National Park Service
U.S. Department of the Interior

Natural Resource Program Center

# Framework for Linking Climate, Resource Inventories, and Ecosystem Monitoring

Natural Resource Technical Report NPS/GRYN/NRTR–2008/110

Printed copies of reports in this series may be produced in limited quantity, and are only available as long as the supply lasts. You may send a request to:

Greater Yellowstone Network
229 AJM Johnson Hall
Montana State University
Bozeman, Montana 59717

This report is also available electronically from the Greater Yellowstone Network website, http://science.nature.nps.gov/im/units/GRYN/index.cfm or from the NPS Natural Resouce Publications Management website, http://www.nature.nps.gov/publications/NRPM.

When original printed copies are exhausted, copies can be obtained from:
Technical Information Center (TIC)
Denver Service Center
National Park Service
P.O. Box 25287
Denver, CO 80225-0287

Please cite this publication as:
Gray, S. T. 2008. Framework for linking climate, resource inventories and ecosystem monitoring. Natural Resource Technical Report NPS/GRYN/NRTR-2008/110. National Park Service, Fort Collins, Colorado.

NPS D-1982, May 2008

**ON THE COVER: Recent willow height increases in the Lamar Valley may be due in part to climate change.**

# Framework for Linking Climate, Resource Inventories, and Ecosystem Monitoring.

Natural Resource Technical Report NPS/GRYN/NRTR–2008/110

Stephen T. Gray
Office of the Wyoming State Climatologist
University of Wyoming, Laramie, WY

May 2008

U.S. Department of the Interior
National Park Service
Natural Resource Program Center
Fort Collins, Colorado

# Contents

# Figures

# Tables

# Acronyms

| | |
|---|---|
| ACIS | Applied Climate Information System |
| COOP | Cooperative Observer Program |
| CPC | Climate Prediction Center |
| GRYN | Greater Yellowstone Network |
| GYE | Greater Yellowstone Ecosystem |
| I&M | Inventory and Monitoring Program |
| NCDC | National Climatic Data Center |
| NDVI | Normalized Difference Vegetation Index |
| NIDIS | National Integrated Drought Information System |
| NOAA | National Oceanic and Atmosphic Administration |
| NPS | National Park Service |
| NRCS | Natural Resources Conservation Service |
| NWS | National Weather Service |
| PDSI | Palmer Drought Severity Index |
| RAWS | Remote Automated Weather Station |
| RISA | Regional Integrated Sciences and Assessments Program |
| ROMN | Rocky Mountain Network |
| SPI | Standardized Precipitation Index |
| SWE | Snow Water Equivalent |
| SWSI | Surface Water Supply Index |
| USDA | United States Department of Agriculture |
| WSCO | Wyoming State Climate Office |

# Abstract

Climate is one of the strongest factors controlling ecosystem processes and, in turn, so-called "vital signs" within National Park Service units. The importance of climate as a primary driver of park ecosystems, combined with ongoing droughts and the threat of climate change, emphasize the need to integrate knowledge of climate into the NPS' Inventory and Monitoring (I&M) Program. Limited access to climate data and a paucity of efforts to convert raw observations into a form that can be used by most I&M personnel have greatly limited this integration.

The following report contains a series of recommendations for bridging the gap between climate-data providers and personnel involved in the inventory and monitoring of NPS resources. More specifically this report concentrates on the needs of NPS-I&M personnel and cooperators involved in ecologically-oriented work. Key recommendations include:

- Establishing a three-tiered system that would provide basic climate summaries at the park and network level; improved access to basic climate data; and a variety of tools to aid in the analysis of these climate data.

- Developing "climate atlases" that would serve as a reference for those seeking general information about park and network-scale climates.

- Developing education and outreach components to help NPS personnel and cooperators locate, analyze, and interpret climate-related products.

Overall, this report emphasizes the pressing need for improved data access, and the creation of a variety of products that track and summarize park to network-level climate. Many of these recommendations—especially those related to the creation of a data-distribution portal—are currently being implemented as part of the NPClime program (see http://science.nature.nps.gov/im/inventory/climate/). Important future steps include the continued funding and development of NPClime, and the regular production of "climate almanacs" that describe conditions at the park to network or regional level.

# Acknowledgements

This report relies heavily on input from the many NPS and I&M personnel that attended workshops on this topic in 2005 and 2006, as well as comments from over two-dozen non-NPS researchers who agreed to be interviewed or surveyed for the analyses in Section II. Tony Bergantino (Wyoming WRDS and WSCO) provided invaluable assistance related to electronic tracking of climate-data requests used in Section II.

# I. Overview

Climate exerts strong controls over almost all physical and ecological processes. In particular climate regulates ecosystem fluxes of energy and matter as well as the geomorphic and biogeochemical processes underlying the distribution and structure of ecosystems (Jacobson et al., 1997; Schlesinger, 1997; Bonan, 2002). Climate also regulates the frequency and intensity of disturbances (Swetnam and Betancourt 1998), and paces the rate at which species can invade a given area (Lyford et al. 2003, Gray et al. 2006). Ecologists and ecosystem managers must in turn possess a working knowledge of climate variability and the potential for future climatic change.

The use of climatic data to help understand and interpret ecological events is becoming an increasingly important component of the National Park Service (NPS) Inventory and Monitoring (I&M) Program. Climate has also been identified as a primary vital sign by all I&M networks. Unfortunately obtaining useful climatic data and climate-related information can be extremely difficult for workers outside of the atmospheric sciences. Even in this age of the World Wide Web climate data for a specific park unit or location within a park can be almost impossible to obtain, and the quality of metadata often leaves much to be desired. Moreover ecologists have few opportunities to place recent climatic events in a longer-term perspective, or to study how local climatic variability fits into a larger spatial context.

Recognizing a need for improved access to climate data and climate-related information, the Greater Yellowstone Network funded this one-year pilot study aimed at:

(1) Identifying requirements for climate data among NPS ecologists and I&M personnel.
(2) Developing a model for improved climate-data delivery and analysis within the I&M Program.

These issues were first addressed by using a variety of survey techniques to identify needs within the NPS' ecosystem sciences user community. These surveys focused on singling out preferred means of data delivery, and identifying potential applications within the NPS and I&M Program. Requirements for data on specific climatic elements (e.g. precipitation, wind, solar radiation), as well as the necessary spatial and temporal resolution of these data, were also assessed.

Based on these analyses, this report goes on to make recommendations concerning an improved system for the delivery of climate-related data and information. Specific data products and analyses required by NPS ecologists and I&M staff are also discussed. This effort was designed to complement a number of recent and ongoing projects related to inventories of climate-monitoring resources and the treatment of climate as a "vital sign". This report should then be viewed as an ecosystem science and I&M perspective on climate data requirements and data delivery.

# II. Assessing Potential User Needs

*Motivation*

Between the threats posed by climate change and a growing recognition that atmospheric variability is a key driver of park vital signs, the importance of climate data within the I&M Program will undoubtedly continue to grow. According to its stated goals for NPClime and other components of an improved climate-monitoring program, NPS-I&M is seeking to create a long-term solution for meeting both routine and sophisticated data needs (NPS 2007). In order to better anticipate what these long-term needs might be, this section includes a substantial treatment of current high-end applications. While several of the applications described here may not reflect the present state of climate studies within the NPS, it is hoped that these case studies will help us anticipate of the needs of the I&M climate program as it evolves over the next several years.

*General Approach*

Assessment of user requirements for climatic data began with a series of small meetings, teleconferences and workshops involving NPS personnel and I&M cooperators working in the Intermountain West. While many issues related to climate monitoring were raised in these discussions, the single most important, overriding theme was that limited access to data was the greatest obstacle facing NPS and I&M personnel.

These discussions also showed how the range of climate-data applications within the NPS and I&M program is still somewhat limited, as are the number of researchers and collaborators using these data on a regular basis. Moreover, this preliminary work showed how temporal and spatial perspectives on climate vary widely from park unit to park unit. While staff within a smaller park unit may be concerned with data from only one climate station, staff within larger parks or at the I&M Network level generally concentrate on observations from a much wider array of sites. There are marked differences in how individual park units or networks focus on climate (i.e. longer term variability) vs. weather (i.e. short term events). In light of these facts, this report relies heavily on input from groups that are already deeply involved in the use of climate data. This approach should allow us to better anticipate the needs of NPS ecologists, I&M staff, and collaborators as they continue to develop.

Information on user needs gathered from NPS personnel and I&M cooperators was supplemented in variety ways. First, a group of extension agents, foresters, and members of various "drought task forces" from the Intermountain West were asked how they obtain climate data and information related to climate. Though this group is not strictly representative of the needs of NPS-I&M personnel, all sixteen respondents have backgrounds in ecosystem science, and all are required to incorporate climate-related information into their work. Next, Federal (i.e. Bureau of Land Management, U.S. Geological Survey and USDA-Forest Service) and academic researchers working with the NPS were polled to determine (1) how they obtain climate data; (2) what climatic elements they use in their analyses; (3) requirements for spatial and temporal resolution; (4) how these data are applied. At the same time a review of all climate data requests processed through the Wyoming State Climate Office (WSCO) over a twelve month period (January 2006 through December 2006) and a review of logs tracking internet hits and downloads from the WSCO web pages were used to develop a broad view of the types of climatic data and information are most often used in the Intermountain West, and to determine what delivery formats are most desirable. Finally documentation and published studies from a suite of ecosystem- and natural-process models were reviewed as an indication of what climatic elements are required in different simulation studies, and what the spatial and temporal resolution of climate-data in these models might be. Such a wide ranging survey should provide a more complete view of existing and future climate-data needs than would be offered by examining the NPS and I&M programs alone, and should in turn lead to the development of a more comprehensive and effective system for improving the distribution and analysis of those data.

*Data Access Survey*

Sixteen participants were asked a series of questions related to how they access climate data and climate-related information. Responses to these questions and brief comments are listed below.

Question #1.

What is your primary method for locating climate data and climate-related information? Do you…

a) Search for data over the internet or by some other electronic means?
b) Search for data in hardcopy archives?
c) Ask collaborators or co-workers for data?

Responses

Electronic Search 8 Hardcopy Search 1 Co-workers 7

Comments

Many respondents expressed frustration with previous attempts to search for climate data over the internet, particularly when using National Oceanic and Atmospheric Administration (NOAA) or National Weather Service (NWS) websites. Interestingly, several respondents spoke of using in-house datasets or electronic databases compiled locally. Follow-up questions revealed little knowledge concerning the source of these data and any measures related to record maintenance, quality control, or updates. Several also expressed concern that they were likely missing important data sources, especially when they depended on others “around the office” to help them locate information.

Question #2

Do you most commonly access data from…

a) Individual climate stations?
b) Summaries for multiple stations or regions?
c) Both?

Responses

Individual Station 2 Summaries 7 Both 7

Question #3

What is the most important barrier to the use of climate data in your work? Is it…

a) Difficulty locating appropriate sources for data?
b) Difficulty working with electronic files?
c) Lack of adequate metadata?
d) Lack of suitable data for location or variable of interest?

Responses

Data Sources 8 Electronic Files 1 Metadata 0 Suitable Data 7

Comments

The majority of respondents (12/16) suggested that locating data and the lack of suitable data were equal or nearly equal in their importance. Follow-up questions showed that most respondents had never dealt directly with metadata for weather and climate records.

Question #4

Which of the following climate-data providers have used in the last six months?

a) State Climate Offices
b) Regional Climate Centers
c) NOAA (NWS or NCDC)
d) Commercial websites such as Weather.com

Responses

State Offices 7 Regional Centers 3 NOAA 3 Commercial 8

Comments

Participants were allowed to select more than one option. Seven participants also responded that they had obtained data from sources other than those listed. Because many of the participants had worked previously with the WSCO or their state's equivalent, the 7 positive responses for choice "A" are not likely to reflect the population at large. The high percentage of users who obtained data from commercial websites is somewhat disturbing; quality control measures for these outlets are relatively weak, and spurious observations can persist on these pages long after they have been corrected in NOAA databases such as Applied Climate Information System (ACIS) and the official National Climatic

Data Center (NCDC) records.

*The Ecologist's Perspective on Climate Data*

Based on interactions with NPS-I&M personnel, cooperators, and the research community at large, ecologists tend to fall into three general classes of climate-data user. Each general class of user is described below using information provided by a group of eight research ecologists working either in the academic or federal systems. All of the researchers who provided input work in or near National Parks in the Intermountain West, and all have worked in or near multiple NPS units. It should also be noted that there is a great deal of overlap between the groups; the majority of researchers contacted for this report provided comments related to two or more of the general user-types.

<u>Class I</u>

The first user group (Class I) employs climate data in a general, qualitative sense to help understand ecological phenomena of interest. One example might be users who cite notable drought events as a the cause of a string of active fire seasons, or users whose work makes a general connection between wet years and the abundance of exotic plant species. Overall, what separates Class I users from the other groups is that they tend not to explore potential climate-ecosystem relationships in a rigorous statistical framework.

One federal agency ecologist working in western Wyoming illustrates several aspects of the typical Class I user. He generally locates climate data and related information through internet search engines (e.g. Google), and has also obtained summary graphics and other figures via the internet. Like many in this group he "rarely if ever" makes direct use of climate-data portals offered by NOAA or other agencies. Other researchers that fall into this group also reported that they often use data or figures obtained from co-workers, even though they may not always know the provenance of this information. This researcher says that data access is a major problem, and that it can often be difficult to relocate a good data source on the internet. This researcher adds that he would like to see more products related to regional forecasts and trends, as well as information on the general climatology of his research area. He also says that the ability to consistently locate high-quality and "trustworthy" data is far more important than issues such as high-temporal resolution, data from additional sensors, or high-level analysis tools. This general sentiment was echoed by several other researchers.

Another federal ecologist working in the central Rocky Mountain region highlights what appear to be the general requirements for climate data among Class I users. As in the case of most researchers in this group, he commonly searches for temperature and precipitation data. However, he uses summary products like the U.S. Drought Monitor to provide an overview of past climatic conditions in his research areas. Like most Class I users he generally deals with monthly to annual data, but says that daily/hourly observations are usually not available for the areas he works in. He does not usually have a preference for station-level data or regional summary products, but instead uses "whatever [he] can find".

Class II

The second group of users (Class II) does look at the relationship between climate and ecological events in a statistical framework, most often through the use of regression or ordination techniques. Here the researcher might look at the correlation between average daily-minimum temperatures and mortality for a species of interest, or develop a multiple regression model to explain the role of precipitation and temperature in determining forage production.

Interestingly many of the researchers who fall into this class collect much of their own data. One academic researcher working in Yellowstone and Glacier National Parks said, "Short of sticking a thermometer on every tree in the Park, putting out our own stations was the only way to collect the data we need." This strategy results from the need to collect data related to ecological variability at the stand to landscape/watershed level or to collect data for soil temperature, photosynthetically active radiation, and other variables not generally captured at standard climate stations.

Where such researchers do rely heavily on data from outside sources is in developing baselines for climatic variables or general descriptions of spatio-temporal variability across a park. Much like the typical Class I user, many in this group are not utilizing the best available sources for climatic data. Another researcher working in Yellowstone NP said that he often uses climate-related information contained in reports from the early 1980's. He went on to say that access to climate data has not been a problem because he and his collaborators have been using the same set of summary records for nearly twenty years. As he said, "It's just the way we've always done things." Numerous researchers working in Yellowstone—including several not formally interviewed for this project—reported that they obtained climate data from NPS fire-suppression personnel, but did not know where these data originated or if they were archived elsewhere. Several of the researchers interviewed for this study worried that they were missing important information related to the climate of their study area.

Class III

The final group (Class III) generally uses climate data to drive ecological process models, or to make model-based predictions for future ecosystem conditions. These users also tend to collect much of their own data. In addition to the reasons for this cited by Class II users, this group often requires data with a short time step (hourly to sub-hourly) that is not available from most in-park stations. Two academic researchers who fall into this category suggested that a lack of distributed data—maps of gridded snow depth, minimum daily temperature, etc.—was among the most critical challenges for those working in the National Parks. Three other academic researchers mentioned that a lack of region-specific scenarios for future climatic conditions was another major problem for ecologist working with the NPS. As in the other two "classes" there was a sense of frustration among Class III users regarding the lack of general park-level climate information or baseline/reference data for parks or regions within a park. While the Class III ecologists contacted for this study show a great deal of sophistication in their modeling work, most did not posses much expertise related to climate and climate-related data. In the case of data not collected directly by the researcher, members of this group still tended to use whatever data they could find rather than the most appropriate data available.  One academic researcher who has worked in Yellowstone and Grand Teton National Parks used precipitation data collected from a single Remote Automated Weather Station (RAWS) in southeast YNP to represent conditions at all of his study sites.  He was not aware that (1) there were NWS stations closer to his sites and (2) RAWS stations provide relatively poor records of longer-term precipitation variability.  It appears instead that he simply used the first data he came across on the internet, or at least the data that were easiest for him to obtain.

<u>Summary:</u>

- Discussions with ecologist working in the Parks revealed that many researchers are not aware of critical data resources for their study areas.
- Users of all types showed a disturbing lack of knowledge with respect to quality control, metadata, and suitable data sources.
- Many researchers must collect their own weather/climate data because it would not be practical for NPS monitoring systems to meet these needs.
- In cases where researchers do not need to collect fine-scale data, monthly to seasonal data would likely be sufficient.
- Most researchers contacted for this study expressed a desire for better baseline data and basic climatological information for the parks.

*Data Transfer Study*

Another telling exercise is to examine what data are actually requested or downloaded from providers. The Wyoming State Climate Office received nearly 300 direct (i.e. via phone, email, or in person) requests for climate data during calendar year 2006.  Approximately 110 requests pertained to natural resource management or other issues closely related to the work of NPS ecologists and I&M staff (requesters are asked to describe how they will use these data, and this information is stored in a WSCO database).  Some 60% of these queries called for precipitation or temperature data at a specific site, or precipitation and temperature data at a group of geographically-clustered sites. The remaining requests were divided into roughly equal percentages for wind data, streamflows, and snow-related data (e.g. snow water equivalent).   Across all of these categories the majority of requests called for observations over a given period of time (ranging from a single day to multiple years), but requests for information on climatic extremes were also quite common (roughly 25% of cases).  Out of all of these examples the need to access information that could not be located via the internet or the need to obtain data summaries where most often cited as reasons for contacting the WSCO directly.

Indirect requests for WSCO data via the internet are more difficult to interpret; there is no information that might indicate how the data will be used, and the influence of automated scripts that continuously scan the World Wide Web (i.e. web crawlers or web bots) must be removed from the request statistics.   However, a wealth of useful information can still be drawn from these web hits. First, summary products that compile observations on a multi-site or regional level are far more popular than are products that include observations from individual sites. In fact, for some climatic elements (e.g. snow water equivalent) web hits for regional summaries outnumber those for individual stations 100 to 1. Graphical summaries of climatic conditions or events are also extremely popular, especially when they are delivered in the form of color-coded maps (Figure 1).

Interestingly, when the same products are presented in both HTML and PDF formats, the HTML versions are accessed 2-3 times more often (after repeat hits to HTML sites have been accounted for).

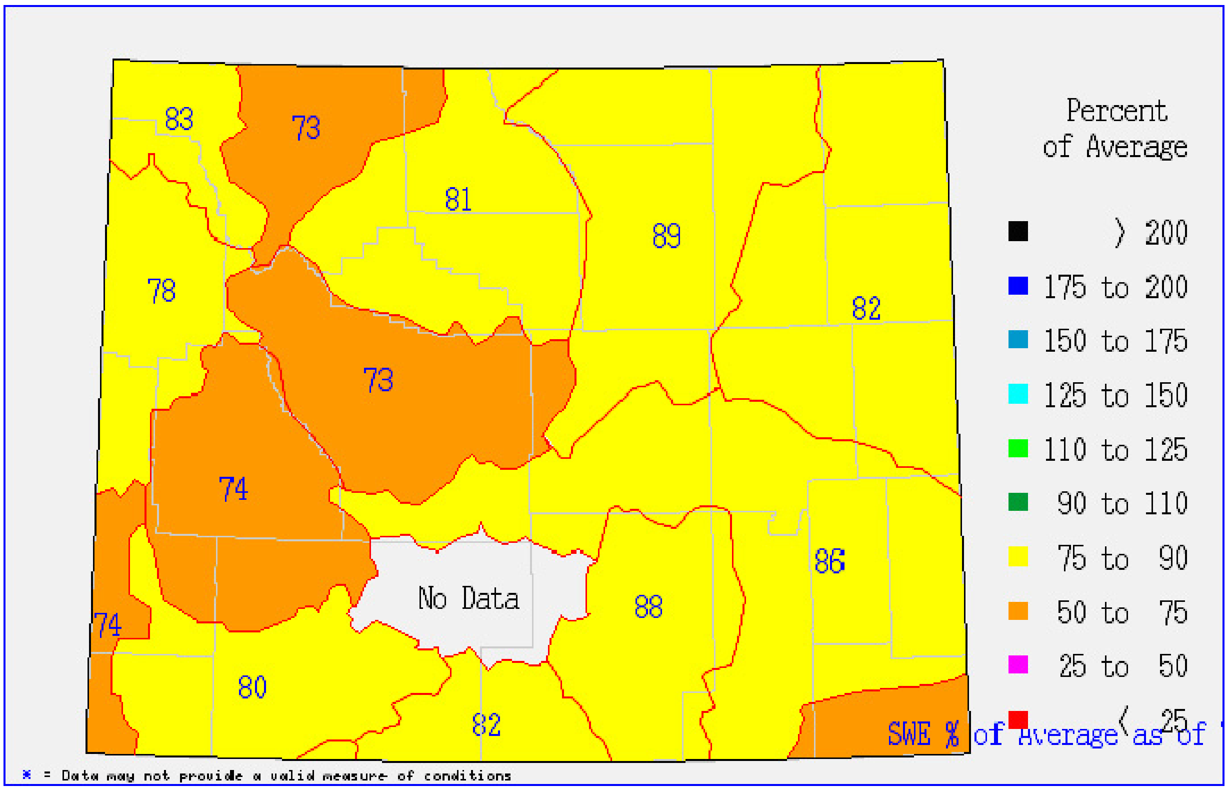


**Figure 1.** Map-based summary products such as this plot of Wyoming snow water equivalent are some the items most frequently downloaded from the Wyoming State Climate Office websites. Source: http://www.wrds.uwyo.edu/ wrds/nrcs/snowmap/snowmap.htm

<u>Summary</u>

- Regional summary products or products that summarize conditions observed at multiple sites are among the most popular downloads from the WSCO website.

- Graphical summaries—maps or plots—are downloaded far more often than numerical summaries or raw data files.

- Similar data-access studies that capture a wider user-audience (e.g. users of Regional Climate Center websites) would likely yield a wealth of relevant information.

*Climate Data for Simulation Models*

The use of models to help understand complex processes in natural systems, as well as developing predictions for the future state of those systems, is becoming increasingly prevalent (Odum and Odum 2000). Models can be used to examine the potential outcomes of a disturbance event or management decision, and models allow ecologists and managers alike to summarize complex information derived from observations of natural systems (Dale 2003). Modeling studies will undoubtedly become more and more common in the context of the I&M program because they can be used to explore different sampling strategies and look for gaps in monitoring arrays. Simulation models are also widely used to examine the effects of missing or corrupted data and, in a growing number of cases, to provide a substitute for missing observations.

Many relevant ecological models require some form of climatic data input. However, a key question is whether or not an improved climate data system for use throughout the NPS ecology program could or should be tasked with delivering this input data? More specifically:

(1) Given the budget constrains on the national and network-level I&M programs, can a new system deliver data at the spatial and temporal resolutions required for many types of ecological modeling studies?

(2) Are the investments in data and related infrastructure (e.g. servers and storage media) that will be required to deliver the climate inputs for modeling studies justified by the potential benefits?

In short, the cost and complexity of the system will rise dramatically as the number of climatic elements and temporal resolution of observations increases. Here the inputs required for three general cases or classes of models are reviewed as a "first pass" at understanding potential needs for climate data within the NPS and affiliated ecological modeling community. The temporal resolution or time step of the required data is given the greatest degree of importance, and specific climatic elements used in common types of modeling studies are give secondary consideration.

<u>Modeling Ecosystem Productivity</u>

Productivity is widely used as an indicator of ecosystem function over time, and productivity is often viewed as a key measure of ecosystem change after disturbance. In the GYE, for example, net primary productivity (NPP) and related carbon fluxes have been widely used to evaluate post-fire recovery of lodgepole pine stands (e.g. Reed et al. 1999, Litton et al. 2003, Kashian et al. 2006), and to assess potential responses to regional climate change. Literally dozens of models describing ecosystem productivity are now available. However, a brief survey of seven of these models (Table 1) is sufficient to highlight the types of climate-data inputs that are generally required. The majority (4/6) of these models use precipitation and temperature data on a daily time-step. The remaining two require hourly data or data related to specific storm events. Another interesting feature of these models is that most (5/6) require some form

of incoming solar radiation as an input. Such radiation measurements, especially when they are required as photosynthetically active radiation, are rare in most park units. It is worth noting that the models discussed here are relativelycomplex for use in park-level or regional applications, and that most of these examples are commonly run over very large spatial domains. What these examples offer is insight into the upper limits of climate-data requirements for most ecosystem modeling applications.

**Table 1.** Climatic data inputs and time-steps required by six simulation models commonly used to estimate carbon fluxes at landscape and regional scales.

| | Century | Biome-BGC | TEM | PnET | LoTEC | SiB2D |
|---|---|---|---|---|---|---|
| **Climate drivers** | monthly | daily | monthly | monthly / daily | daily / hourly | hourly / 30-min. |
| Avg. mean air temperature | | | X | X | X | X |
| Avg. maximum air temperature | X | X | | X | | |
| Avg. minimum air temperature | X | X | | X | | |
| Total precipitation | X | X | X | X | X | Convective precip. |
| Relative humidity | | X | | | | |
| Dewpoint temperature | | | | | | X |
| Vapor pressure | | daylight average VP deficit | | | X | |
| Solar radiation | | average | X | average | X | Total |
| Photosynthetically active radiation | | X | | | | Calculated internally |
| Longwave radiation | | | | | | X |

Adapted from http://www.archive.arm.gov/Carbon/dataneeds/dataneeds.html. Additional information and model descriptions available at http://eco.wiz.uni-kassel.de/ecobas.html.

Predictive Models for Key Ecosystem Processes

Predicting the outcomes of disturbance, introductions of novel species, climate change and countless other events will be a key challenge for ecologists in coming years. Simulation models are particularly well suited to aid ecological forecasting because of their ability to condense complex processes into a tractable framework, and because they allow researchers to consider multiple scenarios for future conditions (Root and Schneider 2002). A survey of predictive models for ecosystem change in the Intermountain West reveals that most efforts employ weather and climate data (actual or simulated) with relatively long time-steps. In a study of potential climate change impacts on whitebark pine (Pinus albicaulis) in the Greater Yellowstone Ecosystem, Koteen (2002) related the potential for blister rust spread to climatic variability over interannual timescales. Similarly Bartlein et al. (1997) used relationships between contemporary vegetation and historical averages for monthly-annual climate as a basis for understanding the impacts of future climatic change. Though used less frequently in a forecasting context, monthly to seasonal climate is often employed in modeling studies that link wildlife population dynamics to environmental variability (e.g. Schwartz et al. 2005). Overall, the majority of models used to explore the relationship between ecological processes and climate in the Intermountain West use seasonal to interannual climate data, and simple measures of precipitation, temperature or their derivatives are the most common input variables. Notable exceptions come from studies of short-lived or extremely dynamic processes such as forest crown-fires (e.g. Finney 1998). Such tools are usually intended for very specific management purposes, and are not likely to be applied in a research capacity by NPS ecologists and I&M cooperators.

## Using Models to Link Satellite Observations and Ecosystem Processes

Remote sensing is now commonly used to inventory natural resources and monitor ecological patterns at landscape to regional scales (Lillesand and Kiefer 1994, Wilkie and Finn 1996). One key challenge for ecologists using remotely sensed data is to devise a means for linking this imagery to actual processes of interest occurring on the ground (Peterson and Parker 1998). Simulation models are often employed to bridge the gap between remote sensing and ecological processes. METRIC, a model developed to estimate landscape to regional-scale evapotranspiration from satellite data and ground-based meteorological data (Allen et al. 2004) is one such example. The model estimates are spatially distributed, and have been successfully linked to other models of fire and vegetation change. The METRIC model is currently used across the Intermountain West in a variety of natural resource applications.

Meteorological data required to run the METRIC model include hourly temperature, humidity, solar radiation and wind speed for the day of image acquisition, along with precipitation over the previous five days. These data are not necessarily collected at sites within the modeling domain, but must be "representative" of conditions within the area of interest (Allen et al. 2004). Similar models requiring additional inputs or a shorter time-step are not rare. SEBAL (Bastiaanssen et al. 1998), a more complex version of METRIC, is often run using 15-min observations. In those cases where data with a shorter time-step is required, other factors (e.g. requirements for data at a high spatial resolution) usually force the researchers to collect their own meteorological observations.

## Summary

- While the ideal system would deliver every available observation of climate, for most modeling applications daily to monthly observations of primary climatic elements would suffice.

- When additional measurements (e.g. soil temperature) or measurements with a short time-step are required, the researchers usually collect these data themselves.

- These findings suggest a system that focuses first on providing high quality, long-duration records of park climate, and leaves improvements in spatial and temporal resolution and the addition of new climatic elements for subsequent development efforts.

# III. Strategies for Effective Data Analysis and Distribution

Based on the findings contained in Section II, an improved system for the analysis and distribution of climate data must:

(1) Provide NPS-I&M personnel basic information on park-level climate and keep them informed about recent and ongoing climatic events (e.g. drought).
(2) Provide simple, on-demand access to data.
(3) Include complete and "user friendly" metadata
(4) Be accompanied by education and outreach on how best to utilize this resource.

The following is a proposed framework for addressing these issues. At the core of this framework is a three-tiered system for improved data summaries, data delivery, and analysis. Descriptions related to the general format of each tier are followed by specific recommendations for inclusion of data and required analyses.

**Tier I: Climate Summaries for Parks, I&M Networks and Regions**

General

Keeping abreast of current climatic conditions and trends is, at best, a daunting task for most NPS-I&M personnel. In short, timely access to observations is often limited, and the processing of these data into meaningful summaries can be extremely difficult. This is particularly true for workers attempting to understand climate at the scale of a large park or I&M region. Like most personnel dealing with issues in ecosystem science and management, NPS-I&M staff usually have very little training in or experience dealing with climate data. There is, in turn, a tremendous need for products that both summarize current conditions and recent trends in an easy to access format, and provide a means for connecting the work of the NPS-I&M program with expertise from the climate sciences. Parks and I&M Networks are also charged with developing a variety of reporting products related to climate. Unfortunately the same obstacles that make climate data challenging for the individual NPS-I&M user would likely make these summaries very difficult to produce on a local level.

Several outstanding models for meeting these needs already exist. NOAA's Regional Integrated Sciences and Assessments (RISA) Program produces climate summaries for areas throughout the U.S. These climate summaries are delivered in the form of glossy publications written in an open, narrative style. The summaries lean heavily towards presenting information in graphical rather than tabular formats. The RISA summaries also include forecasts or outlooks for the coming months or seasons, along with short pieces that describe relevant research, document new sources for obtaining data, and provide expert analysis of climatic events. Sample products from the Western Water Assessment (RISA for the Intermountain Region) can be accessed at:

http://wwa.colorado.edu/products/forecasts_and_outlooks/intermountain_west_climate_summary/

Products from CLIMAS, the RISA for the Southwestern U.S. RISA:

http://www.ispe.arizona.edu/climas/forecasts.html

A slightly different approach to summarizing and reporting on climatic events can be found in the National Resources Conservation Service's (NRCS) weekly snowpack and drought reports (see http://www.wcc.nrcs.usda.gov/water/drought /wdr.pl). Again, these reports place an emphasis on graphical representations of climate data, but the accompanying narrative is written more in the format of a technical report.

Based on these examples, the first tier of this proposed system would be a product that offers a narrative summary of recent network-wide climatic conditions with mention of any notable extreme events on both a park and regional level. Given the apparent needs of NPS-I&M and the success of the models described above, this document would include:

(1) Reviews of recent conditions focused on key indicators of climate (a description of "key indicators" follows)
(2) Brief reviews of park-level conditions for each unit or cluster of neighboring units
(3) Seasonal forecasts or outlooks
(4) Information or expert analysis relevant to the incorporation of climate data into the NPS-I&M program.

Findings from Part II of this study suggest that this product should be distributed via email and the internet in both PDF and HTML formats. PDF and HTML versions should provide some level of interactive content (e.g. hotlinks to additional information) and access to graphics contained within the summaries. Links that take readers directly to the data or data sources used in these analyses would also be highly desirable. These summaries will be updated regularly (monthly to quarterly updates plus annual or water year summaries), and additional updates will be available when dictated by extreme events (e.g. drought).

While these summaries might be produced at a variety of levels within NPS-I&M, development at the Network or Region is most desirable. Problems with data availability or quality are often masked at these larger scales, and most climatic events of interest (e.g. droughts, harsh winters, heat waves) tend to have regional footprints. Moreover, many of the anticipated effects of global climate change will play out at the regional level (IPCC 2001), and numerous factors make climate change detection most feasible at these larger spatial scales (Stott and Tett 1998, Allen et al. 2000). Providing NPS-I&M personnel stationed within an individual park unit with a regional perspective on local events is also highly desirable.

<u>Key indicators for climate in the Intermountain/Rocky Mountain West</u>

Key indicators for use in products addressing conditions at the multi-park, I&M network, or regional level include:

- 1. Precipitation
    - o Key variables:

Total precipitation since last update, or total precipitation over some interval of interest. In most cases total precipitation should be compared to average precipitation received over some baseline or "normal" period. Climatologists often use 30-yr periods as the basis for climate normals (e.g. 1971-2000), and this approach should work well for most Tier I applications. Averages over the period of record may also be used when 30 years of record are not available for a station, or it is desirable to place observations in a longer-term context. It is imperative that "normals" not be portrayed as the weather/climate we should expect for a location (Hays 2006). "Normals" should only be viewed as a statistical benchmark that is used to facilitate comparisons within a climate record. Staff preparing these reports might consider discarding the term "normal" in favor of phrases such as "baseline average" or "historical average".

Precipitation can also be expressed in terms of anomalies (i.e. departure from a baseline value) or percent of average over various windows (e.g. 1, 3, 6, and 12 mo). Again, anomalies and percent of average values should not be presented in the context of weather/climate we should "expect" for a location. It should also be noted that anomalies and percent of average may not accurately depict "on the ground" or ecologically-relevant conditions. For example, percentage of average precipitation over what has historically been the driest month of the year may not be as important an indicator of ecosystem impacts as percent of normal over the wettest months or season of the year. Likewise precipitation amounts over monthly and longer timescales are not normally distributed, and the mean of precipitation is often noticeably different than the median (Hays 2006). Here temporal windows may also be based on length of reporting cycle (see "Recommendations for Reporting Timelines").

The Standardized Precipitation Index (SPI; McKee et al. 1993, 1995) provides a means to overcome many of the potential problems discussed above. The SPI is calculated by fitting a precipitation record to a probability distribution and then normalizing the record so that its mean equals zero. Positive values of the index are wetter than the median, negative values drier. The SPI can be calculated over various windows that, in turn, portray different aspects of "on the ground" conditions. SPI calculated over 1 mo intervals might, for example, provide information related to topsoil moisture, whereas SPI calculated over 12-24 mo windows might relate to overall ecosystem status or availability of surface water (Hays 2006). SPI can also be calculated for single stations or a network of stations. SPI does have significant drawbacks in that users of these Tier I products must be taught how to interpret the index, and the calculations are somewhat more involved than those for anomalies, etc. More information on the SPI and links to scripts for calculating the index can be found at: http://www.drought.unl.edu/monitor/ spi/program/spi_program.htm.

The Palmer Drought Severity Index (PDSI; Palmer 1965, Alley 1984, Heddinghaus and Sabol 1991) and other drought indices (Table 2) may also be useful for providing a generalized overview of moisture conditions. Such indices have the advantage of incorporating multiple climatic variables into a single value that broadly describes conditions at the level of a large park or small region. PDSI, for example, combines observed precipitation over various time windows and temperature data to produce an index that is correlated with vegetation health, fire danger, and ecosystem productivity. Likewise the Surface Water Supply Index (SWSI; Shafer and Dezman 1982), an alternative to PDSI often used in mountainous regions, condenses data related to snowpack, precipitation, and runoff into one comprehensive portrayal of regional moisture status. Such indices are best employed over large areas, and care must be taken to ensure that the index is appropriate for the region of interest (see Hays 2006).

**Table 2.** Drought indices commonly used in the western US.

| Drought Index | Key References |
|---|---|
| **Palmer Drought Severity Index** | Palmer 1965, Alley 1984, Heddinghaus and Sabol 1991 |
| *Pros:* Incorporates precipitation, temperature and evaporation in one index | |
| *Cons:* Not well-suited to complex terrain or snow-dominated areas | |
| **Palmer Hydrologic Drought Index** | Alley 1984, Guttman 1991, Karl and Knight 1985 |
| *Pros:* Focused on longer-term changes that may impact ecosystems, etc. | |
| *Cons:* Does not directly incorporate snowpack or runoff | |
| **Surface Water Supply Index** | Shafer and Dezman 1982, Heddinghaus and Sabol 1991, Doeskin et al. 1991 |
| *Pros:* Incorporates information on snowpack and surface water | |
| *Cons:* Can be difficult to calculate and compare across regions | |
| **Standardized Precipitation Index** | Edwards and McKee 1997, McKee et al. 1993, 1995 |
| *Pros:* Versatile; incorporates information on precipitation probabilities | |
| *Cons:* Relies on precipitation inputs alone | |

*Adapted from Hays 2006 (http://www.drought.unl.edu/whatis/indices.htm).*

o Required analyses and resulting products:

Must first identify stations with adequate length of record for use in calculating anomalies, SPI, etc. In cases where missing data and length of record are a problem, methods for correcting these observations must also be employed (e.g. Mott et al. 1994, Ashraf et al. 1997).

For these multi-park to regional analyses, an operational area for examining climate must first be identified. In a large and dispersed network like the Rocky Mountain Network (ROMN), averaging observations across all parks would be of little value for understanding climate. However, climatic “zones” or sub-units might be identified within ROMN, and these sub-units would then form the basis of subsequent large-scale analyses. Many methods now exist for regionalizing climate (e.g. Fovell 1997), and such studies would be a logical prelude to the development of these Tier I products. One such method that shows particular promise is being developed by Klaus Wolter (University of Colorado-CIRES; Klaus.wolter@noaa.gov) and collaborators. The Wolter et al. approach uses multivariate cluster analysis to identify groups of climate stations where temperature and precipitation tend to vary in a coherent manner. The resulting station clusters are grouped into geographic climate regions, and initial results indicate that this approach has many advantages over previous efforts.

Must then select appropriate normal or reference periods and calculate relevant statistics for each station over these periods. Thirty year normal periods are standard for analyses in the western US. Longer or shorter periods may be used as needed, but it is highly preferable that all stations be compared across the same base or benchmark period.

Must develop a means to calculate SPI and PDSI for selected stations, or obtain index values form existing providers (e.g. Western Regional Climate Center, NOAA-CPC)

Multi-site to regional level conditions are best expressed using summary maps

Maps can be generated to show conditions at multiple sites within a region (e.g. Figure 2a)

In the case of analyses over very large areas (i.e. large networks or geographic regions such as the Intermountain West) observations from individual sites may aggregated (e.g. choropleth maps) or interpolations can be made across sites (e.g. shaded or isopleth maps; Figure 2b). However, interpolations at the level of individual parks or small networks should be used with great caution, and only when (1) the effects of topography can be thoroughly addressed and (2) density of observations allows for statistically robust interpolations.

- 2. Temperature

  o Key variables:

Average daily temperatures over 1 mo and seasonal windows.

Average maximum daily temperatures over 1 mo and seasonal windows.

Average minimum daily temperatures over 1 mo and seasonal windows.

Temperature anomalies (departure from normal) over 1 mo and seasonal windows. Again, caveats related to the use of climate “normals” apply (see above).

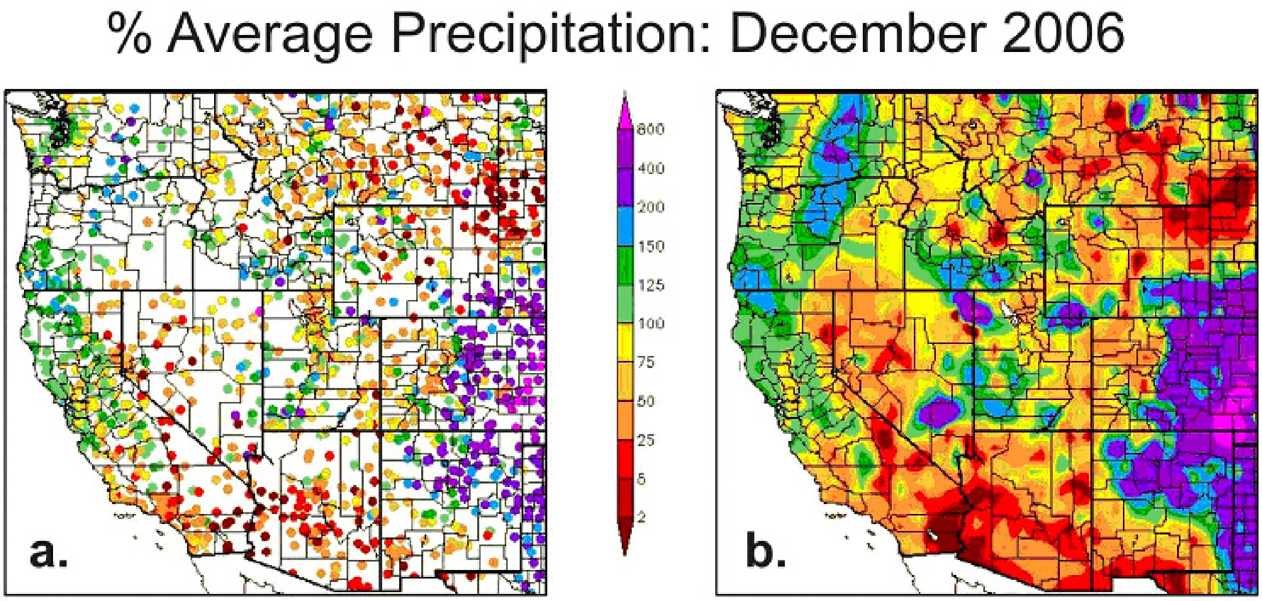


**Figure 2.** Two map-based depictions of precipitation for the month of December 2006. Both maps are based on the same data, but the map on the left shows percent of average (as compared to 1961-1990) precipitation received at all available stations in the western U.S., while the map on the right shows values interpolated across sites. Data courtesy High Plains Regional Climate Center.

o Required analyses and resulting products:

Same basic analyses used for precipitation.

Must develop normal or reference period statistics similar to those listed for precipitation.

Recommend summary maps similar to those for precipitation.

• 3. Snowpack (Generally November through May)

o Key variables:

Current total snow depth at representative stations.

Current total snow water equivalent (SWE) at representative stations.

Current snow depth and SWE as a percentage of normal (i.e. compared to average over some base period) at representative stations or averaged across some hydroclimatic area of interest.

Current values vs. previous year and past five years.

o Required analyses and resulting products:

Must first identify stations with adequate length of record for use in calculating anomalies, etc.

Must then identify stations that would best represent conditions at the park level or some other geographic level of interest.

Select appropriate normal or reference periods and calculate relevant statistics for each station over these periods. Thirty year normal periods are standard for analyses in the western US. Longer or shorter periods may be used as needed, but it is highly preferable that all stations be compared across the same base or benchmark period.

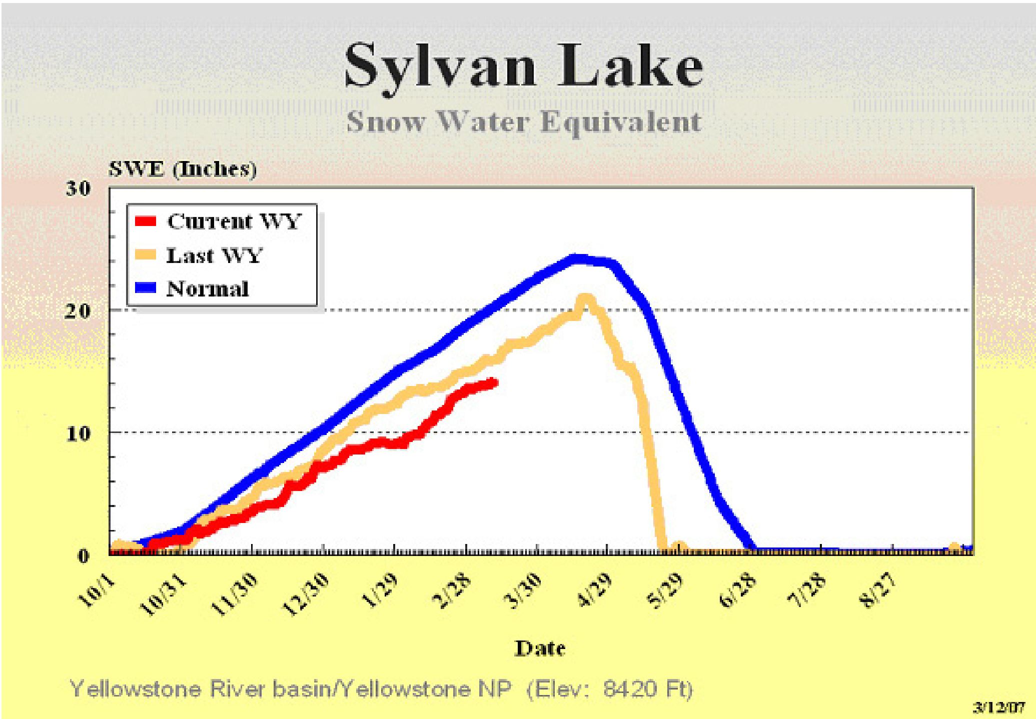


**Figure 3.** Graph showing snow water equivalent at a single site in Yellowstone National Park for mid-March 2007. Similar graphs can be generated for observations that have been aggregated at the park to river basin level, or at any other scale relevant to the NPS-I&M program. Plotting these observations against the long-term average (i.e. normal) and previous year's observations provides valuable context for understanding current snowpack conditions. Graph courtesy Tom Dietrich, Wyoming Water Resources Data System.

Snow data are best displayed using a combination of map-based summaries and time-series graphs (e.g. Figure 4)

Map-based depictions may either show conditions at a collection of individual sites (Figure 4a) or conditions aggregated to some geographic region of interest (Figure 4b).

- 4. Streamflow (Generally March-October)
  - o Key variables:

    Percentiles for current observed flows at select gages or averaged across some hydroclimatic area of interest

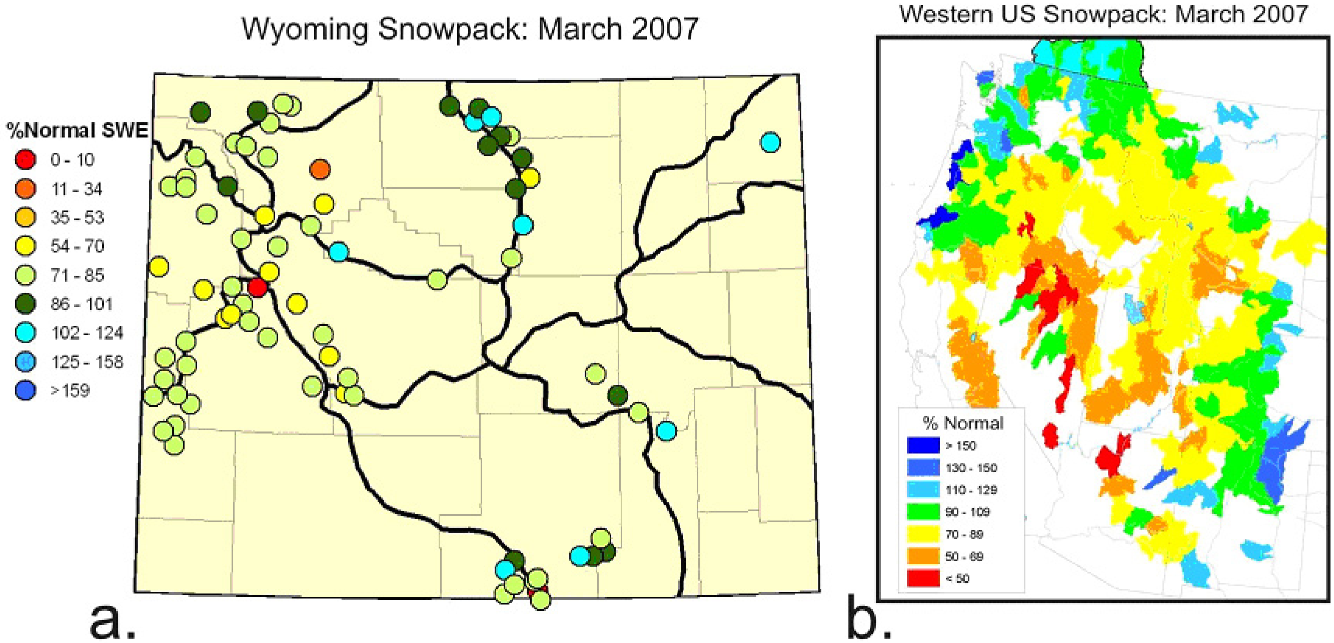


**Figure 4.** Depictions of snowpack conditions in Wyoming and the western United States. Both maps incorporate the same data, but observations for individual reporting sites are shown on the left (a), while individual observations are aggregated at the level of major river basins on the right (b). Data courtesy NRCS and Wyoming Water Resources Data System.

Percentiles for flows averaged over 2 week and 1 mo periods.

Percentiles for total discharge since start of spring or other relevant seasonal benchmark

Summaries of peak/low flows; reports on peak/low flows in terms of discharge or stage may also be enhanced by including information on the timing and duration of these peak/low flow events

o Required analyses and resulting products:

Identify gages with suitable length of record for calculating relevant streamflow statistics. In some cases identification of unimpaired streams may also be necessary.

Select gages that best represent conditions at the park level or across some other hydroclimatic area of interest

Must obtain or calculate percentiles and basic hydrologic time-series statistics (e.g. mean, median, mean, max, etc.) for all gages or collections of gages used in these analyses. Ideally these statistics should by calculated for daily, monthly and seasonal flows

Must identify or develop criteria for identifying peak flow in these gages

As with snow data, streamflow conditions are best summarized using a combination of map-based depictions and time-series graphs of gage data

• 5. U.S. and state-level drought status

o Why is drought status a critical component of Tier I reports?: Drought results from the cumulative effects of variations in precipitation, temperature and evaporation over a variety of spatial and temporal scales. Drought is, in turn, a primary driver of ecosystem processes and disturbance, particularly in semi-arid regions like the Intermountain West. Many drought monitoring products condense a multitude of ecologically-relevant climate variables into a single easy-to-use and easily interpretable overview of effective moisture conditions. In the western US, tracking drought as major focus of the I&M Program is especially important given that predictions for future climatic conditions call for increased frequency and duration of dry periods (e.g. Hoerling and Eischeid 2007; McCabe and Wolock 2007).

o Key variables:

Status or condition class from US Drought Monitor (Figure 5; http://www.drought.unl.edu/dm/monitor.html).

Status or condition class based on regional or state-level analyses (Figure 6).

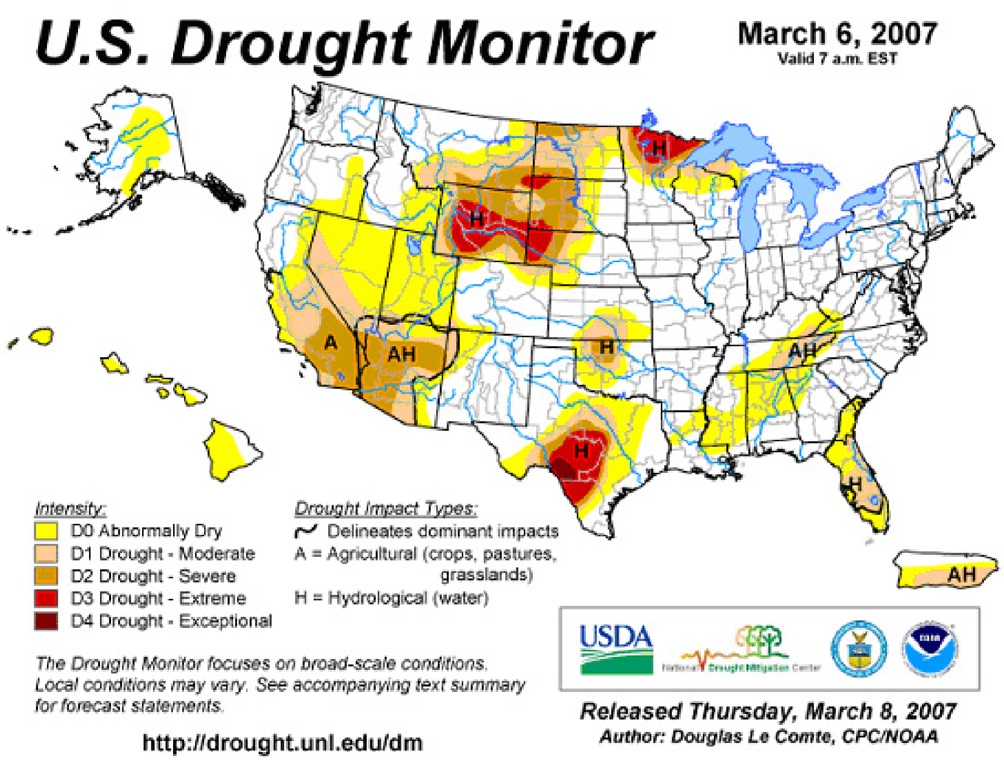


**Figure 5.** The US Drought Monitor synthesizes multiple climatic indices, outlooks, and input from federal and academic scientists to generate a national representation of drought conditions. The product is updated every week, and is available online at http://www.drought.unl.edu/dm/monitor.html.

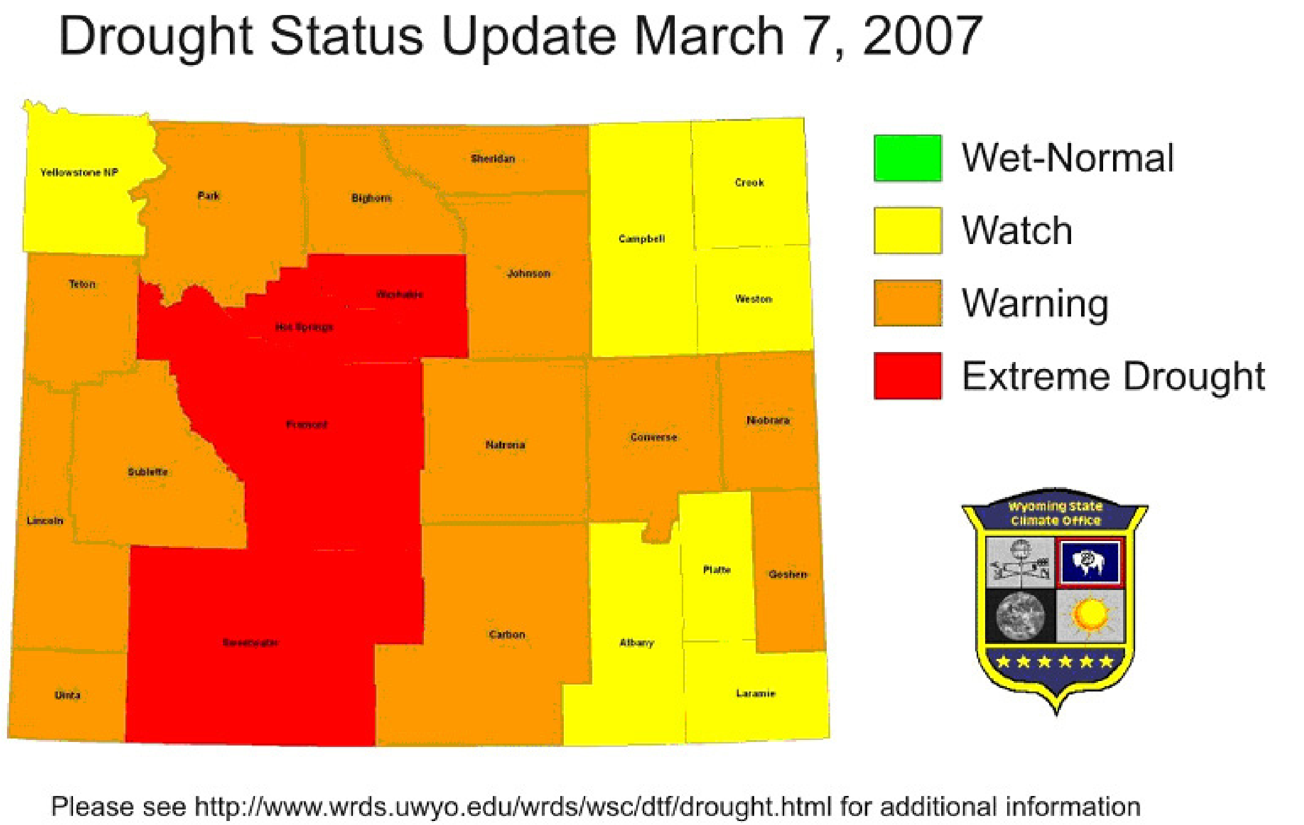


**Figure 6.** Many state climate offices also offer drought status assessments that could be incorporated into the proposed Tier I summary reports. The example given above is for the state of Wyoming, and is generated at least monthly by the Wyoming State Climate Office.

o Required analyses and resulting products:

Assessments from existing drought monitoring networks (e.g. US Drought Monitor) should provide the backbone of these analyses. Once in full operation, the National Integrated Drought Information System (NIDIS) will also provide an excellent source of information regarding regional drought status. For more information on NIDIS and an overview of existing clearinghouse functions see http://www.drought.gov/.

• 6. Seasonal Forecasts over 1-3 month (or longer) windows

o Key variables:

Outlooks for precipitation, temperatures, runoff, lake levels, drought, fire, or large-scale climatic drivers (e.g. El Niño).

o Required analyses and resulting products:

Report authors must rely on forecast products provided by the NOAA-Climate Prediction Center, National Weather Service Weather Field Offices, state and regional climate offices, or other similar groups/agencies.

<u>Key indicators for products addressing park-level conditions or conditions within a cluster of</u>

neighboring parks

- 1. Precipitation, temperature, snowpack, and streamflow
  - o Key variables:

    Same as for the multi-park to regional analysis, with the addition of summaries of recent conditions at one or more key stations within a within the park.

    Should also report any notable extremes (e.g. record maximum/minimum daily temperatures, record snowfalls, extreme high/low stream discharge or river-stage values, etc.) for a park or station within a park.

  - o Required analyses and resulting products:

    Most required analyses are the same as those for reporting at the multi-park to regional level.

    Must also compile records of previous extreme events at both the station and park level.

- 2. Drought status
  - o Key variables:

    Report of any notable drought indicators (e.g. large precipitation deficits, low streamflows, poor vegetation condition, fires) in addition to a mention of US Drought Monitor status or status from other relevant state to regional-level assessments.

  - o Required analyses and resulting products:

    Must first identify key indicators of drought for each park or area of interest.

    If necessary, thresholds for different levels of drought status must then be identified for these indicators.

Recommendations for Tier I Reporting Timelines

Under the current paradigm responsibility for the creation of Tier I reports will fall to individual parks or networks. While monthly or seasonal summaries would be ideal for conveying key aspects of park or network climate, tight budgets and staffing issues may preclude such frequent reports.

Optimal reporting schedules will vary by region. However, for the Intermountain West and other regions with pronounced wet and dry seasons it is recommended that reports be generated at least twice each year. For the Intermountain West the first report would include a summary of events over the previous fall and winter months, and its release would coincide with the start of the summer growing season (which is also the start of peak visitation in most western US parks). The second

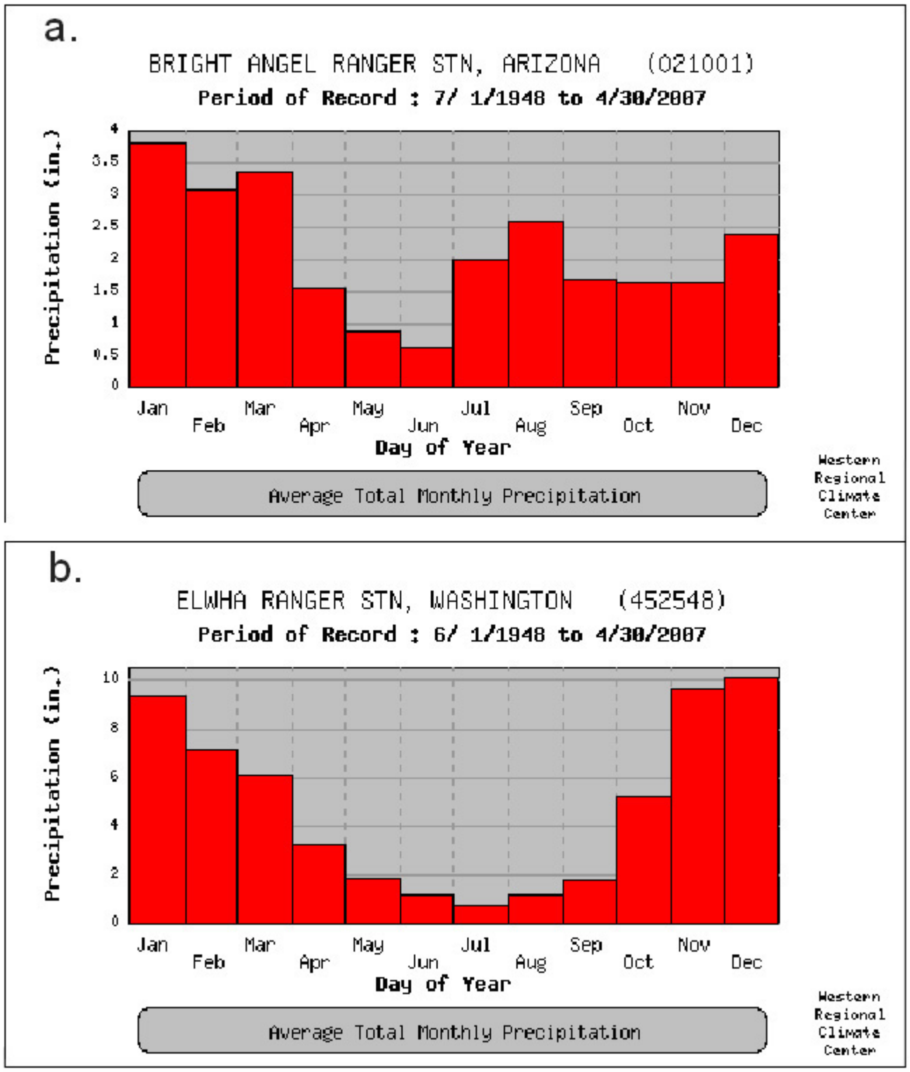


**Figure 7.** Average monthly precipitation for two stations in Grand Canyon National Park, Arizona (a) and Olympic National Park, Washington (b). Figures courtesy Western Regional Climate Center.

report would encompass conditions over the length of the growing season.

In the case of the Greater Yellowstone Network (GRYN) the recommendation would be for the first report to track conditions from October 1 of the previous year through May 1 of the present year. The start of this period roughly coincides with the end of the previous summer (also the start of the "water year") and runs through the period of maximum snow accumulation. As envisioned here, this cool season GRYN report would focus on snowpack (evolution and total accumulation), snow cover, and general snow conditions (e.g. formation of durable crusts or depth hoar). Temperature extremes, both in terms of single day max/mins and extended cold/warm periods, would also receive significant attention. Runoff forecasts for the upcoming summer and indices related to hydrologic conditions would also be featured in this report.

The second recommended GRYN report would cover the period from May 1 through September 30 of the current year. Here the emphasis would shift towards indices of drought or growing season moisture status and other integrators of climate such as streamflow. Temperature extremes and notable precipitation events would be included in this report, as would information related to vegetation health/vigor (e.g. satellite-derived “greenness” or NDVI).

Splitting these reports into seasonal components has several advantages. First and foremost, if the release of these summaries is timed correctly, such a retrospective examination of recent climatic events could be a great aid in planning for the next season. This approach also recognizes how seasonal variations in climate have differential effects on park ecosystems. In the case of GRYN, winter snow-cover and temperature extremes can have a particularly strong impact on ungulates (Pearson et al. 1995), whereas climatic conditions over the summer months usually have a relatively small influence on these populations.

As for other regions, and examination of month to month or seasonal variations in climate should provide a first-order indication of suitable reporting schedules. In the cases shown in Figure 7, one sees that different regional climates can

suggest natural “breakpoints” in the reporting cycle. In the case of the Bright Angel Ranger Station record from Grand Canyon National Park, AZ (Figure 7a) there is a prominent break between the wetter months of the winter and spring and the arid fore-summer that precedes the annual monsoon. The end of the monsoon season in late August or early September then marks the transition back to a cooler-season pattern. In turn two reporting windows that ran from October of the previous year through the end of March in the current year and from the beginning of April through September would be well suited to the bimodal nature of this region’s climate. Likewise the pronounced winter-wet and summer dry pattern in Olympic National Park, WA (Figure 7b) might lend itself to an October through March and April through September reporting schedule. While these examples focus solely on precipitation, other factors such as temperature or the timing of key phenological events might inform the creation of reporting schedules. As stated previously, the optimum reporting schedule may vary from region to region and as budgets and other constraints allow. However, there are few locations in the western US where a single calendar-year report would be among the best options.

<u>Overall Recommendations</u>

- No one metric or index can adequately describe variations in precipitation, temperature, drought status, etc. Each climate metric or index also suffers from its own unique set of problems and limitations. Tier I reports should therefore use multiple approaches to represent climatic conditions. Examples include using a combination of calculated anomalies, percent of average and SPI to portray recent precipitation totals, and using both raw streamflows and SWSI to represent surface water status.

- Tier I reporting schedules should be designed around the seasonal climatology of a park/network rather than administrative calendars. In most cases (especially in the Intermountain/Rocky Mountain West) twice-yearly reports will be required to capture import characteristics of wet and dry-season climate.

- Interpolation between climate stations for the purpose of producing maps, filling data gaps, etc. should be done with the greatest caution, and only in circumstances where the effects of topography and stations density are well understood. In many cases—particularly for depictions of park-level conditions in the mountainous West—presentation of data from individual stations rather than interpolated data may be most appropriate.

- Climate "normals" must not be presented in a way that implies that such statistical baselines represent the weather/climate we should expect in a given area.

- Presentation of drought indices and drought-related summary products should be a key component of Tier I products, especially in the Intermountain/Rocky Mountain West.

### Tier II: Climate Data Access and Distribution Portal

General

Based on several years of input from NPS personnel and the analyses presented in Section II, obtaining and managing data is by far the largest barrier to the use of climate-related information in the I&M program. Most relevant data are available over the internet, but I&M personnel often struggle to find these data or to place them in a useable format once they are located. In other cases access to data requires special passwords or payment for services.

A system for addressing these issues is already in development at the National I&M Program office. This proposed "NPClime Interface" would incorporate climate records stored in the Applied Climate Information System (ACIS; http://rcc-acis.org), and provide access to these data through a variety of query methods. What follows is a list of key elements that this system should include if it is to meet the needs of NPS ecologists, I&M personnel, and cooperators.

Format

Online portal that will access either existing databases of climate observations or access an NPS-maintained database of observations compiled from a variety of sources.

Objectives

- To provide on-demand access to existing climate data (recent and historical). MUST allow users to obtain data for manipulation in other platforms.

- Provide basic statistical summaries of climate data (e.g. normals and extremes).

- Provide access to metadata for all records housed within the system.

Scope

- Includes information on primary climatic elements (temperature and precipitation) as well as key secondary elements (e.g. wind, humidity, solar radiation, etc.) and key integrators of climate (e.g. snowpack)

- Includes relevant observations taken within participating parks, as well as surrounding areas

- The majority of user needs would be met with daily or monthly data. However, the costs and benefits of including higher resolution (e.g. 15 min) data in the Tier II system should also be explored.

Suggested Key Features

o Should have capability to access data from:

Individual stations

Data averaged over an entire park or all stations in a park

Data averaged over climatic-sub regions as identified in the analyses related to Tier I products

Data averaged over an entire network (or other pre-defined region of interest)

All stations within a user-selected geographic window (e.g. box defined by lat/lon, on-screen selection, etc.)

o Must allow easy access to observations from different agencies

o System should allow queries that select for data over a period of interest or the entire period of record

o System should allow for queries that produce summaries for the observations within a record, or identification of extreme values within a record. Users should, for example, be able calculate average values over some period of interest, or query the system to find a set of the highest values, lowest values, etc. within a record.

o Must provide multiple output options, including the ability to download data files and produce (at least) medium resolution graphics. At a minimum output formats should include:

Space, comma and/or tab delimited files

Files in Microsoft Excel format or other formats easily exported to common spreadsheet programs

Files formatted for direct input to the Tier III analysis tools

o Must provide metadata in user-friendly, easily accessible formats. For individual station records this may be achieved by linking to existing sources of metadata (e.g. http://www.wrcc.dri.edu/Climsum.html), or through queries to a database created by ingesting metadata directly from the responsible agencies. In any case, easy to interpret depictions of data quality and completeness will be key. Graphical depictions of quality and completeness (e.g. Figure 8) may be particularly useful for users within the NPS-I&M program. In the case of products that include data from multiple observational records, compilations of metadata for each site—or a means to access these metadata—must be made available. In addition, metadata summary

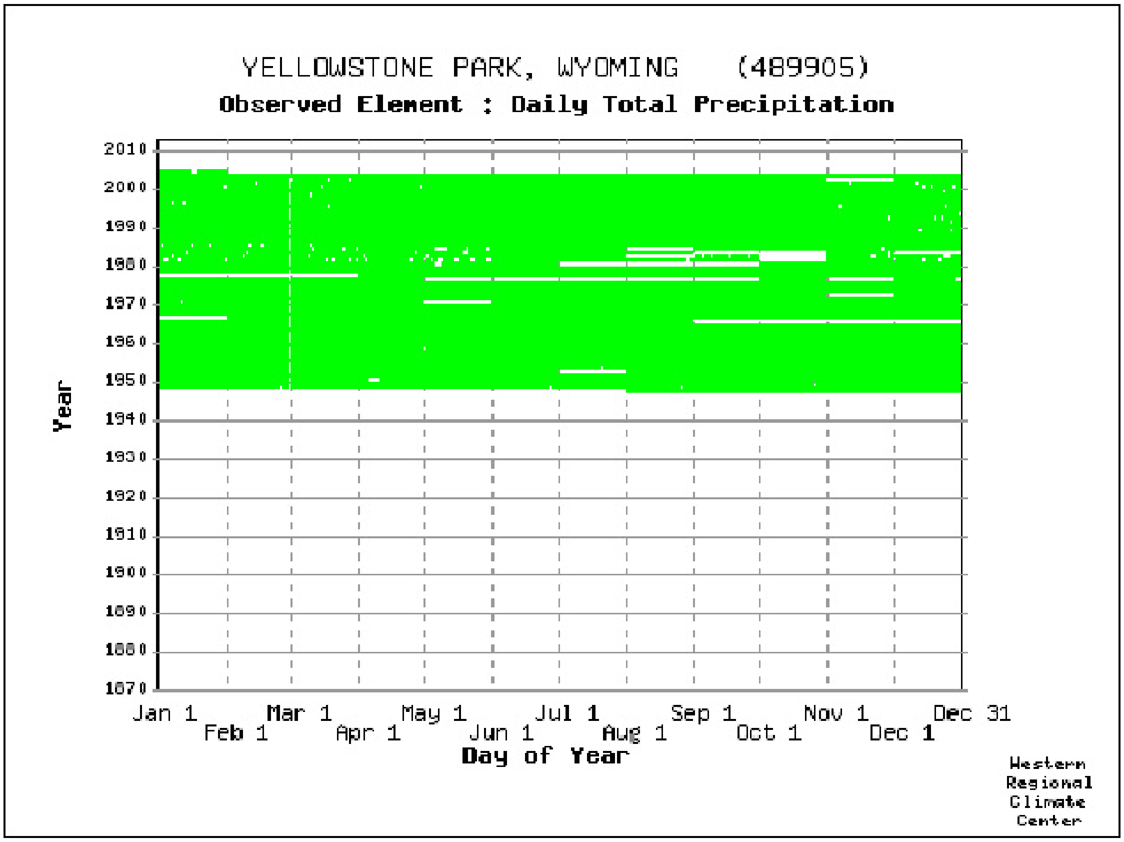


**Figure 8.** Graph showing availability of total daily precipitation as measured at the Yellowstone Park (Mammoth), Wyoming NWS-COOP station. Available data are shown in green, missing data in white. Such graphical representations can be quickly interpreted by new users. Courtesy Western Regional Climate Center.

products such as found in Figure 9 might be generated for these multi-site products.

Other Potential Features

• Given the limited amount of experience most I&M personnel have with climate data, providing links to information about sensor platforms and monitoring networks used to produce the data they download may be useful. Expert advice on how data from specific sensors or network might or might not be applied should also be considered.

• In many cases missing or suspect data will present significant problems for users of climate data. Therefore the proposed Tier II system might also include a means for estimating missing data or calculating the influence of suspect observations on statistics of interest. However, depending on the level of difficulty involved with implementing such tools in Tier II, such capabilities might be better met through the Tier III products (see below).

• The use of gridded climate data or other spatially distributed estimates of climate is becoming more and more common in ecology, and will undoubtedly play an important role in future I&M activities. Recent advances in GIS technologies and geospatial analysis make the creation of such distributed products feasible within the Tier II system, given adequate observations within an area of interest. However, the bulk of recent research (e.g. Thornton et al. 1997, Daly 2006) suggests that creating such distributed products "on the fly" would be problematic from a product-quality standpoint, particularly when the area of interest encompasses complex terrain. A more reasonable solution might be to rely on existing products (e.g. output from the PRISM model; http://www.ocs.oregonstate.edu/prism/). In some cases (e.g. distributed estimates of snow depth) few suitable distributed products currently exist, so an additional investment in developing these data may be warranted.

• Streamflow and runoff are important integrative measures of climate, as well as key drivers for many physical and ecological processes of interest. In contrast to data for primary climatic elements, in many cases streamflow observations (e.g. stage, discharge, etc.) can be easily accessed via the internet. The U.S. Geological Survey, in particular, does an excellent job of providing surface water data (see http://waterdata.usgs.gov/nwis) that they and their partner agencies collect. Therefore it is recommended that access to streamflow measurements and other observations of surface water be given a relatively low priority in the development of the Tier II system.

## Tier III: Advanced Analysis Tools

Format

Local or online application that will allow users to analyze, summarize and present climatic data in a variety of formats. The advanced analysis tools might be linked directly to the online portal proposed for Tier II. However, a more cost-effective and technically feasible approach would be to develop these applications as a separate "tool kit" for use outside the Tier II system. This latter approach would also give the user community the ability to make updates to the Tier III tool kit, and foster a user-based support system within the NPS-I&M program. Commercially available programs such as the Matlab (www.mathworks.com) could provide the framework for this tool kit, but the cost of Matlab and similar packages puts them out of reach for most I&M personnel and cooperators. Public domain software environments such as R (www.r-project.org) may offer a more viable option for tool kit development. R is a particularly powerful tool for statistical computing, and many of the utilities required by NPS-I&M personnel could be easily created from existing R scripts. However, the learning curve for R is extremely steep. Therefore an alternate suite of analysis products developed for Microsoft Excel or some other inexpensive and widely accessible platform may also be required.

Objectives and Scope

Based on the required analyses identified in for Tier I and Tier II products and the generalized needs of researchers profiled in Section II, the tools developed for Tier III should provide:

• First and foremost the system must offer the ability to calculate all of the standard metrics and composite measures of climate proposed for the Tier I products.

• Ideally the system would be capable of producing the high quality graphics required for Tier I products, but at a minimum that system must provide output that can be easily ported to common graphing and graphics packages.

• Ability to perform complex data formatting and manipulation functions (e.g. transposition, concatenation, automatic conversion between file formats).

• Utilities for performing time-series analysis on individual datasets.  Basic functions should include calculation of min, max, and median values, percentiles, SD, CV, and identification of outliers.  Advanced functions should include tools for examining temporal autocorrelation, performing trend analysis, time-series decompositions, smoothing/filtering, and ARIMA modeling.

• Compositing of datasets using pre-defined and user-defined criteria (e.g. ability to split datasets into subsets of the driest/wettest or coolest/warmest years).

• Tools for homogeneity testing, data homogenization, and estimation of missing data.

• Ability to compare time series for multiple climatic elements via advanced analysis techniques such as bootstrapped and moving-window correlations and cross-correlation functions.

• Ability to generate artificial time series with a variety of user-specified characteristics.

# IV. The I&M Network Climate Atlas

Given the information presented in Section II, there appears to be a strong need for basic summaries of climate at the park and network levels. More specifically, many researchers—and ecologists in particular—require an easily-accessible and comprehensive source of information on spatial and temporal variability of climate in their parks. Inventories of monitoring sites, listings of available datasets, and reference data (e.g. climate normals) will also be key for incorporating climate into the I&M Program.

Several key features (e.g. monitoring and data inventories) of such park or network "climate atlases" are already under development. Additional features could be generated in conjunction with the development of the Tier I and Tier II products described previously. Likewise many relevant analyses of spatial variation of climate could be addressed using existing gridded map products (e.g. PRISM output; http://www.ocs.orst.edu/prism/index.phtml). Information should be presented at the level of individual parks, or in the case of larger park units, for hydroclimatically meaningful regions within a park.

General topics or chapters within a network climate atlas might include:

- Factors that govern climate at the within-park to network level.
- Discussions of available monitoring networks and datasets.
- General information on climate-change (natural and anthropogenic) at the park to regional level.
- Presentation of normals (i.e. averages compared to some baseline or reference dataset) and extremes for primary climatic elements.
- Descriptions of state climate divisions and any relevant climate regionalizations developed for the Tier I and Tier II products discussed previously.
- General information or discussions related to drought, severe storms, clouds, air quality, and visibility.

Specific topics to include:

- Related to precipitation
    - Mean annual, mean monthly and mean seasonal precipitation.
    - Record precipitation events (e.g. most in 24 hrs, longest period without precipitation, etc.) for all parks.
    - Precipitation effectiveness.
    - Variability of precipitation (spatial and temporal).

  - o Orographic effects on precipitation.

- Related to temperature
  - o Mean annual, mean monthly and mean seasonal temperatures.
  - o Average daily highs/lows over monthly, seasonal and annual windows.
  - o Record temperatures and notable temperature events (e.g. extreme daily highs/lows, longest period below freezing, etc.).
  - o Analyses of growing season length/variability.
  - o Frost free days, first and last frost dates.
  - o Growing degree days.
  - o Temperature variations across complex terrain (e.g. valley inversions, temperature vs. elevation, etc.).
  - o Daily temperature swings.
  - o Soil temperatures.
- Related to snowpack
  - o Mean annual and mean monthly snowfall.
  - o Extreme snowfall events and record highs/lows for months, seasons and years.
  - o Topographic influences on snowpack.
  - o Variability of snowpack (spatial and temporal).
  - o Snow-water ratios.
- Miscellaneous
  - o Evaporation/Evapotranspiration.
  - o Wind.
  - o Solar Radiation.
  - o Humidity.
  - o Pressure.
  - o Soil Moisture.

# V. Conclusions

- Simplicity and ease of use should be given the highest priority in any system intended for NPS-I&M personnel and cooperators.

- Most potential users of a system for climate-data delivery and analysis will possess only the most basic understanding of climate-related data and information. More specifically, potential users will have very little knowledge concerning climate-related metadata or quality control measures, and a relatively coarse understanding of how to select datasets for specific applications.

- There is a pressing need for basic information related to park- and network-level climate, as well as a need for information on current conditions and recent trends. These needs will not be met by providing data-access portals and analysis tools alone.

- The Tier I-type products described here would likely be the main source of climate-related information for the majority of NPS staff and cooperators. Such reports should provide multiple perspectives on park and network-level climate (e.g. multiple metrics to describe precipitation conditions), and seek to place climatic events in a long-term, regional context. Timing for the compilation and release of these reports should be designed to capture important aspects of seasonal climate at the park or network level.

- We can anticipate that there will be a significant need for education and outreach related to any climate-data delivery and analysis system

# VI. References


Allen, M. R., P. A. Stott, J. F. B. Mitchell, R. Schnur, and T. Delworth. 2000. Quantifying the uncertainty in forecasts of anthopogenic climate change. Nature, 407, 617-620.

Allen, R. G., M. Tasumi, A. Morse, and R. Trezza. 2004. A Landsat-based Energy Balance and Evapotranspiration Model in Western US Water Rights Regulation and Planning. J. of Irrig. and Drain. Sys, 19, 251-268.

Alley, W. M. 1984. The Palmer Drought Severity Index: Limitations and assumptions. Journal of Climate and Applied Meteorology, 23, 1100–1109.

Ashraf, M., J. C. Loftis, and K. G. Hubbard. 1997. Application of geostatistics to evaluate partial weather station networks. Agric. For. Meteor., 84, 255–264.

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

Bastiaanssen, W. G. M., M. Menenti, R. A. Feddes, A. A. M. Holtslag. 1998. A remote sensing surface energy balance algorithm for land (SEBAL). Journal of Hydrology, 212-13, 198-212.

Bonan, G. B. 2002. Ecological Climatology: Concepts and Applications. Cambridge University Press, Cambridge; 678 pp.

Dale, V. H. 2003. New directions in ecological modeling for resource management. In V.H. Dale (ed.), Ecological Modeling for Resource Management, Springer-Verlag, New York, New York; 238 pp.

Daly, C. 2006. Guidelines for assessing the suitability of spatial climate data sets. Int. J. Climatol., 26, 707-721.

Doesken, N. J., T. B. McKee, and J. Kleist. 1991. Development of a surface water supply index for the western United States. Climatology Report Number 91–3, Colorado State University, Fort Collins, Colorado.

Edwards, D. C. and T. B. McKee. 1997. Characteristics of 20th century drought in the United States at multiple time scales. Climatology Report Number 97–2, Colorado State University, Fort Collins, Colorado.

Finney, M. A. 1998. FARSITE: Fire Area Simulator - Model Development and Evaluation. Res. Paper RMRS-RP-4. Fort Collins CO: Rocky Mountain Research Station, U.S. Department of Agriculture, Forest Service; 47 pp.

Fovell, R. G. 1997. Consensus Clustering of U.S. Temperature and Precipitation Data. Journal of Climate, 10, 1405–1427.

Gray, S. T., J. L. Betancourt, S. T. Jackson, R. Eddy. 2006. Role of multidecadal climate variability in a range extension of pinyon pine. Ecology, 87, 1124-1130.

Hays, M. J. 2006. What is Drought?: Drought Indices. National Drought Mitigation Center White Paper Series. Available at: http://www.drought. unl.edu/whatis/indices.htm.

Heddinghaus, T. R. and P. Sabol. 1991. A review of the Palmer Drought Severity Index and where do we go from here? In Proc. 7th Conf. on Applied Climatology, pp. 242–246. American Meteorological Society, Boston.

Hoerling, M. P., and J. Eischeid. 2007. Past peak water in the Southwest. Southwest Hydrology, 6, 18–19.

IPCC (Intergovernmental Panel on Climate Change). 2001. Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA; 881pp.

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; 523 pp.

Karl, T. R. and R. W. Knight. 1985. Atlas of Monthly Palmer Hydrological Drought Indices (1931–1983) for the Contiguous United States. Historical Climatology Series 3–7, National Climatic Data Center, Asheville, North Carolina.

Kashian, D. M., W. H. Romme, D. B. Tinker, M. G. Turner, and M. G. Ryan. 2006. Carbon Storage on Landscapes with Stand-replacing Fires. BioScience, 56, 598-606.

Koteen, L. 2002. Climate change, whitebark pine, and grizzly bears in the Greater Yellowstone Ecosystem. Pages 343–411, In Schneider S. H, Root T. L (eds.) Wildlife responses to climate change. Island Press, Washington, DC; 438 pp.

Lillesand, T. M., and R. W. Kiefer. 1994. Remote sensing and image interpretation, 3rd ed.: New York, N.Y., John Wiley and Sons, Inc.; 750 pp.

Litton, C. M., M. G. Ryan, D. H. Knight, and P. D. Stahl. 2003. Soil-surface carbon dioxide efflux and microbial biomass in relation to tree density 13 years after a stand replacing fire in a lodgepole pine ecosystem. Global Change Biology, 9, 680–696.

Lyford, M. E., S. T. Jackson, J. L. Betancourt, and S. Gray. 2003. Influence of landscape structure and climate variability on a late Holocene plant migration. Ecological Monographs, 73, 567-583.

McCabe, G. J. and D. M. Wolock. 2007. Warming may create substantial water supply shortages in the Colorado River basin. Geophysical Research Letters, 34, L22708, doi:101029/2007GL031764.

McKee, T.B., N.J. Doesken and J. Kleist. 1995. Drought monitoring with multiple time scales. Preprints, 9th Conference on Applied Climatology, pp. 233–236. January 15–20, Dallas, Texas.

McKee, T.B., N.J. Doesken and J. Kleist. 1993. The relationship of drought frequency and duration to time scales. Preprints, 8th Conference on Applied Climatology, pp. 179–184. January 17–22, Anaheim, California.

Mott, P., T. W. Sammis, and G. M. Southward. 1994. Climate data estimation using climate information from surrounding climate stations. Appl. Eng. Agric., 10, 41–44.

Odum, H.T. and E.C. Odum. 2000. Modeling for all scales. Academic Press, New York; 458 pp.

Palmer, W. C. 1965. Meteorological drought. Research Paper No. 45, U.S. Department of Commerce Weather Bureau, Washington, D.C.

Pearson, S. M., M. G. Turner, L. L. Wallace, W. H. Romme. 1995. Winter habitat use by large ungulates following fire in northern Yellowstone National Park. Ecological Applications, 5, 744-755.

Peterson, D. L. and V. T. Parker. 1998. Dimensions of scale in ecology, resource management and society, Pages 499-522. In: D. L. Peterson and V. T. Parker (eds.) Ecological Scale: Theory and applications. Columbia Univ. Press, NY; 608 pp.

Reed, R. A., M. E. Finley, W. H. Romme, and M. G. Turner. 1999. Aboveground net primary production and leaf area index in initial postfire vegetation communities in Yellowstone National Park. Ecosystems, 2, 88-94.

Root, T. L. and S. H. Schneider. 2002. Climate change: Overview and implications for wildlife, Pages 1-56, In Wildlife Responses to Climate Change: North American Case Studies. S. H. Schneider and T. L. Root, editors. Island Press: Washington, DC; 678.

Schlesinger, W. H. 1997. Biogeochemistry: An Analysis of Global Change. Academic Press, San Diego; 443 pp.

Schwartz, C. C., M. A. Haroldson and G. C. White. 2006. Survival of cub and yearling grizzly bears in the Greater Yellowstone Ecosystem. Wildlife Mongraphs 161, 25-32.

Shafer, B. A.; and L. E. Dezman. 1982. Development of a Surface Water Supply Index (SWSI) to assess the severity of drought conditions in snowpack runoff areas. In Proceedings of the Western Snow Conference, pp. 164–175. Colorado State University, Fort Collins, Colorado.

Stott, P. A and Tett, S. F. B. 1998. Scale-Dependent Detection of Climate Change. Journal of Climate, 11, 3282–3294.

Swetnam, T. W. and Betancourt, J. L. 1998. Mesoscale disturbance and ecological response to decadal climatic variability in the American Southwest. Journal of Climate, 11, 3128-3147.

Thornton, P. E., S. W. Running, and M. A. White. 1997. Generating surfaces of daily meteorology variables over large regions of complex terrain. Journal of Hydrology, 190, 214-251.

Wilkie, D. S. and Finn, J. T. 1996. Remote sensing imagery for natural resources monitoring--A guide for first-time users: New York, N.Y., Columbia University Press; 295 pp.

NPS D-1982, May 2008

National Park Service
U.S. Department of the Interior

**National Resource Program Center**
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov