme- and therefore rare- climatic events.

Analysis of long-duration instrumental climate records for the GYE shows clear decadal-scale variability in regional temperature and precipitation (Figure 5). Paleoclimatic reconstructions also point to the strength of decadal and longer variations in regional climate (e.g. Gray et al. 2003, 2004; Graumlich et al. 2003). In effect, the climate of the GYE tends to switch between persistent hot/dry and wet/cool regimes over 10-30 yr intervals. Regional snowpack also varies strongly over decadal timescales because of links between interdecadal variability in the North Pacific Ocean and winter storm tracks over the western US (McCabe and Dettinger 2002; Gray et al. 2004). At best, shorter-duration (< 50 yr) records might capture only one to three persistent climatic regimes (Cayan et al. 1998, Pederson et al. 2005). Short duration records are also unlikely to capture the full range of natural variability in the region (Cook and Evans 2000).

Overall, these results stress the importance of long-duration climate records in the GRYN program. Only by having 50-100 year's of continuous observations from stations throughout the GRYN parks and surrounding areas can Objective I (Section 2.1) of these protocols be fulfilled. More specifically, shorter records will not be adequate for use as a baseline of regional climate or for defining the range of natural variability. Long climate records are also a vital component of the GRYN I&M program because they provide an essential context for 20th century observations of species distributions, population dynamics and the functioning of natural systems. Comparing observations of plant species'

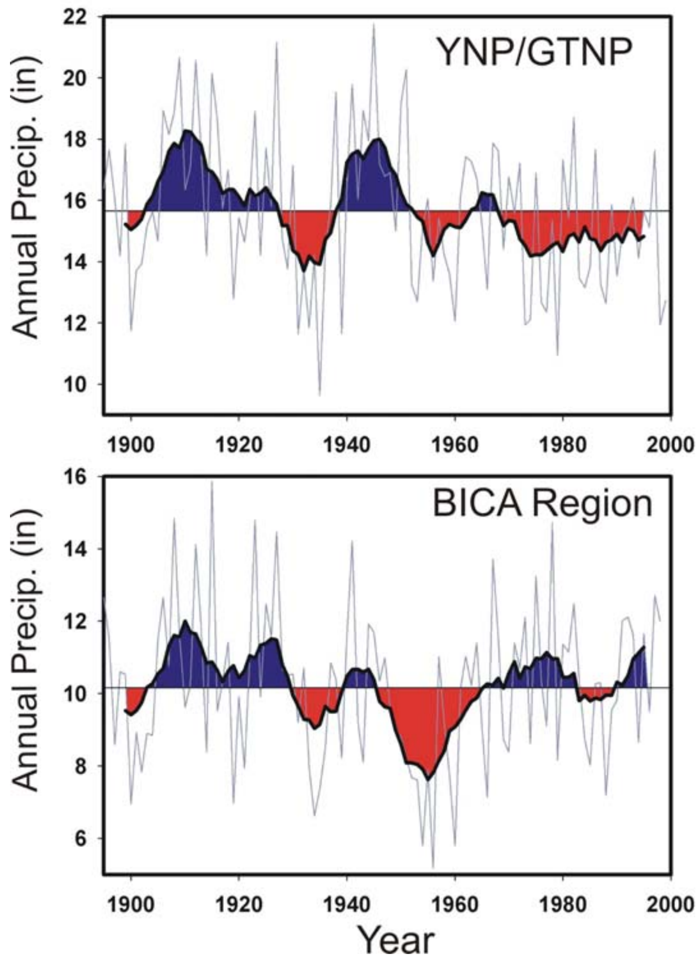

Figure 5. Observed annual precipitation for (top) YNP and GTNP (Wyoming Climate Divisions 1 and 2) and (bottom) the BICA region (Wyoming Climate Division 4). Annual values are shown in light gray. The 10-yr moving average (thick black line) is plotted to highlight decadal variability. Extended wet and dry regimes are shaded in blue and red, respectively. Results are similar for regional temperature observations (not shown).

abundance taken during a decadal-scale wet period against observations during a decadal-scale drought, for example, would indicate changes in the state of the system, even in the absence of land-use change, greenhouse-induced climate change or other anthropogenic forcing.

Strata of Interest: At the large spatial scales considered here, topography and vegetation types can serve as proxies for the major biomes and habitat classes in YNP and GTNP. When the distribution of climate monitoring sites in the GRYN is compared to regional topography (Figure 6) we see few stations

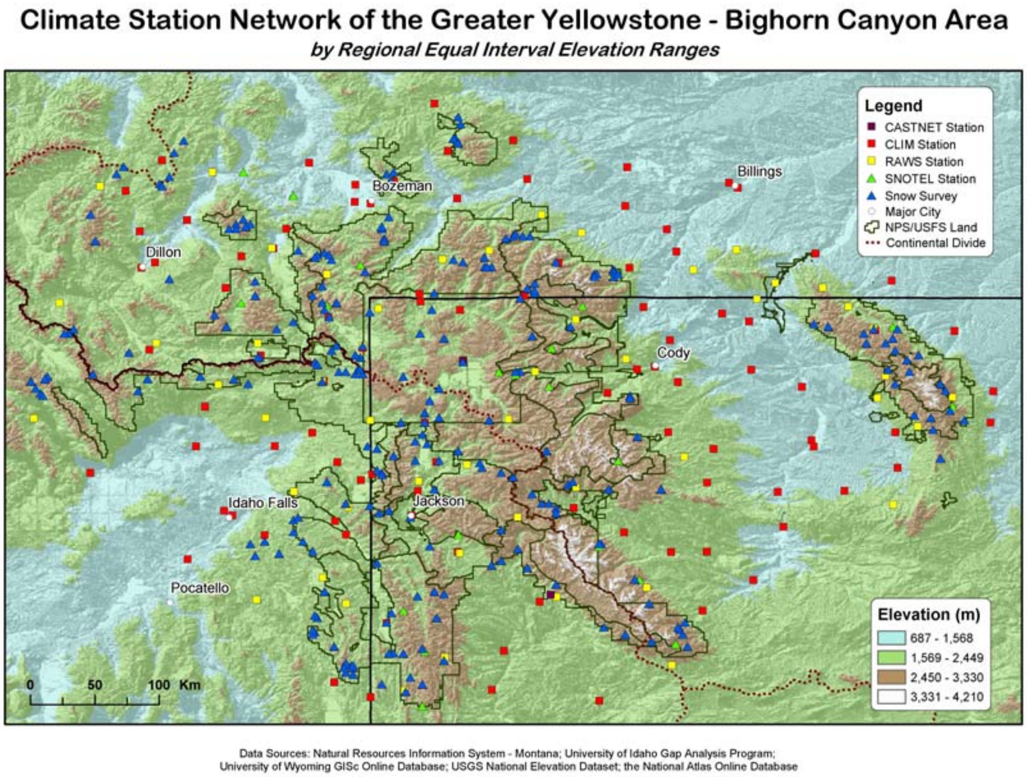

Figure 6. Distribution of GYE climate stations vs. elevation.

of any type above 2450 m (8000 feet). Most of these highest elevation stations are snow courses where the primary and secondary climatic elements (Sections 2.1-2.2) are not monitored. In YNP there are only two snowcourses above 2500 m (8200 feet). Three SNOTEL stations provide all of the primary and secondary climatic observations taken for YNP above 2500 m, even though 25% of the park's land surface is at or above this elevation. Moreover, two of these highest elevation sites (Sylvan Lake and Parker Peak) are located on the park's eastern boundary; in effect only one station in the YNP interior records climate above 2500 m (Two Ocean Plateau). In GTNP there are no stations recording primary and secondary elements above 2150 m (7050 feet), and only one snowcourse above this level. As a result, only about half of GTNP's land surface sees any type of climate monitoring.

Monitoring climate in the higher elevation regions of YNP and GTNP is essential for a number of reasons:

1. Much of the streamflow that provides surface water to lower elevation ecosystems, riparian areas and wetlands comes from high elevation areas.
2. In many analyses ecosystems that are already strongly constrained by climate are predicted to be the most heavily impacted by any future climate change (NAST, 2001). This is especially true for alpine systems

where plants and animals cannot migrate to higher elevations in response to increasing temperatures (Körner, 1999; Hansen et al. 2001; Bowman et al., 2002; Seastedt et al., 2004).

3. Observations and modeling exercises (e.g. Diaz and Bradley 1997, Bradley et al. 2004) indicate that the magnitude of future warming will likely be greatest at higher elevations and middle latitudes (~ 40-55º N). With much of their surface area above 2500 m (roughly 25%), GTNP and YNP would be especially vulnerable to predicted climate change.
4. Whitebark pine, a keystone species in the GYE and a GRYN vital sign, is primarily a high-elevation (high sub-alpine) species.

As for sampling climate relative to major vegetation types, climate stations in both GTNP and YNP are primarily located in areas dominated by lodgepole pine (Figure 7). Of the 42 monitoring stations within the boundaries of GTNP and YNP, 19 are located in lodgepole forest, and another 7 are located in or near burned areas that were once dominated by lodgepole. Lodgepole pine does cover a large portion of the GTNP and YNP land surface (> 30%), but a disproportionate number of stations are located in this habitat type (61%). In contrast, only two stations (one snowcourse, one SNOTEL) are located in either the limber pine or whitebark pine dominated areas that make up ~ 10% of the GTNP and YNP land area. No stations recording primary and secondary climatic elements are located in a wetland/riparian, mixed broadleaf or mixed conifer area.

These comparisons suggest that the current monitoring network in GTNP and YNP may not provide a comprehensive picture of climate variability in some key strata of interest. Based on these analyses alone, climate in the highest elevations of YNP and GTNP is not well sampled. In the case of sampling relative to major vegetation types, on the other hand, additional studies using modeling approaches and ground observations are needed to determine the extent to which observations from existing sites can be applied to surrounding cover types and habitats of interest. Can the climate record from a dry lodgepole pine forest, for example, serve as a proxy for climate in a wetland 10-30 km away? Or, will critical features of local to regional-scale climate be missed under the current system?

While only two stations represent BICA, the land area inside the recreation area is much smaller than that of the other GRYN parks (e.g. 1/5 of GTNP's area). The BICA region is also less topographically complex and features a relatively homogeneous vegetation-cover dominated by semi-arid grasslands, shrublands and woodlands (Figures 6 and 7). Analyses comparing precipitation and temperature recorded at Yellowtail Dam in BICA with observations at nearby stations show that climate in the National Recreation Area is highly correlated with climate in surrounding areas (Table 11). Correlations for precipitation are particularly high over the critical months of late spring and early summer (n = 7,

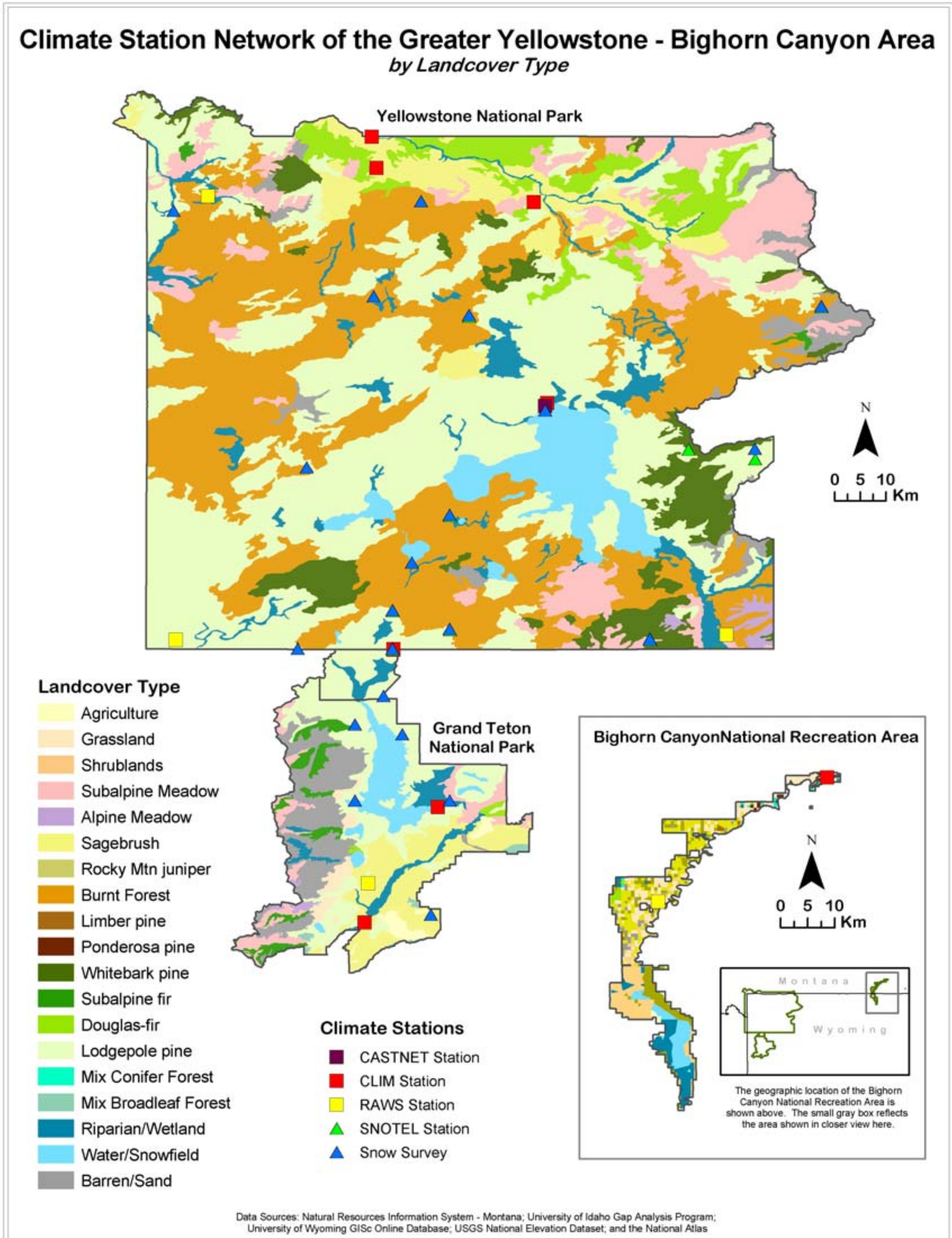

Figure 7. Distribution of GRYN climate stations vs. vegetation cover.

Table 11. Examples of correlations between precipitation at the Yellowtail Dam station and surrounding sites. Results were similar for temperature (not shown).

Yellowtail Dam, BICA			
	January	**June**	**Annual**
Bridger, MT	0.65	0.83	0.64
Lovell, WY	0.64	0.80	0.71

average r = 0.78) when BICA receives the majority of its rain and snowfall. This suggests that information from surrounding stations can serve as a reasonable surrogate for climate in the BICA region as whole.

One item for further investigation is the ability of the current network to capture sub-regional climate variability on the high plateaus and foothills surrounding Bighorn Canyon. These higher elevation areas provide critical wildlife habitat and likely contribute to discharge from area seeps and springs (another GRYN vital sign). While greater than half the national recreation area sits above 1250 m, BICA has no stations higher than this elevation. Most of the stations that surround BICA are also restricted to lower elevations (e.g. Lovell, WY = 1150 m) or, in the case of the Burgess Jct., WY station, found at locations much higher than BICA (2500 m). Additional stations might be desirable in the higher elevations of BICA or on surrounding BLM and Bighorn National Forest land. As suggested for YNP and GTNP, ground-based observations and modeling studies are needed to resolve this issue.

Spatial Variability: As mentioned previously, the topographic complexity in YNP and GTNP produces tremendous spatial variability in regional climate. To explore how well the current monitoring network captures this spatial heterogeneity, the locations of existing climate stations were compared against output from models that distribute climate data across complex terrain (Daly et al. 1994).

In terms of mean annual precipitation the current network fails to capture climate in the wettest areas of YNP and GTNP (Figure 8). Results were similar for a range of precipitation measures including mean monthly and seasonal rainfall or snowfall (not shown). This lack of sampling in the wettest areas of the parks is a direct result of the limited number of stations in the higher elevation snow basins. For this same reason the existing station network fails to measure climate variability in some of the coldest areas of the parks (not shown).

Measuring the most extreme climatic conditions experienced in a region is not an essential component of a successful climate-monitoring program *per se*. However, as mentioned previously the alpine and subalpine areas where the most extreme conditions in YNP and GTNP are likely to occur provide much of the streamflow and, in many cases, ground water recharge that supports key lower elevation systems. Moreover, whitebark pine is a predominant feature of many treeline communities, and higher-elevation ecosystems may be most susceptible to predicted 21st century warming (Diaz and Bradley 1997, NAST 2001, Bradley et al. 2004).

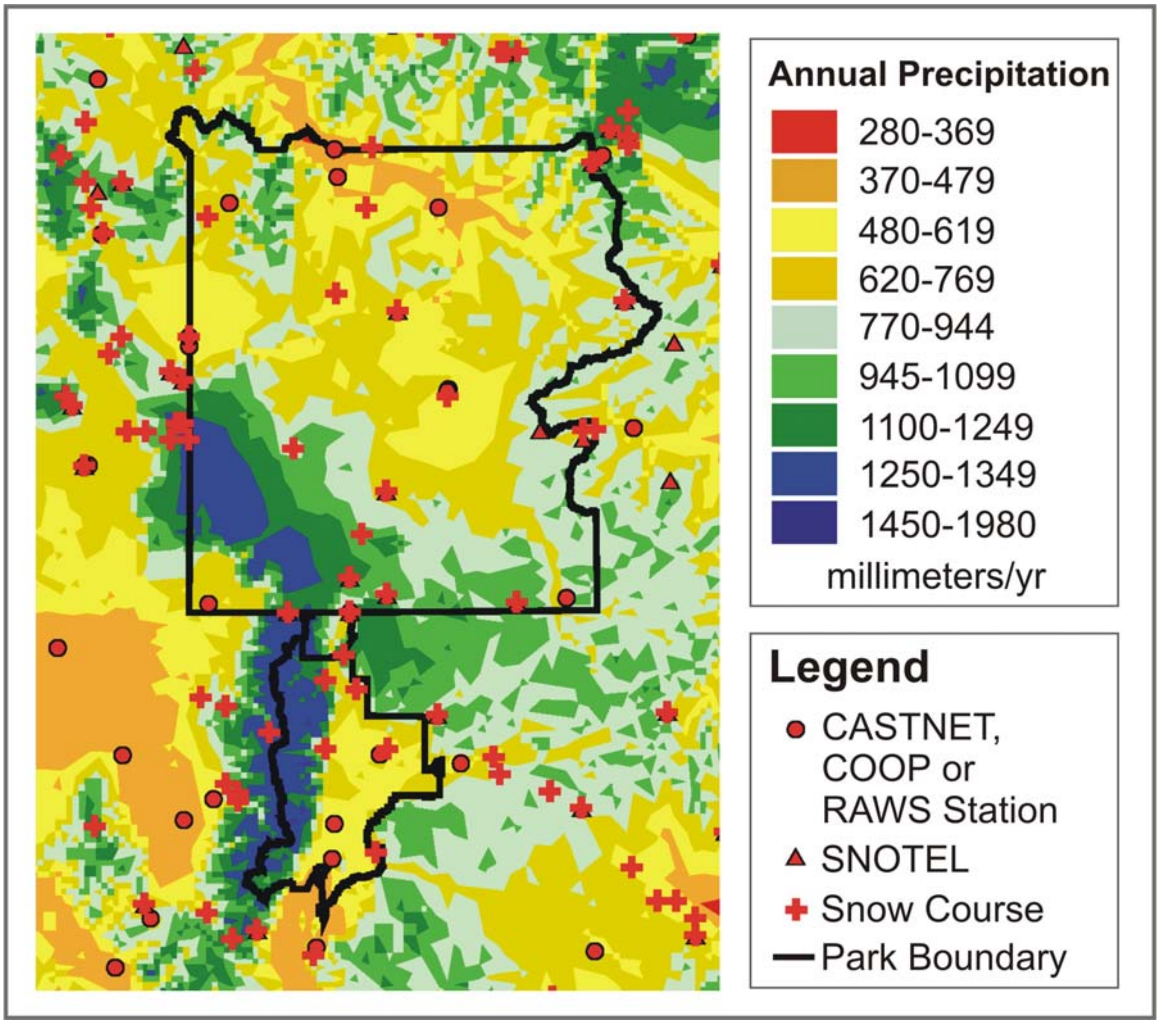

Figure 8. Distribution of climate stations in YNP and GTNP relative to annual precipitation over the period 1961-1990. Source: PRISM model estimates, available from: http://www.ocs.orst.edu/prism/.

Gaps in Geographic Coverage: Related in part to the lack of stations at higher elevations, but also driven by access and technical issues, large portions of YNP have no climate monitoring stations whatsoever. More specifically, in the northeast, southeast and southwest quadrants of YNP there are extensive tracts (2000-3000 km^2 or more) without a station of any type (Figures 6, 7 and 8). Such gaps or “holes” in the coverage of the current monitoring network may also represent key gaps in our knowledge of YNP climate. The coverage gap in the NE portion of the park, for example, coincides with the headwaters of the Lamar

River and vital rangelands and migration corridors for many large ungulates. Further studies using ground observations and modeling exercises are needed to determine how well information from existing stations can serve as a proxy for climate within these gap areas.

Does Data from the Current Network Meet GRYN I&M Needs?: When considering the "test case" of whitebark pine, the current network does not meet GRYN data needs. As detailed above there are no climate stations in areas dominated by whitebark pine, even though weather and climate are major drivers of white pine blister rust, a growing threat to this keystone species (Kendall and Keane 2001, Koteen 2002). Having climate stations in close proximity to whitebark pine communities may be especially important given that local variations in relative humidity are thought to play a major role in the spread of blister rust. Local temperatures also modulate bark beetle outbreaks, another threat to whitebark pine communities. Increasing average annual temperatures, coupled with milder winters and a longer growing season, have been implicated in recent bark beetle outbreaks throughout the Northern Rockies (Logan 2004, Hicke et al. 2004).

Such data gaps are likely for a number of key vital signs. In particular the paucity of stations in wetland/riparian areas might hinder efforts to understand amphibian populations. Likewise a lack of stations in the recharge zones of BICA's seeps and springs may limit our ability to understand these vital systems.

Another area of concern is the lack of automated sampling and reporting at a number of key GRYN climate stations. At stations such as Old Faithful, YNP and Moose, GTNP, for example, NPS personnel must visit the station each day to record observations and reset the instruments. Observations are then phoned in or mailed to the National Weather Service. In addition to the burden on NPS employees, this system has two major shortcomings. First, manual reporting introduces a lag of hours to months between the time of observation and the time when users can access those observations (NWS 2005). Second, this system produces observations with a very low temporal resolution; readings are usually taken once daily and only minimum and maximum temperatures are recorded. This sampling regime may be appropriate for understanding local to regional climatology and long-term climate variability/change. However, the need for greater temporal resolution can be anticipated for a number of vital signs (e.g. whitebark pine), as well as for understanding natural hazards and disturbances.

Finally, the outcomes from a workshop in held in March 2005 (http://www1.nature.nps.gov/im/units/gryn/monitoring.shtml) point to several key areas for improvement of the existing network. The participating NPS and USDA Forest Service personnel, as well as a number of non-agency scientists in attendance, all agreed that access to GRYN/GYE climate data must be improved. Suggestions included generating agreements that allow GRYN cooperators to access restricted or fee for service datasets. There was also a call for an improved web-based interface to access climate data as well as guidance from the climate-sciences community on how those data might be applied to problems in inventory, monitoring and natural resource management. Both NPS and USDA Forest Service personnel mentioned a lack of precipitation data at a high spatial resolution, particularly for rainfall over the summer months.

4.4 Recommendations

These recommendations for the further development of climate monitoring in the GRYN can be divided into two broad categories: (1) needs for additional monitoring and (2) maintenance and upgrades to the legacy system. Recommendations are listed in suggested order of importance.

1. *There must be no loss of climate stations (standard meteorological stations and snow-monitoring stations) with long, continuous records in either the parks of the GRYN or key surrounding areas (Table 12). The preservation of long-duration stations should be given the highest possible priority within the GRYN program.*

- Long-duration station records (50-100 or more years) provide a baseline for understanding climatic variability and change.
- Long-duration observations also provide context for interpreting baseline data for other vital signs.
- Long-duration climate records provide essential information for understanding the past dynamics of other GRYN vital signs.

Table 12. List of key stations with long-duration records within the parks of the GRYN. All stations were in operation at the time of this writing (Spring 2005).

Station Name	COOP ID	Start Year*
YNP Area		
Yellowstone NP	489905	1894
Tower Falls	489025	1948
Lake Yellowstone	485345	1904
Old Faithful	486845	1904
Snake River	488315	1905
West Yellowstone	248857	1924
GTNP Area		
Moose	486428	1958
Moran	486440	1911

BICA Area		
Yellowtail Dam	249240	1948

** Data may not be available for all years from start date through 2005.*
http://www.wrcc.dri.edu/

2. *Additional stations should be added to the network in locations or strata of interest that are not adequately sampled by the current system. The highest priority additions include:*

- High-elevation sites (above 2500 m) in GTNP and YNP.
- High-elevation areas dominated by whitebark pine and other 5-needle pines (key GRYN vital sign).

Higher elevation stations should be sited in areas where future ecological or hydrologic change is most likely. Such locations would certainly include treeline communities as well as sites at or near important biophysical thresholds related to number of frost free days, growing season temperatures, 1st/last freeze dates, etc. Areas where future warming might significantly alter the ratio of annual rainfall to snowfall or the timing of snowmelt/runoff should also be targeted. The ideal high-elevation sampling approach focuses on potential "centers of action" for future physical/biological change rather than placing stations on remote mountaintops for the sake of measuring extreme climatic conditions.

Potential additions requiring further study:

- Monitoring stations outside of lodgepole pine dominated areas in GTNP and YNP.
- New stations to fill geographic "data gaps" described in Section 4.3.
- New stations on the foothills and high plateaus surrounding BICA (including non-NPS lands).

3. *Key stations should be upgraded to new NWS-COOP network or similar standards. Key upgrades should provide:*

- Higher temporal resolution of observations.
- Automatic reporting of observations.

Automatic reporting is particularly important given that observations from old-style NWS-COOP stations within the GRYN must be recorded by park personnel or volunteers. Observations must then be transferred to the NWS by mail or telephone, creating a lag between recording and data access that may be as long as several weeks or months (NWS 2005). The recording and reporting process may also introduce several layers of error into the record. Many of the old COOP station instruments are obsolete, and will not provide the level of accuracy needed for some applications including the creation of a baseline dataset for detecting climatic variability and change (NWS 2005). Stations listed in Table 12 should be given the highest priority for upgrades.

4. *NPS-GRYN should designated a Climate Program Manager (CPM) to oversee:*

- o Production of reporting and analysis products.
- o Development of new monitoring sites.
- o Development of improved data transfer systems.

The CPM would serve as a liaison between park scientists, managers and the climate community. The CPM would also coordinate climate monitoring and reporting between the GRYN and surrounding networks.

4.5 Cost Sharing and Cooperation

Improving the legacy network of climate stations in the GRYN would bring tremendous benefits to a wide range of stakeholders. As a result, efforts to upgrade climate monitoring in the GRYN offer myriad opportunities for cooperation and coordination among agencies working in the GYE. The NPS and NOAA/NWS, for example, have recently developed a cooperative agreement that will lead to the expansion of climate monitoring in some National Parks (http://science.nature.nps.gov/im/monitor/docs/NOAA_NPS_MOA_2005_04_12_JEG.doc). In exchange for recommendations related to equipment and network design from NOAA/NWS, the NPS will purchase and install new climate stations within many national parks. Under this agreement NOAA/NWS furthers its goal of creating a comprehensive Integrated Surface Observing System that brings together weather/climate observations from a number of federal agencies, while the NPS receives the expertise needed to develop a professional grade climate-monitoring network for the national parks. The GRYN should make every effort to take advantage of this program. Similar cost-sharing arrangements could be made with other state and federal agencies working in the GYE, especially when their interests span national park boundaries.

5. COMPLIMENTARY MONITORING EFFORTS AND RESEARCH NEEDS

5.1 Complimentary Monitoring Programs

Monitoring Streamflow and Glacier Mass Balance in the GRYN

State variables that integrate multiple aspects of climate variability should also be considered as part of a comprehensive approach to monitoring the physical and biological impacts of climate on the GRYN. Monitoring of streamflow and the mass balance of glaciers/permanent snowfields is especially relevant because:

1) Changes in these systems result from the combined effects of moisture, temperature and wind regimes (Hall and Fagre, 2003) as well as, in the case of runoff, land cover and land-use change.
2) In many aquatic or riparian ecosystems throughout the Rocky Mountain West the effects of climate variability are often mediated through glacial runoff processes (Fagre et al., 1997; Fagre et al., 2003; Hall and Fagre, 2003).
3) The water provided by glaciers/snowfields and general runoff from the parks represents a primary service to surrounding communities and large portions of the United States as a whole (Fagre et al., 2003; Hall and Fagre, 2003).

Current Monitoring Efforts: Streamflows throughout the GRYN are monitored by the USGS (Table 14). These gages are usually located on the main stems of larger rivers and at easily accessible sites. While this network provides invaluable information on regional hydroclimatic variability, the lack of gages in headwaters areas or on smaller tributaries may represent and important data-gap for the GRYN. Smaller streams generally respond more rapidly to variations in climate (NAST, 2001; Wagner 2003). Small streams also provide key habitats for species of interest within the GYE (e.g. cutthroat trout).

Table 14. Key stream gages for the parks of the GRYN.

Agency	**Gage ID**	**Descriptive Gage Name**
YNP Region		
USGS	06036905	Firehole River near West Yellowstone
USGS	06036940	Tantalus Creek at Norris Junction
USGS	06037100	Gibbon River at Madison Junction
USGS	06187950	Soda Butte Creek near Lamar Ranger Station
USGS	06188000	Lamar River near Tower Ranger Station
USGS	06190540	Boiling River at Mammoth
USGS	06037500	Madison River near West Yellowstone
USGS	06186500	Yellowstone River at Yellowstone Lake Outlet
GTNP Region		
USGS	13010065	Snake River at Flagg Ranch
USGS	13011000	Snake River near Moran
USGS	13011500	Pacific Creek near Moran
USGS	13011900	Buffalo Fork above Lava Creek near Moran
USGS	13013650	Snake River at Moose
USGS	13015000	Gros Ventre River at Zenith

USGS	13016305	Granite Creek Above near Moose
BICA Region		
USGS	06274300	Bighorn River at Basin
USGS	06285100	Shoshone River near Lovell
USGS	06216000	Pryor Creek at Pryor
USGS	06287000	Bighorn River near St. Xavier

http://waterdata.usgs.gov/nwis

Glacier and snowfield monitoring has focused primarily on GTNP. In particular estimates of summer and winter mass balance have been combined with remote sensing data to track the dynamics of key glaciers in the Teton Range (e.g. Elder et al. 1994). Related modeling experiments have also produced forecasts for the response of GTNP glaciers to future climate variability and change (e.g. Plummer and Cecil 2005). The GRYN should consider a more detailed analysis of current glacier and snowfield monitoring with an emphasis on exploring how additional ground-based measurements might complement remotely-sensed data.

Atmospheric Chemistry and Deposition

Deposition of nitrogen (N), as well as other airborne pollutants (e.g. PCBs, organochlorines, lead, mercury, etc.), poses a severe and immediate threat to ecosystems around the globe (Vitousek et al., 1997; NAST, 2001). The impacts of N deposition may be especially strong in alpine environments because high-elevation ecosystems generally lack the capacity to buffer against anthropogenic inputs (Fenn et al., 2003). Atmospheric pollution may also exacerbate the effects of climate change on natural ecosystems through its direct effects on productivity and indirect effects related to altered disturbance regimes and exotic species invasions (NAST, 2001; Bowman et al., 2002; Fenn et al., 2003).

Current Monitoring Efforts: As part of the Clean Air Status and Trends Network program (CASTNET; EPA, 2004), the U.S. Environmental Protection Agency has been monitoring atmospheric deposition in YNP since 1996. This EPA monitoring focuses on dry deposition at one site near Lake Villiage. Over the past decade a number of locations in YNP have also been monitored for wet deposition (http://www2.nature.nps.gov /air/Monitoring/MonHist/staterpt.cfm). Snowpack chemistry is monitored at a number of sites in YNP and GTNP (Nanus and Campbell 2003).

This existing network is not likely to provide a complete picture of airborne pollution in the GRYN. Previous studies have shown that atmospheric deposition in the Rocky Mountains varies greatly from one side of the Continental Divide to the other (Rueth and Baron, 2002), and few of the existing monitoring sites are located east of the divide. Nanus and Campbell (2003) also report discrepancies between readings of pollutants in YNP/GTNP and surrounding areas that may indicate that these stations are not in ideal locations to capture regional pollution trends. There are currently no comprehensive wet monitoring sites (e.g. National Atmospheric Deposition Program/National Trends Network stations) in GTNP. There are no monitoring sites in BICA, although deposition information is available for Little Bighorn Battlefield National Monument. Furthermore, many wet deposition and snow monitoring sites in YNP and GTNP have been discontinued in recent years (Nanus and Campbell 2003).

Because of both its strong relationship to climate and its impact on other vital signs in the GYE (e.g. water chemistry, aquatic invertebrate assemblages, amphibians), expanded atmospheric chemistry and deposition monitoring would be a logical extension of the GRYN program. Simple, cost-effective sensors or collection units might be collocated with climate-monitoring stations and sampling sites for other vital signs. Overall, its location (e.g. straddles the Continental Divide, downwind from several major pollution sources), lack of industry, high biodiversity, abundance of alpine ecosystems, and cultural significance make the GYE, and the parks of the GRYN in particular, key locations for monitoring atmospheric chemistry and deposition.

The National Phenology Network

Phenology is the study of plant and animal life-cycle events, such as first flower openings, insect hatchings, and bird migration dates. Changes in the timing of these events represent the integrated responses of Earth's biosphere to environmental variations. Phenology has been a key component of detecting the impacts of climate variability at individual sites and across regions (e.g. Caprio 1993, Cayan et al. 2001, Schwartz 1993, Zhao and Schwartz 2003), and will likely play an important role in understanding climate-ecosystem and climate-vital sign interactions in the GRYN (See Section 5.2, “Primary Research Needs”).

As an outgrowth of the proposed National Ecological Observatory Network (NEON; www.neoninc.org) a number of universities and federal agencies are developing the framework for a National Phenology Network (NPN) that will facilitate investigations of plant phenological cycles and their relationship to climate. The NPN will encompass up to 10,000 sites and rely heavily on volunteer cooperators. In the GRYN, in particular, NPN data could aid in evaluating the impacts of climate variability and change on pollinators, forest pests, wildfires, and ungulate populations. The GRYN I&M program should consider an active role in the development of the NPN, especially as it relates to the establishment of phenological observing sites in the GYE. Ideally NPN sites could be collocated with GRYN climate-monitoring stations and maintained by volunteer observers. This approach would maximize our ability to link climate and phenology data; engage both the public and scientific communities; and require little or no NPS funding.

5.2 Primary Research Needs

Improved Data Transfer: A large amount of high-quality climate data from the GRYN/GYE is now available via the World Wide Web. Many of these web-accessible records include additional elements beyond standard temperature, precipitation and wind measurements, and much of this data is updated at hourly or better intervals. These datasets are, however, hosted by a number of different agencies, and navigating the vast amounts of available climate information can be a daunting and time-consuming task. Efforts are currently underway to streamline access via the web (see http://www.wrcc.dri.edu/climsum.html and http://www.met.utah.edu/jhorel/html/mesonet/), but there are a number of factors that continue to limit the usefulness of this data for NPS personnel, cooperators and stakeholders. First, many of these datasets are in various states of quality control, and it may not be obvious what level of reliability they achieve. Second, data are only available for point locations within the GRYN/GYE. As a consequence, it is very difficult for users to obtain a mesoscale view of climate variability in the region or, for that matter, a single park.

To maximize the usefulness and accessibility of GRYN/GYE climate data, future efforts must also concentrate on:

1. Rapid data transfer.
2. Improved quality control and network-wide quality control standards.
3. Development of software and web access that allows users to develop a mesoscale or synoptic view of current and past GYE climate (*see* http://www.mesonet.org/ *for examples*).

These goals are almost universal in the climate-monitoring community, and many efforts are underway to achieve them. This means that the parks of the GRYN need not develop these capabilities on their own. Nevertheless, the parks must still recognize the need for these items and, if they are to obtain maximum benefit from this work, become involved in some aspect of their development.

Developing Records of Long-term Climate Variability: Numerous studies from throughout the world demonstrate that instrumental weather records are insufficient for capturing the full range of natural climate variability in a region (Cook and Evans, 1999). This is particularly true for extreme events like droughts. The length of these instrumental records rarely exceeds 100 years, and therefore provides only a small sample of single- and multi-year droughts. Furthermore, instrumental records cannot be used to effectively examine long-term (> 50 year) trends and cycles that may underlie year-to-year variability (Pederson et al. 2005).

Paleo archives such as lake sediments and tree-rings provide a means for developing long-duration climate records that can overcome many of the limitations inherent to instrumental observations. In the Northern Rockies tree-rings can be especially useful sources of paleoclimatic information because they yield continuous, exactly-dated proxies of climate that are highly replicable. Tree-rings provide records of seasonal to annual climate, and can be used to assess climate variability on timescales of decades to millennia. Though annual resolution may not be obtained from all types of lake and wetland sediments, these records often span several millennia, thereby providing a unique source of information on long-term environmental change.

Further development of long-term climate reconstructions is an essential part of a comprehensive climate monitoring program for the GRYN because these paleo-records provide:

1. Insights into long, slow processes not captured in instrumental records (e.g. decadal to millennial variability)
2. A wider range of extreme climatic scenarios than is captured in short-duration instrumental records
3. A true baseline for detecting environmental change

Exploring the influence of climate variability on species and ecosystems in the GRYN: While it is universally recognized that climate plays a key role in controlling species distributions and population dynamics - as well as many other aspects of ecosystem structure and function - in the GYE, the vast majority of research on this relationship has been anecdotal or correlative in nature. Future efforts must move towards a mechanistic understanding of the links between climate and ecological processes. This will, in turn, lead to a more complete picture of climate-ecological interactions, as well as improved predictions for future species- and ecosystem-responses to climatic variability and climate change.

Exploring the role of lower-frequency climate variability in the GRYN: Both natural climatic variability and predicted human-induced climate change include strong decadal to centennial-scale components (Wagner, 2003; Cayan et al., 1998; Gray et al., 2003; 2004). Such low frequency climate variability can have a strong influence on disturbance processes, population dynamics, and ecosystem structure far beyond that of most short-duration (days to months) or annual-scale events (Swetnam and Betancourt, 1998; Chavez et al., 2003; Hessl et al., 2004). Recent research also shows how such lower-frequency climatic variability can affect the services provided by national parks (Pederson et al. 2005). This relationship between lower-frequency climate variability and physical/ecological phenomena has been little explored in the GYE. Future research should concentrate on identifying the mechanisms that link lower-frequency climate variability to physical systems and ecosystem dynamics, as well as exploring how the legacies of long-duration climatic anomalies (e.g. multi-year droughts, the Little Ice Age, etc.) persist on the landscape.

Spatial variability of GRYN climate: The GRYN encompasses a vast area supporting myriad vegetation- and ecosystem-types in a topographically complex setting. Even when one accounts for the enormous technological leaps that instrumental climatology will undoubtedly experience in the future, it will never be possible to fully sample the climate of the GRYN. With a better understanding of spatially variability in GRYN climate we can, however, maximize sampling efforts. New statistical methods and geographic information technologies also allow for robust interpolation between networks of stations and, more importantly, corrections for heterogeneous topography (Running et al., 1987; Daly et al., 1994; Thornton et al., 2000). Much preliminary work employing dense arrays of climate sensors will be needed to define this spatial variability and to develop the calibration datasets needed to accurately apply topographic corrections. Some related efforts, particularly those aimed at understanding the distribution of snowpack in YNP and GTNP have been underway since the early 1990s (e.g. Farnes 1996, Farnes et al. 1999, 2000), but a comprehensive effort to examine both precipitation and temperature variability throughout the year is still needed.

6. LITERATURE CITED

Baker, W.L., 2003. Fires and climate in forested landscapes of the U.S. Rocky Mountains. pp. 120-157, in: Veblen, T.T., W.L. Baker, G. Montenegro, and T.W. Swetnam, (eds.), *Fire and Climatic Change in Temperate Ecosystems of the Western Americas*. Springer, New York.

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

Baron, J.S., 2002. *Rocky Mountain Futures: An Ecologoical Perspective*. Island Press.

Bonan, G.B., 2002. *Ecological Climatology: Concepts and Applications*. Cambridge University Press, Cambridge.

Bowman, W.D., D. M. Cairns, J.S. Baron, and T.R. Seastedt. 2002. Islands in the Sky: Tundra and Treeline Ecosystems of the Rockies. pp. 183-202, in: Baron, J.S., (ed.), *Rocky Mountain Futures: an Ecological Perspective*. Island Press.

Bradshaw, L.S, J.E. Deeming, R.E. Burgan, and J.D. Cohen, 1984. The 1978 National Fire-Danger rating system: Technical Documentation. USDA Forest Service Gen. Tech. Rep. INT-169.

Bradley, R.S., F.T. Keimig, H.F. Diaz, 2004. Projected temperature changes along the American Cordillera and the planned GCOS network. Geophysical Research Letters, 31, L16210, doi:10.1029/2004GL020229.

Burroughs, W., 2003. *Climate into the 21st Century*. Cambridge University Press.

Caprio, J. M. 1993. *Western Regional Phenological Summary of Information on Honeysuckle and Lilac First Bloom Phase Covering the Period 1956-1991*. Montana Agricultural Experiment Station State Climate Center Circular No. 3, 92 pp.

Carter, T.R. and E.L. La Rovere, 2001: Developing and Applying Scenarios. In Climate Change: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the IPCC Third Assessment Report.

Casale, R. and C. Margottini (eds.), 1999. *Floods and Landslides: Integrated Risk Assessment.* Springer-Verlag, New York.

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

Cayan, D. R., Kammerdiener, S. A., Dettinger, M. D., Caprio, J. M., & D. H. Peterson, 2001. Changes in the Onset of Spring in the Western United States. *Bulletin of the American Meteorological Society* 82: 399-415.

Chavez, F.P., J. Ryan, S.E. Lluch-Cota, M. Niquen, 2003. From anchovies to sardines and back: multidecadal change in the Pacific Ocean. *Science*, 299:217-221.

Cook, E.R. and M.N. Evans. 1999. Improving estimates of drought variability and extremes from centuries-long tree ring chronologies: A PAGES/CLIVAR example. PAGES/CLIVAR Newsletter, 8:9-10.

Curtis, J. and K. Grimes. 2004. *Wyoming Climate Atlas*. Office of the Wyoming State Climatologist, Larmie, Wyoming.

Daly, C., R.P. Neilson, and D.L. Phillips, 1994. A statistical-topographic model for mapping climatological precipitation over mountanious terrain. *J. Appl. Meteor.*, 33:140-158.

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

Despain, D.G., 1990. *Yellowstone Vegetation: Consequences of Environment and History in a Natural Setting*. Roberts Rinehart, Inc, Boulder, CO.

Diaz, H.F. and R.S. Bradley, 1997: Temperature variations during the last century at high elevation sites. Climatic Change, 21, 21-47.

Elder, K., S. Fullerton, and K. Tonnessen, 1994. Winter mass balance measurements on Teton Glacier, Grand Teton National Park. *Park Science* 14:11-13.

EPA (Environmental Protection Agency), 2004. Overview of CASTNET Program. Available at: http://www.epa.gov/castnet/overview.html.

Fagre, D. B., D. L. Peterson, and A. E. Hessl, 2003. Taking the pulse of the mountains: ecosystem responses to climate variability. *Climatic Change*, 59:263-282.

Fagre, D. B., P. L. Comanor, J. D. White, F. R. Hauer, and S. W. Running, 1997. Watershed responses to climate change at Glacier National Park. *J. Amer. Water Res. Assoc.*, 33:755-765.

Farnes, P. 1996. An index of winter severity for elk. Pages 303-310, in F. Singer, ed. Effects of grazing by wild ungulates in Yellowstone National Park Technical Report. NPS-96-01, NPS, Denver, CO.

Farnes, P., C. Hayden, and K. Hansen. 1999. Snowpack distribution in Grand Teton National Park and Snake River Drainage above Jackson, Wyoming. Department of Earth Sciences, Montana State University.

Farnes, P., C. Heydon and K. Hansen. 2000. Snowpack in Yellowstone National Park. Department of Earth Sciences, Montana State University.

Fenn, M.E., J.S. Baron, E.B. Allen, H.M. Rueth, K.R. Nydick, L. Geiser, W.D. Bowman, J.O. Sickman, T. Meizner, D.W. Johnson, and P. Neitlch, 2003. Ecological effects of nitrogen deposition in the Western United States. *BioScience*, 53:404-420.

Garman, S.L., M. Beer, M.A. Powell, R. DenBleyker. 2004. Climate Monitoring Protocol for the Park Units in the Northern Colorado Plateau Network. National Park Service, Moab, Utah.

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

Gray, S.T., J.L. Betancourt, C.L. Fastie, and S.T. Jackson, 2003. Patterns and sources of multidecadal oscillations in drought-sensitive tree-ring records from the central and southern Rocky Mountains. *Geophysical Res. Letts.*, 30:10.1029/2002GL016154.

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

Greenland, D. editor, 1986. Standardized Meteorological Measurements for Long Term Ecological Research Sites. Prepared by The Long term Ecological Research Climate Committee. Niwot Ridge/Green Lakes Valley Site. University of Colorado, Boulder, Colorado.

Guttman, N.B. and R.G. Quayle. 1996. A historical perspective of U.S. climate divisions. *Bull. Amer. Meteorological Soc*. 77:293-303.

Hall, M. P. and D. B. Fagre, 2003. Modeled climate-induced glacier change in Glacier National Park, 1850-2100. *Bioscience,* 53:131-140.

Hansen A.J., R.R. Neilson, V.H. Dale, C.H. Flather, L.R. Iverson, D.J. Currie, S. Shafer, R. Cook, and P.J. Bartlein, 2001. Global change in forests: Responses of species, communities, and biomes. *Bioscience,* 51:765-779

Hartman, D.L. 1994. *Global Physical Climatology*. Academic Press.

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

Hicke, J.A., J.A. Logan, J. Powell, D.S. Ojima. 2004. Increasing temperatures in mountainous regions of the western United States and effects on insect outbreaks. *Eos Trans., 85*(47), Fall Meet. Suppl., Abstract U52a-07.

Hughes, P. 1980. American weather services. *Weatherwise*, 33:100-111.

Hulme, M. and M. New, 1997. The dependence of large-scale precipitation climatologies on temporal and spatial gauge sampling. J.Climate, 10, 1099-1113.

Hulme, M., J.F.B. Mitchell, W. Ingram, T.C. Johns, J.A. Lowe, M.G. New and D. Viner, 1999. Climate change scenarios for global impacts studies. Global Environ. Change, 9, S3-S19.

IPCC (Intergovernmental Panel on Climate Change), 2001. Contribution of working group I to the third assessment report of the intergovernmental panel on climate change. In: *Climate Change 2001: The Scientific Basis.* (eds.) Houghton J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, and D. Xiaosu. Cambridge University Press.

Jacobson, M.C., R.J. Charlson, H. Rodhe, and G.H. Orians, 2000. *Earth System Science: From Biogeochemical Cycles to Global Change.* Academic Press, San Diego.

Karl, T.R., and C.W. Williams, Jr., 1987: An approach to adjusting climatological time series for discontinuous inhomogeneities, *J. Climate Appl. Meteor.*, 26, 1744-1763.

Karl, T.R., C.N. Williams, Jr., F.T. Quinlan, and T.A. Boden, 1990: United States Historical Climatology Network (HCN) Serial Temperature and Precipitation Data, Environmental Science Division, Publication No. 3404, Carbon Dioxide Information and Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN, 389 pp.

Karl, T.R., C.N. Williams, Jr., P.J. Young, and W.M. Wendland, 1986: A model to estimate the time of observation bias associated with monthly mean maximum, minimum, and mean temperature for the United States, *J. Climate Appl. Meteor.*, 25, 145-160.

Kendall, K. C. and R. E. Keane. 2001. Whitebark pine decline: Infection, mortality, and population trends. Pages 221-242 in Tomback, D.F., S.F. Arno, and R.E. Keane, editors. Whitebark pine communities: Ecology and restoration. Island Press. Washington, DC.

Körner C., 1999. *Alpine Plant Life: Functional Plant Ecology of High Mountain Ecosystems*. Springer, Berlin.

Koteen, L. 2002. Climate Change, Whitebark Pine, and Grizzly Bears in the Greater Yellowstone Ecosystem. In Wildlife Responses to Climate Change. Eds. H. Schneider and T.L. Root. Island Press, Washington.

Logan, J.A. 2004. Climate Change Altered Disturbance Regimes in High Elevation Pine Ecosystems. *Eos Trans., 85*(47), Fall Meet. Suppl., Abstract U52a-03.

Mann M.E., R.S. Bradley, and M.K. Hughes, 1999. Northern hemisphere temperatures during the past millennium: inferences, uncertainties, and limitations. *Geophysical Res. Letts,* 26:759-762.

Martner, B.E. 1986. Wyoming Climate Atlas. University of Nebraska Press, Lincoln, Nebraska.

Mock, C.J. 1996. Climatic Controls and Spatial Variations of Precipitation in the Western United States. *J. Climate,* 9: 1111-1125.

Mote, P.W. 2003: Trends in snow water equivalent in the Pacific Northwest and their climatic causes. *Geophys. Res. Lett.,* 30:10.1029/2003GL017258.

Nanus, L. and D.H. Campbell. 2003. Analysis of air quality information for vital signs selection: Yellowstone and Grand Teton National Parks, Bighorn Canyon National Recreation Area. National Park Service, Bozeman, Montana.

NAST (National Assessment and Synthesis Team), 2001. *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change.* Report for the U.S. Global Change Research Program, Cambridge University Press, Cambridge, UK.

NPS (National Park Service), 2003. *Vital Signs Monitoring Plan: Phase II Report*. Greater Yellowstone Inventory and Monitoring Network, National Park Service, Bozeman, MT.

NRC (National Research Council), 1990. *Snow Avalanche Hazards and Mitigation in the United States.* National Research Council Committee on Ground Failure Hazards and Mitigation. National Academy Press, Washington, D.C.

NWS (National Weather Service). 2003. *Instrument Requirements and Standards for the NWS Surface Observing Programs (Land)*. National Weather Service Instruction Manual 10-1302. National Oceanic and Atmospheric Administration, Washington D.C. Available at: http://www.nws.noaa.gov/directives/010/pd01013002b.pdf.

NWS (National Weather Service). 2005. Coop Modernization. Available at: http://www.nws.noaa.gov/om/coop/coopmod.htm.

NWCG (National Wildfire Coordinating Group), 2005. *National Fire Danger Rating System Weather Station Standards.* National Interagency Fires Center Publication PMS-426-3. National Interagency Fire Center, Boise, ID. Available at: http://www.fs.fed.us/raws/standards.shtml.

Pederson, G.T., S.T. Gray, D.B. Fagre and L.J. Graumlich. 2005. Long-Duration Drought Variability and Impacts on Ecosystem Services: A Case Study from Glacier National Park, Montana USA. *Earth Interactions* (in press).

Peterson, T.C., and D.R. Easterling, 1994: Creation of homogeneous composite climatological reference series, *Int. J. Climatol.*, 14, 671-680.

Quayle, R.G., D.R. Easterling, T.R. Karl, and P.Y. Hughes, 1991: Effects of recent thermometer changes in the cooperative station network, *Bull. Am. Meteorol. Soc.*, 72, 1718-1724.

Redmond, K.T., D.B. Simeral and G.D. McCurdy. 2005. Climate Monitoring for Southwest Alaska National Parks: Network Design and Site Location. Western Regional Climate Center, Reno, Nevada.

Rueth, H.M., and J.S. Baron, 2002. Influence of elevated nitrogen deposition on Rocky Mountain Englemann spruce forest nitrogen cycling. *Ecosystems,* 5:45-57.

Running, S.W., R.R. Nemani, R.D. and Hungerford, 1987. Extrapolation of synoptic meteorological data in mountainous terrain and its use for simulating forest evapotranspiration and photosynthesis. *Can. J. For. Res.*, 17:472-483.

Schwartz, M. D. 1993. Assessing the Onset of Spring: A Climatological Perspective. *Physical Geography* 14(6): 536-550.

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

Seastedt T.R., W.D. Bowman, T.N. Caine, D. Mcknight, A. Townsend and M.W. Williams, 2004. The landscape continuum: a model for high-elevation ecosystems. *Bioscience* 54:111-121.

Selkowitz, D., 2003. Compilation and Analysis of Climate Data in the Greater Yellowstone Ecosystem/Bighorn Canyon Area: Completed Products, Problems Encountered, and Recommendations for the Future. Greater Yellowstone Network, National Park Service Inventory and Monitoring Program, Bozeman, MT.

Singh, V.P. (ed.), 1996. *Hydrology of Disasters*. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Sousanes, P.J. 2004. Climate Monitoring Protocols for the Central Alaska Network. National Park Service, Denali Park, Alaska.

Stewart, I., Cayan, D.R., and Dettinger, M.D., 2004 Changes in snowmelt runoff timing in western North America under a 'Business as Usual' climate change scenario. *Climatic Change*, 62, 217-232.

Swanson, F.J., 1981. Fire and geomorphic processes. In (eds.) Mooney, H.A., T.M. Bonnicksen, N.L. Christensen, J.E. Lotan, and W.A. Reiners. Fire Regimes and Ecosystem Properties. USDA Forest Service Gen. Tech. Rep. WO-26.

Swetnam, T.S. and J.L. Betancourt. 1998. Mesoscale disturbance and ecological response to decadal climate variability in the American Southwest. *J. Climate*, 11:3128-3147.

Thornton, P.E., H. Hasenauer, and M.A. White, 2000. Simultaneous estimation of daily solar radiation and humidity from observed temperature and precipitation: An application over complex terrain in Austria. *Agricultural and Forest Meteorology,* 104:255-271.

USDA Forest Service, 2004. Remote Automated Weather Stations. Available at: http://www.fs.fed.us/raws/.

USGCRP (U.S. Global Change Research Program), 2003. Strategic Plan for the U.S. Climate Change Science Program. Climate Change Science Program, NOAA-Department of Commerce, Washington, D.C.

Vitousek, P.M., J.D. Aber, R.W. Howarth, G.E. Likens, P.A. Matson, D.W. Schindler, W.H. Schlesinger and D. Tilman, 1997. Human alteration of the global nitrogen cycle: sources and consequences. *Ecological Applications,* 7: 737-750.

Wagner, F.H. (ed.), 2003. *Rocky Mountain/Great Basin Regional Climate Change Assessment. A Report of the Rocky Mountain/Great Basin Regional Assessment Team for the U.S. Global Change Research Program.* Utah State University, Logan, UT.

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

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

WMO (World Meteorological Organization). 1971. Guide to Meteorological Instrument and Observing practices, 4th edition, WMO No 8, TP3. Geneva.

Zhao, T., & M. D. Schwartz, 2003. Examining the Onset of Spring in Wisconsin. *Climate Research* 24(1): 59-70.