A Framework for Climate Analysis and Reporting for Greater Yellowstone (GRYN) and Rocky Mountain (ROMN) Networks

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Executive Summary

Crucial to the Park Service's mission is understanding climate status, variability, and trends given that climate is a key driver of variability in other vital signs and of changes in park natural resources. Accordingly, goals of the Greater Yellowstone (GRYN) and Rocky Mountain (ROMN) Inventory and Monitoring networks are (1) to evaluate variations and change in key climate parameters and (2) to provide climate data for analyses of other vital signs.

GRYN and ROMN are coordinating development of climate monitoring procedures to achieve these goals. To facilitate this, the GRYN hosted a Climate Data Analysis Workshop in Bozeman, MT in April 2009, with participants from NPS and the climate science community. The aim of the workshop was to outline details of data requirements, data cleanup, analysis methods, and reporting timeframes for meeting GRYN/ROMN climate monitoring objectives. This report presents this framework. While laid out specifically for these two networks, the framework can serve as a template for other networks whose protocols are under development.

The protocol framework provides for four monitoring products (§2.1-2.2). These and their timeframes are:

- *Annual Climate Status Report* – Presenting the previous year's climate (for both the calendar year and water-year), based on available data aimed at supporting yearly park science and management planning. Released early each calendar year.
- *Climate Variability and Trends Report* – Providing longterm, decadal, and hemispheric perspectives on changing climate conditions across the network domain. Updated on a 5-year cycle.
- Network climate zones analysis – defining climatically-similar reporting zones within a network for reporting status and trends. Done at initiation of the monitoring protocol.
- High-quality, online historical network dataset – on which to base *Annual Status* and *Variability and Trends* reports and for other vital sign analyses, with a large initial investment over five years and then updated on annual and 5-year cycles.

The framework gives three guidelines for successful implementation of the protocol:

(1) *Staged development* – First-round tasks for completion of these products are staged over the first five years to even out resource demands during the start-up period. Tasks over subsequent 5-year cycles are similarly staged. (§2.3)

(2) *Recommended techniques* – Recommended protocol strategies and techniques for (a) handling data errors, inhomogeneities, and missing values and (b) trend and variability analyses follow those in the I&M Natural Resource Report: *The Development and Analysis of Climate Datasets for National Park Science and Management*. (§2.4)

(3) *Criteria for success* – Criteria for successful protocol implementation are that:

- Dataset creation methods must match and not conflict in any significant way with analysis requirements. (§2.5.1)
- Dataset creation and analysis techniques must be defensible, following well-established, best practices of the climate science community. (§2.5.2)

- These processes must be transparent, with method assumptions and the dataset's intended uses well documented. To assure transparency and maximum utility of network data, final datasets should be open access and online. (§2.5.3)

With these framework elements, the GRYN and ROMN can lay out a joint protocol for climate dataset development, analysis, and reporting essential to accomplishing monitoring goals and objectives. Such a protocol can be established using a *scientifically rigorous approach*, as framed in this report, that will lead to a successful analysis of network climate status, variability, and trends, and with regional and hemispheric perspectives. This will be possible provided that certain limitations and solutions are recognized – summarized in four key recommendations:

(1) The quality of standard station data products from national agency weather/climate monitoring programs is generally adequate to portray the *status of climate for locations* in parks on an annual basis.

There are, nonetheless, two key limitations of these datasets with respect to other I&M climate monitoring objectives: (a) poor suitability for describing variability and trends in climate and (b) low spatial representativeness, especially over topographically heterogeneous domains.

(2) With respect to suitability for longterm climate analyses: Agency station data products, as released, are not suitable to describe variability and trends of climate in a scientifically-defensible manner. Rather, the analysis of climate variability and trends requires a substantial, but worthwhile investment in data quality control.

This entails implementing *QC techniques in keeping with climate-community standards*, under *the guidance of a climate scientist*. Because climate change is a high-profile, contentious topic, reliance on less than high-quality data for monitoring goals poses a high risk to the I&M Program's credibility. Unless able to implement a community-standard QC protocol, the networks should not attempt to evaluate longterm climate trends. (§2.5.2, §2.6.1)

(3) With respect to spatial representation: It is possible to characterize the status of a park's climate to some degree using only point-based station data. However, low station density and low-elevation bias in these stations' locations gives low confidence in how well such a description can represent topographically-heterogeneous parks of the GRYN and ROMN. On the other hand, a *high-resolution gridded climate dataset* can (a) fully represent current status of park climate zones, (b) provide spatial details for important management areas, and (c) put park climates in perspective of the surrounding region's climate.

Of candidate gridded datasets, the workshop identified PRISM monthly products as best matching all monitoring requirements – including (a) portraying key climate features and (b) near-real time availability. The workshop, however, noted longevity of this resource as a potential issue and encourages the NPS to continue to participate in efforts to assure its stability given its monitoring value. (§2.6.2)

(4) A final recommendation is that network climate monitoring programs look for future opportunities to improve their climate station networks and capabilities in ways critical to meeting monitoring goals (§2.7). Areas for future improvement include: (a) building capacity to monitor climate in *alpine areas*, especially important given that climate change is expected to be most dramatic at high elevations, and (b) incorporating *synoptic climate analyses* into the protocol, to reveal the mechanisms driving observed seasonal, interannual, and longer-term shifts in park climates.

List I. Workshop Participants[7]

National Park Service –

Isabel Ashton – RMNO
Rob Daley – GRYN
Brent Frakes (workshop co-organizer, representing RMNO) – Office of Inventory, Monitoring, and Evaluation, Ft. Collins
Cathie Jean (workshop co-organizer and rapporteur) – GRYN
Kathy Mellander – Grand Teton National Park
Stacey Ostermann-Kelm (workshop co-organizer) – GRYN
Roy Reinkin – Yellowstone Center for Resources

Outside expertise –

Christopher Daly – Director, PRISM Group, Oregon State University
Stephen Gray – Wyoming State Climatologist, University of Wyoming
Timothy Kittel (workshop co-organizer) – Institute of Arctic and Alpine Research, University of Colorado
Mike Tercek – Walking Shadow Ecology, Gardiner, MT

[7] Participant contact information is listed in Appendix A.

1.0 Introduction

1.1 Context

The Greater Yellowstone Network (GRYN) and the Rocky Mountain Network (ROMN) are coordinating development of climate monitoring procedures. In this report, we present a framework for establishing a joint Rocky Mountain Climate Protocol and its standard operating procedures.

1.2 Objectives

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

(1) As a vital sign – a key indicator of environmental change.
(2) As a covariate with other vital signs – driving, or responding to, dynamics of network ecosystems.

Corresponding network goals for climate inventory and monitoring are, briefly:[8]

Goal I: To determine variations and changes in key climate variables relative to an established baseline at spatial scales from local sites to parks.

Goal II: To develop climate datasets for use as a covariate in analyses of other vital signs.

Specific objectives for these goals are listed in Appendix B (Frakes et al. 2009).

To guide establishment of the protocol and standard operating procedures (SOP's) to meet these goals, the GRYN hosted a joint GRYN/ROMN Climate Data Analysis Workshop in Bozeman, MT, on 7-8 April 2009. Participants were NPS staff from GRYN, ROMN, and Yellowstone park and outside experts in the field of climate dataset development and analysis (see List I). The workshop's objective was to outline details of climate data requirements, data cleanup, analysis methods, and reporting timeframes for monitoring goals and objectives – to create a detailed framework for establishing a network climate analysis and reporting protocol. This report fleshes out this framework based largely on the outcome of the workshop and subsequent discussions.

In the next sections, we present the framework (section §2.0), layout monitoring variables (§3.0), and outline processing protocols for its components (§4.0-§5.0). An overview of this framework and its processing tasks is given in Figure 1.

1.3 Framework as Template for Other Network Protocols

While this framework is laid out specifically for GRYN and ROMN, we present it as a template for other networks. We recommend comparison with monitoring protocols already established by other networks, as it appears that some critical elements presented here are not included in those. In particular, other network protocols and analyses (e.g., Keen 2008) appear to not include the high-level of data quality control and correction needed to produce credible datasets for longterm trend and other climatic analyses (§4.3). These protocols do, in the minimum, provide for basic error checks and/or rely on QC performed by issuing data centers (e.g., CAKN: Sousanes 2004, NCPN: Garman et al. 2004).

[8] The full statement of network goals are in Frakes et al. (2009), presented in Appendix B. Goal I is stated here with the range of spatial scales consistently the focus of supporting objectives (Appendix B)

2.0 The Protocol Framework

The framework has the following elements:

- Reports (§2.1)
- Foundation analyses – initial tasks (§2.2)
- Staging (§2.3)
- Recommended guide to techniques for SOP's (§2.4)
- Criteria for success (§2.5)
- Key resources (§2.6)

We also discuss seeking future opportunities that would further achievement of network goals (§2.7).

2.1 Reporting – Objectives, Products, and Timeframes

2.1.1 Reporting objectives

In the framework, the monitoring program has three objectives for reporting:

(1) Annual status – a summary analysis of the past year's climate. *(Goal I)*
(2) Long-term change monitoring – an analysis of climate trends, interannual variability, and the role of hemispheric teleconnections (e.g., El Niño). *(Goal I)*
(3) Data access – online access to climate datasets to support I&M analyses (regarding other vital signs) and park science, management, and public programs. *(Goal II)*

2.1.2 Products and timeframes

Each of these three reporting objectives has corresponding products and reporting timeframes:

Product 1 – Annual Climate Status Report. Prepared yearly, the *Annual Climate Status Report* covers the previous calendar and water-years.[9] Depending on data availability and release time, the report could also include a preliminary assessment of the most proximate early/midwinter season as context for the coming plant growing season/summer visitor season.[10] For brevity, we refer to this report as the *Status Report.*

This report presents two portraits of the year's climate:

(1) An extensive *spatial* picture of the year across the network domain and its constituent climate zones. The workshop recommended that this spatial view be based on high resolution gridded data. Delineation of within-network climate zones are developed in *Foundation Task 1* (§2.2).

(2) The year in context of long-term *temporal* dynamics as developed in the *Climate Variability and Trends Report* (discussed shortly) – including comparison to an established baseline (*Goal I*, §1.2). The workshop recommended that this be the most recent 30-year climate normals period: 1971-2000.[11]

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[9] Calendar year = [Jan(-1)-Dec(-1)] and previous water year = [Oct(-2)-Sept(-1)], where the (index) is number of years relative to report release year.
[10] Early/midwinter season might be defined as Oct(-1) through Jan(0), for example, for this report. This assessment could possibly be accomplished with PRISM first-round 'provisional' product (§2.6.2) available at a lag of a month or so.
[11] 1971-2000 normals was recommended because it is currently the community standard. Using 1971-2000 normals will give a conservative assessment of recent climate change, as changes have been most marked since the middle of 20th century, as least as far as temperatures – earlier normals periods would illustrate such longterm changes. Baselines for the normal period will be derived from the networks' historical dataset (§2.2), rather than relying on the NOAA National Weather Service (NWS) normals product.

The intent of the report is to support yearly park science and management planning (*Goal I*, §1.2). Details of the report and processing requirements are laid out in §4.0, with a corresponding flow-chart in Figure 2, Figure 3. *Status Report* data and discussion are provisional, based on data which are available when reports are prepared and which undergo an intermediate level of quality control (described in §4.3.1).

- *Setting a realistic release date.* Report release date would likely be strongly tied to data availability from NOAA and other sources. The workshop suggested seeking ways to shorten the wait-time required for data to be available from NOAA sources so that the report may available in advance of the summer growing/visitor season. One option is basing year-end temperature and precipitation data on paper reports obtained from a few, key COOP stations[12] and provisional results from PRISM gridded data.[13] (See also §4.3.1:)

Product 2 – Climate Variability and Trends Report. This report presents analyses of interannual variability, longterm historical trends, and teleconnections with hemispheric climate patterns (e.g., El Niño, the Pacific Decadal Oscillation) (*Goal I*, §1.2). Updated on a 5-year cycle, the longer cycle permits: (1) a high level of station data quality checks and correction since the previous report and (2) detailed analyses of longterm patterns in the annual, monthly, and daily climate record. For brevity, we will generally refer to this product as the *Trends Report.*

The purpose of this report is to provide park management, research, and public outreach with reliable, periodic, and pertinent assessments of changes in park climates. These assessments will be multi-facetted:

(1) Evaluating a suite of ecologically-significant climate variables – including temperature, precipitation, snowpack, drought, and surface hydrology (§3.0, Table 1)
(2) Assessing a spectrum of climate dynamics – in terms of daily (including occurrence of extremes), interannual, and longterm behavior
(3) Judging connections to regional and hemispheric climatic processes

Details of processing requirements are laid out in §4.0 and corresponding flow-charts (Figure 4, Figure 5).

Product 3 – Network Climate Database. This high-quality historical network climate database is developed and updated as the foundation for *Status* and *Trends* report analyses (*Goal I*, §1.2; *Foundation Task 2*, §2.2). The database will be available to I&M and park staff (*Goal II*) – with final, vetted datasets online with open access (see §2.5, *Criteria for Success*). As well as supporting goals of the I&M networks, benefits of a network database are:

(1) NPS staff, cooperators, and other researchers are more likely to consistently use a central dataset, versus putting in time to develop their own data, if the network database –

- Is of high quality and regularly updated
- Has pulled together climate data from many, quality sources across networks
- Is multivariate and multi-timescale – that is, with climate variables at timesteps that are key drivers of variability in park natural resources
- Is recognized as the park standard source

[12] That is, B-91 forms – available from state climate offices, if not directly from station operators in the parks.
[13] PRISM = Parameter-elevation Regressions on Independent Slopes Model (Daly et al. 2008). PRISM release dates are discussed in §2.6.2. See also footnote 10.

(2) Open access permits critical review by outside users, giving another level of quality checking and assurance.

Data updates will be coordinated with *Status* and *Trends* report cycles, with changes documented and previous versions archived.

- *Shorter update cycle?* Depending on station and/or PRISM product availability and I&M program time demands, provisional data for selected park sites could be made available on a shorter cycle to support research, resource management, interpretation, and operations needing recent climate/weather information. Web updates were discussed at the workshop as a mechanism to support such near-real time needs, eliminating a need to produce mid-cycle reports.

These three reporting products are interconnected (Table 2), with the *Climate Variability and Trends Report* providing longterm context to the *Annual Climate Status Report* and data processing for both reports supplying periodic updates to the Network Climate Database. The reports can be released on the network's website, along with public access to the database.

2.2 Foundation Analyses – Network Zones, Historical Dataset

The *Status* and *Trends* reports and the database rely on two initial analyses:

Foundation Task 1 – Within-network climate zones. A delineation of distinct, internally-consistent climate zones within the network domain will be used for reporting climate vital sign status and trends. The zonation will be based on temporal dynamics of temperature, precipitation, and snowpack, along with other considerations (outlined in §5.0). This process is done at the start of protocol implementation, so that reporting zones are available for the first *Status Report*.

Foundation Task 2 – High-quality historical network dataset. Initial creation of a high-quality historical dataset is needed early to establish (1) the baseline against which changes in annual climate status are judged (§2.1.2) and (2) a longterm, credible historical record as the basis for variability and trend analyses (*Goal I*, §1.2). This foundation dataset requires careful definition of data requirements matching planned analyses (§2.5.1) and careful implementation of data quality checking and correction procedures (§4.3.2). This process is critical to create a scientifically-defensible dataset for climate change analysis – anything less will put this monitoring effort into question.

Developing the dataset will entail a large initial investment over five years in personnel (§2.6.1) and effort. The dataset will be updated on annual and 5-year cycles as part of *Status* and *Trends* reporting processes. Annual updates will be preliminary, with highest level of quality control and final release on the 5-year cycle. Because monitoring objectives are laid out to capture a broad realm of climate dynamics, the networks will need to develop *lineages* of separate climate datasets with different levels of data processing tailored to specific analyses.[14] The framework's proposed dataset lineages are outlined in Table 3, with the differences in processing detailed in Table 4.

[14] For example: a daily dataset used for creating monthly and annual values can have infilled values, while one intended for daily event frequency and extreme value analyses should be free of any estimated data (including those from data processing and distribution centers). Likewise, a longterm monthly or annual timeseries intended for trend analysis should have inhomogeneities corrected, while such techniques will likely interfere with regime shift detection.

2.3 Staging – Incremental Development

Completion of foundation tasks along with initial reporting and database tasks is staged over the first five years to even out resource demands during the start-up period. Tasks over subsequent 5-year cycles are similarly staged. Staging timeline and cross-task data flows are laid out in Table 2.

Foundation tasks are initiated in the start-up year, with climate zonation feeding into station selection for the historical dataset and *Status Reports* (Table 2). A preliminary database for the first *Status Report* is also compiled at this stage. For the first 5 years, the annual *Status Reports* are based on and contribute to this preliminary dataset.

During this initial period, a network's by-zone analyses of interannual variability, teleconnections, and longterm trends will not yet be available from a *Trends Report*. The workshop noted that a limited, but worthwhile perspective of these may be gained by analyzing nearby USHCN station records,[15] provided a station is available within or near the network domain. Results stemming from USHCN data should be accompanied with caveats regarding limitations of these data arising from this source's automated processing of station records[16] and an assessment of whether the stations adequately represent the network domain.

Completion of the historical dataset development in Year 4 leads to the start of analyses for the *Trends Report* and subsequently to a high-quality upgrade of the network database (Table 2). The *Trends Report* is released at the end of the 5-year cycle, and provides underlying information for *Status Reports* in subsequent 5-year cycles. *Status Report* annual data updates then build on data and analyses from the previous 5-year cycle *Trends Report*, and are provisional.

2.4 Techniques for Data Development and Analysis

In implementing this framework at the level of laying out techniques in SOP's, protocol development can draw on the I&M technical report *The Development and Analysis of Climate Datasets for National Park Science and Management* (Kittel 2010a). This report provides:

- Overall strategies for working with climate data[17]
- A primer on techniques for –
    - Handling data errors, inhomogeneities, and missing values[18]
    - Temporal analysis – event, variability, and trend analyses[19]
    - Spatial analysis – regional and teleconnection analyses[20]

Selection of techniques should be subject to on-going evaluation, so that the climate protocol can be flexible enough to:

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[15] The USHCN has both monthly and daily datasets, with far fewer stations for dailies. These data are available with different level of corrections (Endoe 2008; also see ftp://ftp.ncdc.noaa.gov/pub/data/ushcn/v2/monthly/readme.txt).

[16] Manual correction of station records is more likely to produce the highest quality results. Automated processing can introduce its own artifacts. In addition, the workshop recommended caution in using USHCN's highest level of inhomogeneity correction which eliminates real trends due to urban heating in the temperature record.

[17] Kittel (2010a: §2 – "Establish Goals, Identify Requirements," §5 – "Synopsis" of guidelines and strategies)

[18] Kittel (2010a: §3 – "Methods for Making Climate Records Useful")

[19] Kittel (2010a: §4.3, §4.5-4.6 – "Analysis – Tools to Explore Critical Questions:" temporal pattern analyses)

[20] Kittel (2010a: §4.7-4.8 – "Analysis – Tools to Explore Critical Questions:" spatial pattern analyses). Teleconnection analyses include correlation with hemispheric circulation indices.

- Resolve unforeseen data, methodological, and processing issues
- Keep up with shifts in the climate community's "well-established, best practices" (discussed in §2.5.2) away from previously implemented techniques toward adoption of improved methods

Any substantial change ought to be well considered, however, if it will warrant reprocessing of the historical dataset (§2.2). The sensitivity of temporal and spatial analysis results to proposed changes should be tested as part of this evaluation.

2.5 Criteria for Success

Criteria for successful implementation of a climate monitoring protocol are:

2.5.1 Dataset creation methods must match analysis requirements

Dataset development must be tightly integrated with (1) scientific questions being asked and (2) intended climate analyses. GRYN and ROMN's establishment of detailed monitoring objectives (Appendix B) prior to and as a basis for developing this framework and protocol SOP's is an critical step in this regard.

To this end, station selection, quality control and correction, and temporal and spatial aggregation must result in data that meet analysis requirements. Specifically, processing should not interfere with the signal the network is attempting to evaluate nor violate statistical assumptions of the analyses. Keeping in mind that such interference can be in subtle, unintended, or unexpected ways, this concern can be evaluated by:

- *In designing protocol* – Carefully laying out proposed correction processing steps against (1) climate dynamical features being evaluated and (2) requirements and assumptions of proposed statistical analyses.
- *In implementation* – Carefully evaluating resulting data at each step in dataset development in comparison with initial or previous dataset versions looking for processing artifacts and with the same criteria used in the design stage.

This process can be employed to select among various options available for both correction and analysis methods to avoid problems.

As previously noted (§2.2: *Foundation Task 2*), this requirement may lead to different lineages of data being created to address different sets of questions – with different data selection criteria, corrections, and aggregations applied or bypassed. Such lineages are outlined in Table 3 for *Annual* and *Trends Reports.*

2.5.2 Dataset creation and analysis techniques must be defensible

Correction and analysis methods should follow well-established, best practices of the climate science community. By "well-established, best practices," we are not referring to state-of-the-art innovations, but to what are considered to be the best, commonly-applied methods resulting in data suited to analysis needs. These techniques should be scientifically sound and statistically rigorous (§2.4). This all said, there is no document or group that establishes what such community standards are. Establishing and implementing climate protocols for I&M networks will depend on the input climate science expertise. The workshop and this framework report are steps in this process, as will be dedicated expert involvement in putting the protocol into operation (§2.6.1).

As noted earlier, the protocol should include tracking how community practices evolve down the road and evaluating whether SOP's need to be modified to incorporate such advances (§2.4).

2.5.3 Dataset development process must be transparent

Dataset development ought to be transparent to network and outside users. This will assure prudent management and application of the dataset. Transparency is accomplished through:

- *Thorough, up-to-date documentation* for each dataset lineage – including:
  - Processing methods and their assumptions, for:
    - Station selection
    - Quality control and correction
    - Temporal and spatial aggregation
  - Well-defined intended uses of the data
  - Caveats regarding uses the datasets are not well suited for – due to, for example:
    - Original data issues that are not resolved
    - Processing that either obscures other patterns of possible interest or introduces confounding artifacts
- *Version control* – especially given that the protocol calls for multiple dataset lineages
  - Sufficient so can reverse any correction
  - Versions archived – including the original (raw) data, the starting point before corrections applied
- *Open, online access* for final, vetted datasets – to provide for (1) maximum utility of network data and (2) critical review by outside users, giving another level of quality checking and assurance.

These steps provide transparency critical to credibility of the dataset and the monitoring program.

2.6 Keystone Resources

Success also hangs on two crucial resources:

(1) Climate science expertise (§2.6.1)
(2) A high-resolution gridded climate dataset (§2.6.2)

Not being able to secure these will hamper realization of network goals – the networks would as a consequence need to significantly downgrade monitoring goals and objectives.

2.6.1 Climate science expertise

Description of the variability and trends of a climate in a scientifically-defensible manner requires a substantial investment in quality control (§4.3). Such processing – implementing techniques in keeping with climate-community standards (§2.5.2) – is beyond the scope of what can be done in-house based on current I&M program staffing. This effort requires the expertise of a climate scientist.

Because climate change is a high-profile, contentious topic, in the absence of such expertise, reliance on less than high-quality data for these monitoring goals would pose a strong risk to the I&M Program's credibility. The consensus of outside expertise at the workshop was that, unless able to implement a climate community-standard QC protocol, the networks should not attempt to evaluate longterm climate trends.

Requirements for a climate scientist to meet program needs are someone with:

(1) The practical expertise required to develop a creditable climate dataset needed for longterm monitoring.
(2) A professional's historical perspective on recent events and trends to judge their scientific and practical significance.
(3) An ability to communicate climate-related information to a wide and diverse audience in a way non-specialists can grasp while being firmly rooted in the science.
(4) Knowledge about climate system dynamics to link a local climate's changing status to regional and hemispheric circulation features (discussed in §2.7).

This critical role could be filled by either a climate scientist on I&M staff or an outside specialist.

2.6.2 High-quality, high-spatial resolution gridded monthly climate data

Datasets required for reports and supporting analyses are by and large operational station data products available through NOAA and other agencies (§4.1, Figure 2). Alone, these point-based data have only limited ability to provide the broad, spatially-representative view needed to fulfill park- and region-scale components of *Goal I*. This is because of low station density relative to the high spatial heterogeneity typical of western US climates and a low-elevation bias in station locations. These issues lend little confidence to using station data to represent the variety of park environments.

On the other hand, regional gridded monthly climate data present a spatially-explicit understanding of a year's climate needed for the *Status Report's* spatial portrait (§2.1.2, *Product 1*) and for judging connections to regional climatic processes in *Trend Reports* (§2.1.2, *Product 2*). The roles of a gridded dataset in this framework are specifically to:

- Give 'wall-to-wall' representation of climate status across a park and of its climate zones
- Provide spatial details for important management areas
- Put park climate variability in perspective of the surrounding region's climate

To be incorporated into a monitoring protocol, a gridded dataset must meet protocol requirements and be an on-going concern. Requirements of a gridded dataset for network climate monitoring are:

(1) *Standard climate variables* – including at least minimum and maximum temperature (T_{min}, T_{max}) and precipitation (PPT).

(2) *Monthly or finer timestep* – to temporally resolve key seasonal features of climates.

(3) *Spatially extensive*, covering the networks and vicinity – for portraying climate status across network domains, parks, and their climate zone in the *Status Report* and for regional spatiotemporal analyses in the *Trends Report*.

(4) *High spatial resolution* – sufficient to resolve key features of park climates. What is sufficient depends on a park or network's domain size,[21] climatic heterogeneity, and management requirements, but generally should be no coarser than a grid interval of 5 km.

[21] Higher resolution may be valuable for small parks to show gradients within the domain, while lower resolution datasets may be sufficient and easier to manage across large network domains.

(5) *High quality inputs* – High-level quality control processing of station data to provide:

(a) Spatial consistency across the domain
(b) Temporal consistency month-to-month, year-to-year

that are sufficient for reliably evaluating spatial patterns and regional coherence.

(6) *Climate geography in keeping with key climate processes* – To be so, interpolation of station data to the grid must account for climate processes and their controls. Key temperature and precipitation features in mountainous regions include, for example, elevation lapse rates, distinct lee/windward patterns, and inversions.

(7) *Cover the recent historical period* – to provide a 30-year normals climate baseline (e.g., 1971-2000) and to capture recent climate variability.

(8) *Updated on a near real-time and/or annual basis* – to be useful with respect to *Status* and *Trends Report* timelines.

Gridded surface climate datasets that at least:

- Include T_{min}, T_{max}, and PPT (Requirement #1)
- Are at a monthly timestep (#2)
- Cover the conterminous US (#3)
- Have a spatial resolution of ≤4 km (#4)
- Account in part for the effect of elevation on temperature and PPT (#6, in part)

include DAYMET (Thornton et al. 1997),[22] WorldClim (Hijmans et al. 2005),[23] and PRISM (Daly et al. 2008).[24]

In terms of monitoring requirements, these datasets are distinguished by:

- *Climate geography* (Requirement #6) – While DAYMET and WorldClim include local, low-order effects of elevation on climate, PRISM determines and applies complex relationships between climate, topography, and continental position to fill in spatial information about climate.[25] The climate geographies produced by the three approaches are compared in Daly et al. (2008).
- *Recent period* and *Update cycle* (#7 and 8) – While all three sets cover the recent historical period, neither DAYMET or WorldClim are current (DAYMET spans 1980-1997, WorldClim

[22] www.daymet.org. With respect to the first four of these minimum requirements, DAYMET has (1) additional variables of humidity and shortwave radiation (modeled from temperature and precipitation, not directly observed), (2) a daily timestep, (3) a conterminous US domain, and (4) 1-km resolution.
[23] www.worldclim.org. WorldClim has (1) additional thermal and moisture regime variables derived from temperature and precipitation, (2) monthly timestep, (3) global coverage over land, and (4) ~800-m resolution.
[24] http://www.prism.oregonstate.edu/. PRISM has (1) dew point temperature (observed) as an additional variable, (2) monthly timestep, (3) conterminous US domain, and (4) 4-km and ~800-m resolution versions (which differ in their update cycles, discussed shortly).
[25] DAYMET uses local linear relationships with elevation (Thornton et al. 1997). WorldClim allows for a local low-order polynomial-smoothed (thin-plate spline) dependence on elevation (using ANUSPLIN, Hijmans et al. 2005). In contrast, PRISM permits non-monotonic relationships with elevation, and discontinuities in the horizontal. It takes into account terrain elevation, orientation, and profile (affecting, for example, orographic precipitation and rain shadows), coastal influences, separation of the boundary layer and free atmosphere (for temperature inversions), and topography susceptible to cold air pooling (Daly et al. 2002, 2008, Daly 2006).

generally 1950-2000). PRISM covers 1895 to the present, with rolling updates in near-real time and annual final releases.[26]

- *Quality control* (#5) – DAYMET, using COOP and SNOTEL daily data, relies on the source data centers' basic-level quality control checks and corrections. For the US, WorldClim mostly draws on the high-quality USHCN monthly dataset.[15,16] However, the USHCN's low station density and low-elevation bias reduce WorldClim's ability to capture climate spatial details. PRISM implements high-level quality control and correction of station data with manual oversight. To optimize spatial representation of climate, stations are incorporated when available. Changes in what stations are used through the record introduces temporal inhomogeneities – the PRISM dataset is not designed for statistical analysis of trends and variability.

As requirements for a gridded dataset are most closely matched by PRISM, the workshop recommended that networks use this monthly dataset. Key to this recommendation is (1) PRISM's high fidelity capture of climatic geography and near-real time and annual update cycles and (2) that other similar gridded datasets considered do not meet several minimum requirements.

Additional considerations regarding PRISM datasets are:

- PRISM's level of QC permits off-the-shelf use of the gridded data, that is, without additional network in-house quality checking. Because, as noted above, this QC is not designed to be at the level required for trends and variability analyses, its use in *Status* and *Trends Reports* is for giving spatial rather than temporal perspectives.[27]
- PRISM releases are staged, starting with provisional data for earliest reporting stations after 1-2 months, with monthly re-releases until a final product is created after roughly 6 months. The early releases can provide preliminary data for *Status Reports* for the last months of the previous year, speeding up report completion date. Later on, final PRISM releases can be included in any web-based updates (§2.1.2) and used in the *Trends Report.*

A primary concern expressed by participants is regarding PRISM's longevity given that it is not supported on an continuing, operational basis by government agencies or other sources. We recommend that the climate protocol:

(1) Include plans to periodically reevaluate if there are good alternate gridded datasets should PRISM become unavailable

(2) Provide for downgrading corresponding monitoring objectives if no high-quality gridded dataset is available

The workshop also encouraged the I&M Program to continue to participate in efforts to assure PRISM stability because of its crucial monitoring value. An outcome of the workshop was the

[26] PRISM monthly data are available on a 4-km grid on a near-real time basis (1-2 month lag). A higher resolution (800 m) monthly product is released annually, incorporating additional station data and with more consistent modeling applied throughout the timeseries (not online; source contact = http://www.prism.oregonstate.edu/contacts.phtml).

[27] In a preliminary assessment across the Klamath I&M Network, variability and trend analysis results for PRISM 800-m historical data were comparable to those for station data (Daly et al. 2009). This suggests that PRISM and stations can be used as complementary data sources in evaluating temporal patterns: (1) a few stations providing single-point, high-quality assessments and (2) PRISM providing complete 'wall-to-wall' spatial and longterm (>100yr) temporal coverage, but with potential inhomogeneities caused by shifts in station availability and discontinuities in station records. These can be integrated with expert judgment needed to determine which combination of sources best represents the climatic history of a park.

formation of the Surface Climate Mapping Consortium, a user group charged with setting priorities for PRISM surface climate mapping products and finding mechanisms to support those priorities.

2.7 Seeking Future Opportunities

I&M climate monitoring programs are encouraged to look for opportunities to improve their station networks and climate analytical capabilities. Two areas to upgrade the program and protocol are:

- While climate change is expected to be most dramatic at high elevations, the GRYN and ROMN do not currently have the capacity to monitor climate in their highest reaches. The workshop recommends that the networks seek the means to *establish and maintain alpine and subalpine weather stations*. Such observations would add significant value to the climate monitoring program and improve the quality of gridded datasets (such as PRISM) over higher elevations.

- While the protocol is setup to analyze climate variability and longterm trends, there is no provision for *identifying regional atmospheric mechanisms* behind these changes. Synoptic climate analyses,[28] on the other hand, can reveal what daily and weekly patterns of precipitation, temperature frontal passage, and local circulation underlie observed trends in a domain's surface climate. While the protocol's analyses of teleconnections to hemispheric circulation give broad context for these shifts, they do not show the mechanisms by which these connections are played out regionally.

  A workshop recommendation is to, as the climate monitoring program develops, move from a descriptive to a more insightful presentation of climate variability and trends. This will entail developing SOP's for acquisition of regional upper air data and other synoptic data and their analysis to gain such mechanistic understanding as part of the *Trends Reports* cycle. This effort will require guidance by climate expertise. The level of work that can be involved in these analyses suggests that they be initiated stepwise as resources permit.

3.0 Variables

The *Status* and *Trends Reports* utilize the same monitoring variables. These fall into three general categories:

- *Primary variables* – Key climate parameters directly measured – minimum and maximum temperature (T_{min}, T_{max}), precipitation (PPT), snow water equivalent (SWE)[29]
- *Integrative variables* – Variables expressing combined effects of primary variables (e.g., unregulated streamflow, drought: SPI, PDSI)[30]
  - Either directly measured or derived from primaries
  - *Whether to use SPI or PDSI or both?* PDSI has the advantage of integrating effects of temperature as well as precipitation on drought. While PDSI includes some effect of preceding soil moisture conditions on water deficit or surplus, SPI has the benefit of

[28] Synoptic analysis is over the scale of extensive weather systems (1000-2500 km), such as mid-latitude cyclonic storms and surface high pressure circulations.
[29] 1 April SWE is a standard climatological variable used to reflect spring snowpack as a leading indicator of summer runoff. 1 January SWE is suggested as an additional monitoring variable reflecting mid-winter pack, sensitive to teleconnections and longer term change.
[30] SPI = Standardized Precipitation Index, PDSI = Palmer Drought Severity Index (see Table 1).

being calculated for retrospective timescales from most immediate (proximate month and season) to sustained (multiyear) durations. In the Western US, PDSI does not always adequately reflect droughts because of their often long duration.

- *Timing variables* – Variables indicating the timing or length of a seasonal process (e.g., accumulated growing degree days, frosts, snowpack duration, peak unregulated streamflow)
    - Calculated from primary or integrative variables

For these variables, their sources, timestep, aggregation levels, and related derived variables are laid out in Table 1. While both water- and calendar years are used for reporting in the *Status Report* (§2.1.2), it may be unnecessary to present all variables for both timeframes – rather, variables can be selectively reported for the more relevant timeframe. For example, reporting temperature, precipitation, degree days, frost-free period, and drought indices by calendar year, while discussing streamflow and snowpack variables in the context of water-years[31] (e.g., Frakes et al. 2009).

Other possible climate-related variables of interest noted by the workshop include: surface wind, solar radiation, and lake ice on/off date. SOP's for these are currently not proposed to be covered by the protocol (Frakes et al. 2009), though ice on/off date is included in GRYN/ROMN Goals and Objectives (Objective 4; Appendix B).[32] If these variables are to be included in the protocol, the protocol needs to identify data sources and develop SOP's for acquisition, QC, analysis, and reporting – criteria for these are not covered in this framework.[33]

4.0 Processing for *Status* and *Trends* Reports

From data source identification through final product, there are three general data-flow pathways – these are for: (1) climate zonation, (2) the *Status Report*, and (3) the *Trends Report* (Figure 2). Data processing for zonation is discussed in §5.0 and that for the two reports in this section.

Data development, analysis, and reporting tasks for *Status* and *Trends* reports are:

- Identification of data sources (§4.1)
- Station selection and acquisition (§4.2)
- Data quality control – development of datasets appropriate to analysis tasks (§4.3)
- Analyses – meeting monitoring objectives (§4.4)
- Reporting elements – narrative and graphics (§4.5, §4.6)
- Documentation, archiving, and providing community access (§4.7)

4.1 Data Sources

Primary variables and directly-measured integrative and timing variables (Table 1) are readily available from government agencies (NOAA, NRCS, USGS) and other sources (Figure 2, Table 4).

[31] To facilitate discussion of surface hydrology, it may be useful to report precipitation for both calendar and water-years.
[32] Ice on/off data are available for Jackson Lake from the Bureau of Reclamation.
[33] The GRYN and ROMN not likely to find adequate wind or solar radiation data unless the networks establish their own means for collecting these (Steve Gray, personal communication, 8/04/09).

Some datasets are point observations (at COOP, SNOTEL, USGS streamflow stations),[34] others gridded regional datasets based on observations and modelling (PRISM, §2.6.2; NOHRSC[35]). Selection of stations by monitoring objective is covered next (§4.2).

4.2 Station Selection 'Triage'

4.2.1 Selection objectives

Station selection is based on two objectives:

(1) To provide an *extensive spatial picture* of climate across the network domain, its constituent climate zones, and the region immediately around the network. Across key variables (§3.0), this is a key part of describing the year in review in the *Annual Climate Status Report*.

(2) To provide for a *rigorous temporal analysis* of interannual variability, regime shifts, and longterm trends in key daily, monthly, seasonal, and annual variables (§3.0). This is for the *Climate Variability and Trends Report.*

To achieve these goals, selection entails both objective (§4.2.2) and subjective processes (§4.2.3).

4.2.2 Triage criteria – Objective standards

Selection is a 'triage' process, resulting in stations for temporal analyses, spatial analyses, and, lastly, auxiliary stations (Figure 2):

- *Temporal analysis stations.* The strictest selection criteria identify daily and monthly stations suitable for temporal analyses (Figure 2; Table 4a: *Input* columns for *Annual Status / Multiyear Perspective* objective, Table 4b: for *Variability & Trends / Multiyear Analyses* objective). These criteria are largely based on Gray (2008). Selection favors stations characterized by:

[34] Remote Automated Weather Station (RAWS) data might also be considered for filling in observations in remote locations (Myrick and Horel 2008, Redmond et al. 2008), however, these data are problematic for climate monitoring. Issues are:
(1) RAWS networks are mainly established for real-time weather reporting (e.g., fire weather monitoring) rather than with climate monitoring maintenance and instrumentation criteria in mind. In assessing data sources for GRYN annual climate reports, Gray (2008) rejected RAWS sites in favor of COOP stations for instrumentation issues.
(2) Instruments are not designed for winter use – precipitation gauges poorly handle snow and ice (Daly et al. 2008) and wintertime temperatures have a warm bias (Myrick and Horel 2008).
(3) For upland locations, there can be a siting bias toward warmer fire-prone slopes (Meyers and Steenburgh 2010).
(4) No or little initial quality control and poor station metadata (Guido 2009). WRCC has undertaken preliminary QC for selected stations: http://www.cefa.dri.edu/Cefa_Products/FPA_RAWS.php, http://www.raws.dri.edu/index.html.
(5) The earliest records extend back only to the 1980's.
(6) Little temporal continuity in the case of stations run only seasonally or portable stations moved year-to-year or seasonally (Guido 2009).
Nonetheless, RAWS sites can occupy important niches (1) at mid-elevations, largely above COOP stations and below SNOTEL stations, or (2) in cold-air pooling locations, e.g., in the Intermountain West (Myrick and Horel 2008). For very critical park locations that would enhance spatial coverage for an Annual Report's description of the year (see "*Spatial coverage stations*," §4.2.2), it may be considered worth the effort required to handle the major data issues mentioned – especially if a park has a well-maintained "trusted" RAWS site. Yet, even for these cases, RAWS data are not appropriate for climate trends and variability analyses.

[35] NOHRSC=National Operational Hydrologic Remote Sensing Center. This dataset is discussed in §5.3.

- Long, continuous[36] record –
  - At least 25-40 years depending on variable and analysis (Table 4b), 50 years for regime shift analysis.[37]
  - Within a given climate zone, stations with longer records given preference over others of similar quality.
- For monthly COOP temperature and precipitation: records covering at least the 1971-2000 period for calculating climate normals. This normals period is that for baseline comparisons in the *Status Report* (Table 4a: *Multiyear Perspective*)
- Relatively high quality – that is, records with manageable data issues (biases, errors, inhomogeneities, missing values). See Gray (2008, p. 1-7) for specifics.
- Providing representation for a climate zone –
  - The above criteria can be relaxed if needed to get at least one good station to represent a zone.
  - Stations with problematic records but in critical locations will warrant a high level of effort to create a 'clean' dataseries.
- Finally, as "best of the best," narrowing the selection down to a few key stations per zone – This is to make quality control and correction tasks manageable during the 5-year *Trends Report* cycle.

- *Spatial coverage stations.* Stations to provide greater geographic coverage include the above 'temporal analysis stations' *plus* additional stations (Figure 2; Table 3, Table 4a: *Input* column for *Year over the Domain* objective).[38] These stations:
  - Are *currently reporting* – record length requirement is that it is complete[39] for the water- and calendar year being reported on.
  - *Contribute significantly to spatial coverage* within each climate zone – that is, are not redundant in terms of climate information with other stations in the same zone.
  - Have *sufficient quality during the previous water- and calendar years*, requiring minimal quality correction or whose problems can be ignored for the purpose of spatial coverage for *Status* reporting (Table 4a, *Quality Control and Correction* columns for *Year over the Domain* objective).
  - May be "stations of opportunity" that have good data for one year and are not operational the next. These could be stations set up for research purposes for a year or two and which capture a poorly represented part of the domain. Each year, as a network reviews what stations can provide spatial coverage, candidate sites should include these stations of opportunity.

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[36] "Continuous" = no gaps longer than a year (per Gray 2008)

[37] The longer period for regime shift analyses is to limit analyses to records most likely to capture multidecadal shifts. However, 50 years is an arbitrary cutoff and can be relaxed.

[38] The premise is there are not enough longterm high-quality stations (those selected for temporal analyses) to capture important spatial heterogeneity in park/network climate zones. The *Status Reports* can portray spatial heterogeneity in two ways: by using (1) PRISM fields – for T_{min}, T_{max}, PPT, and (2) any stations operating for not necessarily any more than the report year – for SWE and streamflow, as well as T_{min}, T_{max}, PPT. Note that 'important spatial heterogeneity' just referred to is in terms of biological and physical vital signs – that is, not solely from a climatologist's point of view.

[39] See Table 4a for completeness criteria under *Quality Control and Correction* columns (for *Year over the Domain* objective).

- *Auxiliary stations.* Available stations that remain, while not used directly in temporal or spatial analyses, may yet have value during the infilling process if they span gaps in the otherwise higher quality stations (Figure 2).

The selection process is not complete without expert review, covered next (§4.2.3).

4.2.3 Subjective review – Completed station selection for GRYN

For the GRYN, Gray et al. (2008) selected 14 COOP, 9 USGS stream gauge, and 7 SNOTEL stations for monitoring network climate. Their selection criteria (Gray 2008) are largely the basis for the objective criteria just given for temporal analysis stations (§4.2.2) to meet the high-quality demands of trend and variability analysis.

Their protocol was part objective (applying numerical criteria) and subjective (expert review of station records). The latter took advantage of climate experts' extensive experience of working with station data – this was required to successfully balance requirements for quality and spatiotemporal coverage. This process cannot be shortcut by using just an objective approach.

The joint GRYN/ROMN climate monitoring protocol can use the Gray reports as a strong base for selecting temporal analysis stations:

- For GRYN – Gray et al.'s (2008) COOP, USGS, and SNOTEL stations provide a select set for temporal analysis in the GRYN's *Trends Report.* These can be further paired down if the number of stations is unmanageable, provided there is spatial redundancy by network climate zone. All are also good candidates for the larger pool of spatial analysis stations for the *Status Report*.
- For ROMN – Gray's (2008) numerical+expert process as modified here (§4.2.2) is an appropriate protocol for the ROMN.

4.2.4 Selection changes

A periodic review of selected stations meeting the two objectives (§4.2.1) will be called for as stations are dropped and others added within network domains (as previously noted for "stations of opportunity"). While preparing the first *Status Report* and historical database during early stages of implementing the protocol, station selection may be refined as unidentified station data problems arise, putting aside that station and selecting a previously discounted one.

4.3 Data Quality Control

Status and *Trends* reports require different levels of quality control (§4.3.1, §4.3.2). This is primarily because the *Status Report* is a one-year snapshot for which it is not so critical that data be extremely well vetted. On the other hand, temporal analyses for the *Trends Report* require carefully scrutinized station records – this is especially important as these analyses are addressing critical questions with respect to climate change in the parks and network.

Required techniques are discussed in general in §2.4; an overview of dataset development strategies and specific techniques is provided by Kittel (2010a: §3.0).

4.3.1 QC for Annual Climate Status Reports

The annual *Status* updates build on data and analyses from the previous 5-yr cycle *Trends Report*, and are provisional as they are based on (1) data available at time *Status Reports* are being prepared[40] and (2) limited QC.

Data availability and use of provisional data. For the latter months of the year being reported on, NWS-processed COOP data may not be available early enough for preparing the *Status Report* in a timely manner in the following year. Rather than delay the report waiting on NWS releases, the workshop recommended that the network arrange to obtain observer forms directly from observers or state climatologist offices (as noted in §2.1.2 re setting a realistic release date). Finalized releases of SNOTEL, USGS streamflow, SNODAS, and PRISM data will also most likely not be available for all of the report year – provisional releases should be acceptable for purposes of the *Status Report.*

Limited value-added QC. The guiding strategy for *Status Report* quality control (Figure 3, Table 4a) is to:

(1) Implement an in-house protocol to catch and deal with most obvious and most readily corrected problems. Problems can be handled by correcting or tossing values.
(2) For some datasets, accept quality control and corrections of originating data centers.
(3) Ignore complex issues. Include caveats in report as to their possible presence and potential effects on temporal and spatial analyses. Document specific problems that are identified.

These tasks are outlined in Table 4a by reporting objective and variable. This strategy generally encompasses levels of QC implemented in other network protocols and analyses, such as for Northern Colorado Plateau Network (NCPN: Garman et al. 2004) and Central Alaska Network (CAKN: Sousanes 2004, Keen 2008).

Because of the intermediate level of quality control, analyses presented in the *Status Report* and online should include caveats that data and results are provisional, subject to being updated in the *Trends Report* and subsequent releases of the *Network Climate Database.*

4.3.2 QC for Climate Variability and Trends Reports

Quality control for *Variability and Trends* analyses is far more rigorous in handling complex data issues (cf. Kittel 2010a). Data checking and cleaning steps are outlined in Table 4b by analysis objective and variable, and in Figure 5's flow chart.

These processes are time consuming (requiring adequate staging, §2.3; Table 2) and involve experienced, hand-tailored treatment of station records (requiring outside or hired expertise, §2.6.1).

4.4 Analysis

Status and *Trends* reports differ in their objectives (§2.1) and so in their key analyses. They include descriptive statistics and analyses of daily frequency distribution, interannual variability, teleconnections, longterm trends, and regional coherence. The *Status Report* relies more heavily on

[40] For the last months of the year being reported on, NWS-processed COOP data may not be available early enough for preparing the *Status Report* in a timely manner the following year. Rather than delay the report, the network can arrange to obtain observer forms directly from observers or state climatologist offices (as noted in §2.1.2 re setting a realistic release date). Finalized releases of SNOTEL, USGS streamflow, SNODAS, and PRISM data will also most likely not be available for all of the report year – provisional releases should be acceptable for purposes of the *Status Report.*

descriptive methods, the *Trends Report* on statistical analysis.[41] Analyses and their supporting graphics are laid out by objective in report narrative outlines (§4.5, §4.6) and Table 4.

As discussed with respect to staging (§2.3), the *Status Report* will draw on statistical temporal analyses from the previous 5-yr cycle's *Trends Report* to give perspective on the new year's status. While data QC for the *Status Report* is not sufficient for reanalysis of variability and trend patterns, each new year's datapoints can be appended to the more recent *Trends Report's* trend/variability/ teleconnection graphics. The purpose is for the *Status* narrative to use the earlier analyses to give context to the 1-4 years since the last *Trends Report*. In presenting new data in the *Status Report*, it will be important:

(1) Not to extend *Trends Report* graphs' trendlines and interannual smoothing filter lines, lest this suggests that revised lines are based on new statistical analyses.

(2) To include caveats as to the provisional nature of the newly posted data (as noted in §4.3.1).

Each year's new data will be revisited in the next *Trends Report* cycle with high-level QC, statistical analysis, and updated graphics (§2.3, Table 2).

Selection of analysis techniques is discussed in §2.4; analysis strategies and specific methods are given in Kittel (2010a: §4.0).[42]

4.5 Narrative from Analysis

4.5.1 General guidelines

For both reports, the narrative integrates information across variables from descriptive statistics and analysis results (Figure 3, Table 4). The intent is not to be all inclusive of information available, but to tell a story of the year in the *Status Report* and over the longer term in the *Trends Report.* Spatially, these narratives cover the network domain as a unit and by its climate zones. The *Status Report* also puts the year in regional context through PRISM, Drought Monitor,[43] and NRCS snowpack[44] regional maps (for example, as used in Frakes 2007, Gray et al. 2008, and WWA 2009) (Figure 3). *Status* and *Trends Reports* can also draw on US and global perspectives in NOAA's *State of the Climate* websites[45] and reports (e.g., Peterson and Baringer 2009).[46]

The reports need only include graphs (§4.6) that pertain to that report's narrative. Extended discussion, graphics, and tables which cover the full set of analyses, variables, and zones prepared in each reporting cycle can made available on the network's climate public website – as an online appendix to the report. This will save much effort in preparation of physical reports and keep the narrative to the most important annual features and longterm dynamics, while still making more intensive and extensive information available to users (as an example, see WWA 2009).

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[41] Or more explicitly: hypothesis testing using statistically rigorous methods, to address science questions tied to specific monitoring objectives (Appendix B; see also §1.2, §2.5).
[42] Sections in Kittel (2010a) corresponding to analysis tasks are noted in Figure 4.
[43] Drought Monitor: http://drought.unl.edu/DM/
[44] NRCS snowpack: http://www.wcc.nrcs.usda.gov/gis/snow.html
[45] NOAA's *State of the Climate*: http://www.ncdc.noaa.gov/sotc/. See also http://www.ncdc.noaa.gov/climate-monitoring/ for other NOAA monitoring products and related links.
[46] Paleoclimate studies can provide additional temporal perspective on longterm patterns.

4.5.2 Status Report narrative

The *Status Report's* narrative structure follows the general outline:

I. Executive Summary / Introduction

- A. Objectives of the report
- B. Snapshot summary of the year
- C. Caveats – noting that most recent years' data and discussion are provisional, pending the next *Trends Report*.

II. The Year over the Domain – Narrative of seasons and particular events by network climate zones (Table 4a, Figure 3).

- A. Seasonal view
  1. Monthly and seasonal discussion by climate zone, integrative across variables
     a. Including annual timing and integrative variables (Table 1)
- B. Daily event structure by season, climate zone
  1. Key daily events in record noted[47]
  2. Frequency distribution features

III. Multiyear Perspective – Narrative of the year in spatiotemporal perspective gained from baseline comparisons and in the context of previous *Trends Report* results (Table 4a, Figure 3).

- A. Baseline comparisons
- B. Interannual variability – Discussion exploring temporal patterns by zone and over the domain. Narratives are more interesting and insightful if integrative across variables. Discussion also portrays spatial connections to:
  1. Region –
     a. PRISM and NOHRSC maps – descriptive (no regional analyses)
     b. Drought, snowpack, surface hydrology reports (§4.5.1, Figure 3)
  2. Hemispheric circulation – teleconnections (using correlation analysis with hemispheric circulation indices[48]; Table 4a, Figure 3)
- C. Longterm trends – as for Interannual variability

IV. Integrative Summary

4.5.3 Trends Report narrative

The *Trends Report* follows an outline of:

I. Executive Summary / Introduction

- A. Objectives of the report
- B. Summary of results
- C. Caveats

II. Variability/Teleconnections and Trends – Narrative of recent climate trends and variability in from longterm, regional/hemispheric perspectives

- A. Daily structure/extreme value analyses – discussion of variation and change in the probability of extreme events and other features of daily frequency distribution.

[47] Recognizing that important daily events may be missed by station records, the workshop suggested that narratives can include notable observations made by park staff as available (= "ancillary reports").
[48] See techniques in Kittel (2010a: §4.8).

B. Interannual variability – discussion examines temporal patterns by zone and the domain, integrative across variables. Also explores spatial connections to:
    1. Region – regional coherence
    2. Hemispheric circulation – teleconnections
C. Regime shifts – as for Interannual variability
D. Longterm trends – as for Interannual variability

III. Integrative Summary

4.6 Graphics Supporting Narratives

4.6.1 General considerations

Some information reported by climate zone may best be shown as single station plots, and other results as zone maps and averages. Such graphics can also be developed for management units of interest as needed.

Reporting by station. Where details of temporal structure are key to understanding a zone's climate, then graphics should portray individual stations in that zone. This is especially the case for showing daily events, either as timeseries or event structure plots (box plots, frequency distribution diagrams). One to several stations can be used to portray a zone, with stations selected (1) as representative of the zone (determined by an initial cross-comparison of stations[49]) or (2) to illustrate anomalous events at specific locations within the zone.

Climate maps and zone averages from gridded data. Where spatial details are needed to illustrate differences among climate zones, these differences can be revealed by (1) climate maps across the domain (with zones delineated) and (2) bar graphs or timeseries of zone averages. These are most appropriate and most easily rendered for variables in gridded form – such as for monthly T_{min}, T_{max}, and PPT from PRISM and snowpack variables from NOHRSC (e.g., SNODAS).[50] When zone grid averages are plotted, standard deviations (SD) should also be reported.

Station-based zone averages. Other variables can be given as zone averages of 'spatial-coverage' stations (§4.2.2). However, although the climate zonation process (§5.0) is supposed to create zones with similar climates, care needs to be taken in averaging within-zone stations (1) with widely differing annual means[51] or (2) with locations that unevenly represent variation within zones. For some variables, it may be better to plot single-station data as representative of a zone, rather than using an average of available stations. In the case of station averages, either standard deviations or standard errors[52] should also be reported.

Graphics in support of report narratives are specified in Table 4a, b (final column). The next section (§4.6.2) lays out those for the *Status Report* in more detail.

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[49] Such as part of the zonation process (see, e.g., §5.1)
[50] SNODAS = Snow Data Assimilation System – see §5.3
[51] While stations are classified as belonging to the same zone based on similarity, their means may differ strongly because in the zonation process stations are clustered by similar seasonality and interannual variability not by absolute mean values (§5.0).
[52] Standard error of the mean, SE = [SD/square root(#stations)]. Note: it is not appropriated to report SE's for averages of gridded data because gridcell values are not independent observations.

4.6.2 Status Report graphics

Graphics for the *Status Report* can be selected from those outlined below, as best supports the narrative (§4.5.2):

Year over the Domain narrative (§4.5.2 Outline: II.A, II.B, III.A; Table 4a) – by climate zone:

- Annual (§4.5.2 Outline: II.A.1.a) – bar graphs of:
  - Primary annual variables – of single stations or zone averages: e.g., 1 Jan / 1Apr SWE
  - Integrative variables (see Table 1) – of single stations or zone averages: e.g., mean temperature (T_{mean}), accumulated growing degree days (AGDD), SPI/PDSI
  - Timing variables (for daily stations) – of single stations or zone averages: e.g., freeze-free period, snow on/off, unregulated streamflow center of mass (or could be indicated on a hydrograph, included below)
  - Plotted with baseline values[53] – for temporal analysis stations only (III.A)
- Seasonal progression (II.A.1) – bar graphs of seasonal pattern of:
  - Monthly average/accumulated values – of single stations or zone averages: e.g., T_{min}, T_{max}, PPT, SPI/PDSI
  - Daily, to show actual events through year – of single daily stations: e.g., daily T_{min}, T_{max}, ppt, seasonal hydrograph (daily streamflow) (II.B)
  - Plotted with baseline values – for temporal analysis stations only (III.A)
- Daily event frequency structure – of single daily stations: box-and-whisker plots, by season (II.B)

Variability narrative (§4.5.2 Outline: III.B; Table 4a) –

- Timeseries plots:
  - Current year datapoints appended to corresponding *Trends Report* historical plots, with *Trends Report* interannual smoothing-filter lines not updated.
  - Same, but for *Trends Report* teleconnection plots (III.B.2)
- Network domain in regional and hemispheric perspective – maps:
  - PRISM and NOHRSC maps of domain (with climate zones delineated) and of adjacent region.
  - Drought, snowpack, surface hydrology reports (§4.5.1; e.g., as in Gray et al. 2008) (III.B.1)
  - Hemispheric conditions maps from teleconnection websites[54] (III.B.2)

Trends narrative (§4.5.2 Outline: III.C; Table 4a) –

- Timeseries plots:
  - Current year datapoints appended to corresponding *Trends Report* historical plots, with *Trends Report* trendlines not updated.

[53] e.g., 1971-2000 normals, depending on variable (see Table 4a)
[54] For websources, refer to Kittel (2010a: Table 4).

4.7 Documentation, Access, and Archive

The importance of dataset documentation, open access, and archiving was stressed earlier (§2.5.3). Documentation should be included with other metadata in online and archived datasets (Figure 1). The workshop suggested that the networks consult with the NPClime Team[55] regarding SOP's for web access tasks.

5.0 Zonation – Creation of within-network zones for reporting

In this section, we outline the process and data requirements for defining within-network climate zones – a foundation task (§2.2). The goal is to devise distinct zones with recognizable, internally-consistent temporal dynamics. An important criterion is that distinctions in zone dynamics be interpretable in terms of climatological processes.

The zonation is guided by a multivariate, multi-timescale approach to identify climatic zones. The approach has three components – each which takes a different perspective on local climatic processes. Two are based on temporal patterns in surface weather variables (e.g., temperature, precipitation, and humidity) at seasonal and interannual scales, respectively, and the third on snowpack:

(1) Mean seasonal cycle of mean temperature (T_{mean}), diurnal temperature range (DTR), precipitation (PPT) (§5.1)
(2) Interannual variability of T_{mean} , PPT, and dew-point temperature (T_d) (§5.2)
(3) Snowcover timing – to discriminate elevational zones by snowpack initial development and melt regimes (§5.3)

The integration of these three and an option of applying criteria to reflect management reporting needs is presented in §5.4. Resulting zones need not be continuous, but may reflect areas that are disjunct but with similar climatic behavior.

This foundation analysis provides network zones for climate vital sign analysis and reporting for both *Status* and *Variability and Trends* reports. Completion timeframe is early in protocol implementation, so that zone delineations are available for the initial *Status Report*. The process should be adaptable to what is found out during implementation – that is, the corresponding SOP should encourage exploration rather than adherence to a set script.

We expect that the zonation process laid out here for the GRYN and ROMN should be applicable to other network domains, allowing for modifications for differences in key features of their climates (e.g., whether snowpack is a factor, see §5.3: footnote 63).

5.1 Zones Based on Seasonal Variability – Cluster Analysis

This approach relies on mean seasonal temperature and precipitation patterns found in different parts of network domains, as represented by station longterm normals. A similar approach was recently applied to Yellowstone and Grand Teton parks and vicinity, resulting in 5 climate zones (Tercek 2008, 2009; following on the work of Whitlock and Bartlein 1993).

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[55] Key contact is Greg Hill (NPS Natural Resource Program Center, Fort Collins, CO). NPClime Intranet (NPS only): http://www1.nrintra.nps.gov/NPClime/

The proposed procedure is as follows:

(1) *Seasonal station data.* Base the analysis on 1971-2000 station normals for monthly mean temperature (T_{mean}), diurnal temperature range (DTR), and precipitation (PPT) for all stations with normals available in network domains.[56,57,58]

(2) *Standardized seasonal series.* To remove within-zone elevational effects and other processes that just modulate the seasonal pattern, create monthly standardized series – subtracting the annual mean and dividing by the annual standard deviation of the monthly means. This process will emphasize the *relative* seasonal pattern.[59]

(3) *Cluster analysis.* Perform a single cluster analysis on these data to group similar stations.[60] Inputs are 36 independent variables: 12 monthly means × 3 climate parameters (T_{mean}, DTR, PPT). The similarity threshold, used to define which stations are lumped together, will be determined during the process guided by the interpretability criterion noted in the beginning of §5.0.

(4) *Cluster characteristic seasonal cycle*. Calculate each cluster's characteristic seasonal T_{mean}, DTR, and PPT cycles, as the average across clustered stations of both (1) monthly means and (2) monthly standardized series – both are valuable descriptors of the cluster.

(5) *Correlation maps.* To explore the spatial extent of the clusters' patterns, correlate each cluster's characteristic seasonal T_{mean} , DTR, and PPT standardized series (from step 4) with gridded PRISM monthly T_{mean}, DTR, and PPT normals for cells in the network domain.[61] Map these correlations. Ideally for each cluster, the mapped pattern will have a 'hotspot' centered within a possible climate zone and from there, diminishing correlation with distance. GIS-based overlays of correlation maps by variable and by cluster can be interpreted to delineate zone boundaries.

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[56] Sources for normals are COOP and SNOTEL stations. It was recommended not to use temperatures from SNOTEL sites because of quality issues.

[57] Station density is the key criterion for defining the normal period for this analysis; earlier 30-y normal periods may considered if they have a higher station density in the domain. See footnote 11.

[58] Mean temperature (T_{mean}) and DTR derived from minimum and maximum temperature normals are commonly orthogonal and can reveal different processes controlling a climate's thermal regime, such as for areas prone to cold air pooling, an important feature of Yellowstone's climate and other intermountain basins in the West. On one hand, cluster analysis could be done with T_{min} and T_{max} to try to discriminate these areas – as cold air pooling alters the linkage between T_{min} and T_{max} compared to that in surrounding areas. However, the high correlation between T_{min} and T_{max} tends to obscure differences in these dynamics. On the other hand, DTR is sensitive to changes in this relationship. A valuable attribute of DTR is that it and T_{mean} are generally uncorrelated – useful given that cluster analysis is more powerful when variables are not strongly correlated.

[59] Otherwise (1) stations with high absolute seasonality will dominate the clustering and (2) those stations with a distinct seasonal pattern but low amplitude will be discounted.

[60] This follows the use of cluster analysis in numerical taxonomic classification: all seasonal features of the climate (variable × month) are entered into the analysis together, the clustering process emphasizes features that most strongly discriminate the zones.

[61] PRISM's standard normals product is at a spatial resolution of 800km, but is also available at 4km. (http://www.prism.oregonstate.edu/products/matrix.phtml?vartype=tmax&view=data). The 4km product would be easier to handle in terms of computation and should be sufficient re the goal to discern broad correlation patterns. However, finer scale (800m) analysis could resolve regional boundaries within networks with high topographic heterogeneity, such as ROMN and GRYN.

5.2 Zones Based on Interannual Variability Modes – PCA

Specific seasonal patterns generally indicate the role of certain climate processes. We thus expect zones with similar seasonality to be defined by similar interannual and multidecadal dynamics (Kittel 2010b). We can explore such spatiotemporal coherence with principal component analysis (PCA). The proposed procedure is:

(1) From the PRISM historical timeseries, extract/derive year-month T_{mean}, PPT, and dew-point temperature (T_d) for the cell closest to each longterm station in the domain.

(2) Separate analyses for winter (DJF) and summer (JJA), for seasonal average T_{mean}, PPT, and T_d – giving 6 PCA analyses (3 parameters × 2 seasons). This choice of two seasons was made to limit the number of PCA's but can be altered in implementation.

(3) Detrend data with linear regression prior to performing the PCA. The PCA will be conducted on the residuals of the regressions. Data will either be transformed if needed[62] or normalized by dividing detrended values by the standard deviation. This procedure will be verified in literature before implementation.

5.3 Snowcover Commencement and Melt-off as an Elevational Discriminant – Cluster Analysis

Within climate zones distinguished by these two methods, sharp environmental contrasts may yet occur with elevation, where surface climates are similar but where snowpack stays on the landscape late into the spring.[63] For these areas, the growing season does not begin until the snowpack is nearly gone. For this reason, snow on/off dates could be used as additional discriminants, based on either SNODAS's SWE or satellite-observed fractional snowcover, both from NOHRSC.[64,65]

Longterm average on/off dates derived from these data could be used in a cluster analysis (as in §5.1) to distinguish zones dominated by early and/or late snowpack vs. lower zones.[66] These data need to be evaluated as to whether sufficient to the task. One approach would be to see how variable the dates are year to year relative to the mean – e.g., using a simple metric: mean±SD on/off dates, for

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[62] See Wilks (2006: §3.4.1) for determining the most appropriate power-based transformation; cf. Kittel (2010a: §3.4.2.1).

[63] For networks outside of *winter-snow environments* either this step is dropped or an alternative elevation-discriminant would be needed. For example, a discriminant in summer monsoonal and maritime climates (e.g., the Southwest and Pacific Islands, respectively) may be *dew point*. In maritime climates, very sharp vegetation gradients are marked by dew point where the top of the maritime layer intersects orography.

[64] http://www.nohrsc.noaa.gov/interactive/html/map.html. For satellite-derived daily Fractional Snow Cover, select from *Physical Element* pull-down menu: "Daily Satellite Obs," then "Snow Cover (Percent)" [alternatively "Snow Cover (Binary)]." For SNODAS 6-hourly SWE, select from *Physical Element*: "Hourly Snow Analysis," then "Snow Water Equivalent." A description of the observation+model-derived SNODAS datasets is at: http://www.nohrsc.noaa.gov/archived_data/ (NOHRSC 2004); see also: SNODAS: http://nsidc.org/data/g02158.html. Snow Cover (Binary) data start in Oct 2002, SNODAS SWE in April 2003.

[65] Tim Szeliga (NOHRSC, personal communication 4/14/09) related the following points regarding these datasets:

- SWE can be used as a binary snow mask, noting that certainty is higher away from edges of the snowpack and highest earlier in the season.
- When the snowline thins out at mid-elevations, where SNOTEL stations are located, their model results for surrounding terrain gets less reliable. There may still be plenty of snow at elevations above the sensor but their analysis will not see it.
- For satellite-derived Fractional Snow Cover late in the snow season, there is more confidence in cells where no snow is detected than where snow is reported.

[66] Earlier discussions considered using the yearly record of on/off dates in PCA following the procedure in §5.2 (step 3). However, both NOHRSC datasets' records are 6-7 years which is may be too limited to give useful PCA results. Satellite Cover-Binary starts in April 03 and SWE in October 02 [documentation (NOHRSC 2004) says October 03, but on-line data start October 02].

each cell. If widely varying, then there would be low confidence in using these data to define snow-belt elevation zone.

5.4 Integration and Additional Criteria

Steps for integrating these approaches are:

(1) Manually blend maps of zones from T_{mean}, DTR, and PPT cluster and PCA results (§5.1-5.2)

(2) Divide these zones elevationally using snow on/off results (§5.3)

(3) Use additional climate-related management and ecological criteria to further define reporting zones, as called for. For example, Tercek (2009) used management criteria to further divide out the Northern Range in the Yellowstone domain, due to the importance of reporting climate status in this critical winter range.

6.0 Summary – Key Points

GRYN and ROMN can establish a climate monitoring protocol using a scientifically rigorous approach, as framed in this report. This will lead to a successful analysis of network climate status, variability, and trends, and with regional and hemispheric perspectives. To accomplish this, key points are:

- Station data from national climate agencies and other sources are generally of sufficient quality to portray the *annual status* of climate at locations within the parks (§4.3). However, two limitations of these datasets are:
  (1) Poor suitability for describing variability and trends in climate
  (2) Low spatial representativeness, especially over topographically heterogeneous domains
- With respect to suitability for longterm climate studies – Analysis of climate variability and trends in a scientifically-defensible manner requires a substantial investment in quality control. Implementing techniques in keeping with climate-community standards requires the expertise of a climate scientist. Because climate change is such a high profile, contentious topic, reliance on less than high-quality data poses a strong risk to I&M Program credibility. (§2.5.2, §2.6.1)
- With respect to spatial representativeness – A high quality, up-to-date gridded surface climate dataset is required to (1) spatially represent the status of climate zones, (2) provide details for important management areas, and (3) put park climates in perspective of the surrounding region's climate. Of candidate gridded datasets, PRISM monthly products were identified as matching all monitoring requirements – including (a) portraying key climate features and (b) near-real time availability. The workshop noted longevity of this resource as a potential issue and encourages the NPS to continue to participate in efforts to assure its stability given its crucial monitoring value. (§2.6.2)
- Network climate monitoring programs should be looking for opportunities to improve their station networks and capabilities (§2.7). Key areas are:
  - While climate change is expected to be most dramatic at high elevations, the networks do not currently have the capacity to monitor climate in most alpine areas.

  - Synoptic climate analysis would enhance understanding of local climate changes – such analyses can reveal the regional mechanisms underlying observed seasonal, interannual, and longer shifts in a domain's climate.

And some operational recommendations –

- To make data quality control tasks manageable and successful, networks should focus on a few key stations from select monitoring networks (e.g., COOP and SNOTEL) to develop a robust dataset for variability and trend analysis. (§4.2.2)
- The networks' monitoring objectives call for a broad range of analyses intended to capture different dynamics (e.g., daily extremes, vs. regimes shifts, vs. longterm trends). For data quality assurance methods to match and not interfere with analyses, networks will need to develop lineages of separate climate datasets tailored to specific monitoring questions. (§2.2, §2.5.1)

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Tables and Figures

Table 1. Station variables for Status and Trends Reports.
Table 2. Staging timeline.
Table 3. Overview of network climate dataset products.
Table 4. Dataset inputs, products, quality control/correction, and analysis tasks.

Figure 1. Network Climate Monitoring Protocol Framework – Processing Overview
Figure 2. Climate Data Sources, Acquisition, & Station Selection – Processing Framework
Figure 3. Annual Climate Status Report – Processing Framework
Figure 4. Climate Variability and Trends Report – Processing Framework
Figure 5. High-Level QC – Processing Framework

Table 1. Station variables for *Status* and *Trends Reports* – by variable category (see text, §3.0). Shown for each variable: source, original timestep, addition temporal aggregations for analysis, and from this, other variables derived (each derived variable is listed as a variable lower in the table). Baseline averages are for the 30-yr normals period, 1971-2000 (unless otherwise defined, see §2.1.2). Note that gridded datasets (PRISM and those from NOHRSC) are additional sources for these and other variables (Figure 2).

Variable Category	Variable	Source	Original Timestep	Temporal Aggregation	Derived Variables
Primary	Minimum temperature (T_{min})	COOP	Daily	Monthly, Baseline	T_{mean}, DTR, Freeze timing
	Maximum temperature (T_{max})	COOP	Daily	Monthly, Baseline	T_{mean}, DTR, Freeze timing
	Precipitation (PPT)	COOP	Daily	Totals: Monthly, Annual. Averages: Baseline	SPI, PDSI
	Snow water equivalent (SWE) – at key times of the year: • Mid-winter (1 Jan) • During spring snowpack (1 Apr)	SNOTEL	Annual	Baseline	
Integrative	Mean temperature (T_{mean})	(derived)	Daily	Monthly, Annual, Baseline	AGDD, PDSI
	Diurnal temperature range (DTR)[1]	(derived)	Daily	Monthly, Annual, Baseline	
	Accumulated growing degree days (AGDD)[2]	(derived)	Annual	Baseline	
	PDSI and/or SPI[3]	(derived)	Monthly[4]	Baseline	
	Unregulated streamflow – spatially (basin) integrative	USGS	Daily	Totals: Monthly, Annual. Averages: Baseline	Streamflow timing
Timing	Snowcover[5] – • Snowpack duration • 1st snow on • last snow off	SNOTEL	Annual	Baseline	
	Freeze-free timing[6] – • Last spring freeze • 1st fall freeze • Freeze-free period	(derived)	Annual	Baseline	
	Streamflow[7] – • Peak & minimum flow dates • Center-of-mass date	(derived)	Annual	Baseline	

[1] Kittel (2009, §3.4.3 and §4.2) discusses the benefits of looking at DTR.

[2] For the AGDD base temperature, the workshop recommended 0ºC for GRYN and ROMN, as being appropriate for cold-temperate alpine and montane environments (Billings and Bliss 1959, Kimball et al. 1973). Other base temperatures might well be selected for more cold-intolerant systems of other networks.

[3] Palmer Drought Severity Index (PDSI) and Standardized Precipitation Index (SPI) are discussed by Heim (2002) and Kittel (2009, §4.2).

[4] SPI is reported monthly, but for a range of retrospective timescales from past month, season, etc. on out to multiyear periods.

[5] Care needs to be taken in defining snowcover on/off dates. Some of the difficulties associated with this issue are discussed in §5.3's footnotes 64 and 65.

[6] Kittel (2009, §4.2) discusses various ways for defining freeze-free period. The workshop recommended defining this using last/first day with $T_{min} \leq 0$ºC.

[7] To identify seasonal shifts in hydrographs of unregulated streams.

Table 2. Staging timeline, showing timing of foundation, reporting, and database tasks and cross-task data flow (→) for the startup year (Yr 0) and initial and subsequent 5-year cycles (see text for description of timeline and information flow, §2.3).

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

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

Table 3. Overview of network climate dataset products, their lineages, and report tasks for *Status* and *Trends* reports. A horizontal arrow (→) in the 'Linkage' column and continuation of row colors indicate where a provisional product leads into a high-quality final product. A vertical arrow indicates where one product is a broader set to the next (e.g., as spatial coverage stations are more inclusive than temporal analysis stations, §4.2.2). The importance of maintaining distinct lineages is discussed in §2.2: *Foundation Task 2* and §2.5.1. Products and corresponding tasks are further laid out in Table 4.

Annual Status Report					Linkage →	*Trends and Variability Report*				
Provisional Product*			Report Tasks*			High-Quality Final Product**			Report Tasks**	
Timestep	*Space or Time Coverage*	*Station or Gridded Data*	*The Year over the Domain*	*Multiyear Perspective*		*Timestep*	*Space or Time Coverage*	*Station or Gridded Data*	*Multiyear Analyses*	*Regional Analyses*
Daily	Spatial Coverage	Station Product	Daily Event View							
	Temporal Analysis	Station Product		• Baseline Comparison – Daily Event Structure View	→	Daily	Temporal Analysis	Station Product	Daily Event Structure	
Monthly/ Seasonal/ Annual	Spatial Coverage	Station Product	Seasonal View							
		Gridded Product[1]	Seasonal View		→	Monthly/ Seasonal/ Annual	Spatiotemporal Analysis	Gridded Product[1]		Regional Coherence
	Temporal Analysis	Station Product		• Baseline Comparison – Seasonal View • Interannual Variability • Longterm Trends • Teleconnections	→		Temporal Analysis	Station Product – Full Set	• Interannual Variability • Longterm Trends • Teleconnections	
								– Regime-shift Subset	• Regime Shifts	

* Product and task categories correspond to those in Table 4a columns 'Network Dataset Product' and 'Objective Temporal or Spatial Frames,' respectively.
** As in note(*), but for Table 4b.

[1] PRISM and SNODAS

Table 4. Dataset inputs, products, quality control/correction, and analysis tasks for (a) *Annual Climate Status Report* and (b) *Climate Variability and Trends Report.* An overview of product lineages and reporting tasks is presented in Table 3. The table is organized by reporting objective: 'The Year over the Domain' and 'Multiyear Perspective' for the *Status Report*, and 'Multiyear Analyses' and 'Regional Analyses' for the *Trends Report*. Abbreviations: Tn, Tx, Tm = minimum, maximum, and mean temperature, respectively, Td = dew point temperature, DTR = diurnal temperature range, ppt = precipitation, SWE = snow water equivalent, vars = variables, obs = observations, QC = quality control. **Bolded** cell text accentuates differences in a task from other cells in the same column in the same table, or, in the *Trends Report* table (b), a change from same cell position in the *Status Report* table (a). For quality control tasks, common tasks can be performed together until different corrections lead to separate dataset lineages. Data correction and analysis techniques are discussed in Kittel (2010a). See Table 1 for variable aggregations and derived integrative and timing variables.

(a) Annual Climate Status Report

Report	*Objective Temporal or Spatial Frames*	*Input*			*Network Dataset Product*	*Quality Control and Correction* (Processing Order →)				*Analyses*	*Graphics*
		Datasets	*Timestep*	*Continuous*[1] *Record Length*		*Data Errors, Biases, Outliers, Multiday Obs*	*Inhomogeneities*		*Completeness*		
							Known	*Unknown*	*For Source = Dailies*	*For Source = Monthlies*	
Annual Status	***The Year over the Domain***	***Spatial Coverage Stations***			***Provisional***						***Stations By Zone***[2]
Annual Status – The Year over the Domain	***Seasonal view*** - Station data[3]	COOP *Tn, Tx, ppt* *(+monthly derived vars –Table 1)*	Monthly	≥ Report year[4]	**Monthly-Seasonal-Annual Dataset (Provisional) – Spatial Coverage Stations** (includes integrative & timing vars – Table 1)	• Numerical & visual checks • Consult forms and observer • Manual removal • **Multiday obs crossing month boundary parsed (e.g., ppt) or omitted**	Accept source QC Known but not corrected by source – only correct if easily done If not, document for next *Trends* report	Accept source QC Attach caveats to results	**Missing values – toss month if # > threshold:** • missing T >5d • missing ppt >3d • other vars: 15% missing	Accept source QC, document missing months Attach caveats to results	Descriptive→ Derive annual vars (Table 1)	Year plotted by month Bar graphs[5]
		SNOTEL provisional release[6] – *1 Apr(-1) & 1 Jan(0) SWE*[7] *(+annual derived vars –Table 1)*	Annual	≥ Report year	as for COOP	• Numerical & visual checks • Manual removal	as for COOP	as for COOP	**Accept Source QC**	N/A	Descriptive: Annual values →	Bar graphs[5]

[1] Continuous operation = no gaps > 1 year (per Gray 2008).
[2] Where zones are represented by analyses and graphs of characteristic stations – except for PRISM and SNODAS, where zones are represented by spatial averages.
[3] Stations selected to contribute significantly to spatial coverage within each climate zone (text §4.2.2).
[4] "Report Year" = Complete for the water- and calendar year being reported on (see *Completeness* criteria under *Quality Control and Correction* column)
[5] An option is to overlay bar graphs on park/domain maps (as in Tercek 2008)
[6] NRCS SNOTEL considered provisional well after released via the internet.
[7] Because of reporting timeframes, *Annual Status Reports* would only be able to report SWE for 1 April for the previous year [1 Apr(-1)] and for 1 Jan of the year the report is being released [1 Jan(0)]. (0) and (-1) are a year index relative to the year Annual Report will be released: (0) = current year, (-1) = previous year.

Report	*Objective Temporal or Spatial Frames*	*Input*			*Network Dataset Product*	*Quality Control and Correction* (Processing Order →)					*Analyses*	*Graphics*
						Data Errors, Biases, Outliers, Multiday Obs	*Inhomogeneities*		*Completeness*			
		Datasets	*Timestep*	*Continuous*[1] *Record Length*			*Known*	*Unknown*	*For Source = Dailies*	*For Source = Monthlies*		
Annual Status – The Year over the Domain		USGS provisional release[8] – *Streamflow annual timing vars –Table 1*	Annual	≥ Report year	~as for COOP – **Unregulated Flow Stations**	as for SNOTEL	as for COOP/ SNOTEL	as for COOP/ SNOTEL	as for SNOTEL	N/A	as for SNOTEL	as for SNOTEL
	– Gridded data	***Gridded data*** PRISM[9] provisional to final releases – *Tn, Tx, Td, ppt*	Monthly	since 1895	**Monthly-Seasonal-Annual Dataset (Provisional) – Gridded Data** PRISM cutout for region	**Accept source QC**	**Accept source QC**	**Accept source QC**	N/A	**Accept source QC**	Descriptive: climate zone geography & averages[2] →	• Maps • Bar graphs
		Gridded data SNODAS – variables as for SNOTEL	Daily	since Apr 2003	~as for PRISM **SNODAS cutout**	as for PRISM	as for PRISM	as for PRISM	Accept source QC	N/A	as for PRISM – including aerial snowpack extent	as for PRISM
	Daily Event Structure view	COOP *Tn, Tx, ppt* *(+daily derived vars Tm, DTR – Table 1)*	Daily	≥ Report year[4]	**Daily Dataset (Provisional) – Spatial Coverage Stations**	~as COOP Seasonal view ***except:*** • **Multiday obs omitted**	as COOP Seasonal view	as COOP Seasonal view	**Missing values not infilled**	N/A	Descriptive→	• Year plotted by day • Box plots
		USGS[8] *Streamflow*	Daily	≥ Report year	~as Daily COOP – **Unregulated Flow Stations**	as SNOTEL/ USGS Seasonal view	as COOP/ USGS Seasonal view	as COOP/ USGS Seasonal view	Missing values not infilled	N/A	Descriptive→	Hydrographs (Year plotted by day)

[8] USGS stream gauge data considered provisional well after released via the internet.
[9] Monthly gridded data: http://www.prism.oregonstate.edu/

Report	*Objective Temporal or Spatial Frames*	*Input*			*Network Dataset Product*	*Quality Control and Correction* (Processing Order →)				*Analyses*	*Graphics*
		Datasets	*Timestep*	*Continuous[1] Record Length*		*Data Errors, Biases, Outliers, Multiday Obs*	*Inhomogeneities*		*Completeness*		
							Known	*Unknown*	*For Source = Dailies*	*For Source = Monthlies*	
Annual Status	***Multiyear Perspective***	***Temporal Analysis Stations***			***Provisional***						***Stations By Zone[2]***
Annual Status – Multiyear Perspective	***Baseline Comparison*** – Seasonal	COOP *Tn, Tx, ppt* *(+monthly derived vars –Table 1)*	Use **Monthlies** whenever available (otherwise derive from Dailies)	**≥ 30 y – operation covering 1971-2000 normals period[10] –** Including Report Year[4]	**Monthly-Seasonal-Annual Dataset (Provisional) – Temporal Analysis Stations** (includes integrative & timing vars – Table 1)	• Numerical & visual checks • Consult forms and observer • Manual removal • **Multiday obs crossing month boundary parsed (e.g., ppt) or omitted**	Accept source QC Known but not corrected by source – only correct if easily done If not, document for next *Trends* report	Accept source QC Attach caveats to results	**Missing values – toss month if # > threshold:** • missing T >5d • missing ppt >3d • other vars: 15% missing	Accept source QC, document missing months Attach caveats to results	Monthly deviations from 30-y normals	• Year plotted by month – along with normals from *Trends Report* • -or- as deviations from normals
											Derive annual vars (Table 1) →Annual deviations from normals	• Bar graphs
		SNOTEL[6] *1 Apr(-1) & 1 Jan(0) SWE[7]* *(+annual derived vars – Table 1)*	Annual	**~≥ 25 y([11]) –** Including Report Year	as for COOP	• Numerical & visual checks • Manual removal	as for COOP	as for COOP	**Accept Source QC**	N/A	Annual deviations from normals	Bar graphs
		USGS[8] *Streamflow annual timing vars –Table 1*	Annual	as Monthly COOP dataset[12]	~as for COOP – **Unregulated Flow Stations**	as for SNOTEL	as for COOP/ SNOTEL	as for COOP/ SNOTEL	as for SNOTEL	N/A	Annual hydrograph timing vars → comparison to baseline	Bar graphs

[10] The continuous record length requirement here (≥ 30y) is less than the stricter threshold for Interannual Variability given below (≥ 40y). However, note that if these stations meet the operation period requirement (1971-2000) and were operating through the reporting year, then the stations will likely meet the ≥ 40y requirement by end of 2010.
[11] Less restrictive record length requirement for SNOTEL data reflects generally shorter records for these stations (per Gray 2008).
[12] Record length requirements for USGS stations could be shortened (e.g., to 25 yrs) if ≥ 30 yrs severely reduces number of qualifying stations.

Report	*Objective Temporal or Spatial Frames*	*Input*			*Network Dataset Product*	*Quality Control and Correction* (Processing Order →)					*Analyses*	*Graphics*
		Datasets	*Timestep*	*Continuous*[1] *Record Length*		*Data Errors, Biases, Outliers, Multiday Obs*	*Inhomogeneities* *Known*	*Inhomogeneities* *Unknown*	*Completeness* *For Source = Dailies*	*Completeness* *For Source = Monthlies*		
Annual Status – Multiyear Perspective	***Baseline Comparison*** – Daily Event Structure	COOP *Tn, Tx, ppt* *(+daily derived vars –Table 1)*	Daily	as Monthly COOP dataset[13]	**Daily Dataset (Provisional) – Temporal Analysis Stations**	as Monthly COOP dataset, ***except:*** • **Multiday obs omitted**	as for COOP Seasonal Baseline Comparison	as for COOP Seasonal Baseline Comparison	Missing values **not** infilled	N/A	Frequency distribution analysis → comparison to baseline	Frequency distribution plotted – along with long-term pattern from *Trends Report*
		USGS[8] *Streamflow*	Daily	as USGS for Seasonal Baseline Comparison	as for Daily COOP – **Unregulated Flow Stations**	as USGS for Seasonal Baseline Comparison	as COOP/ USGS for Seasonal Baseline Comparison	as COOP/ USGS for Seasonal Baseline Comparison	as SNOTEL/ USGS for Seasonal Baseline Comparison	N/A	Descriptive→	Hydrograph –plotted along with long-term pattern from *Trends Report*
	Interannual Variability	COOP *Tn, Tx, ppt* *(+monthly derived vars –Table 1)*	as Seasonal Baseline Comparison	**≥ 40 y – operation covering 1971-2000 normals period** – Including Report Year	as COOP for Seasonal Baseline Comparison **Monthly-Seasonal-Annual Dataset (Provisional) – Temporal Analysis Stations**	as COOP for Seasonal Baseline Comparison	as COOP for Seasonal Baseline Comparison	as COOP for Seasonal Baseline Comparison	as COOP for Seasonal Baseline Comparison	as COOP for Seasonal Baseline Comparison	Descriptive: compare selected key month/seasonal /annual values to longterm **variability** →	Append current year's value to longterm plots by year from *Trends Report* variability analyses **– w/o updating smoothing functions**
		SNOTEL[6] *1 Apr(-1) & 1 Jan(0) SWE*[14] *(+annual derived vars – Table 1)*	as Seasonal Baseline Comparison – Annual values	as SNOTEL for Baseline Comparison/ Seasonal ~≥ 25 y([11])	as SNOTEL for Baseline Comparison/ Seasonal	as SNOTEL for Baseline Comparison/ Seasonal	as COOP/ SNOTEL for Seasonal Baseline Comparison	as COOP/ SNOTEL for Seasonal Baseline Comparison	as SNOTEL for Baseline Comparison/ Seasonal	N/A		

[13] Record length requirements for Daily COOP stations could be shortened (e.g., to 25 yrs) if ≥ 30 yrs severely reduces number of qualifying stations.

[14] Because of reporting timeframes, *Annual Status Reports* would only be able to report SWE for 1 April for the previous year [1 Apr(-1)] and for 1 Jan of the year the report is being released [1 Jan(0)]. (0) and (-1) are a year index relative to the year Annual Report will be released: (0) = current year, (-1) = previous year.

Report	*Objective Temporal or Spatial Frames*	*Input*			*Network Dataset Product*	*Quality Control and Correction* (Processing Order →)					*Analyses*	*Graphics*
						Data Errors, Biases, Outliers, Multiday Obs	*Inhomogeneities*		*Completeness*			
		Datasets	*Timestep*	*Continuous*[1] *Record Length*			*Known*	*Unknown*	*For Source = Dailies*	*For Source = Monthlies*		
Annual Status – Multiyear Perspective		USGS[8] *Streamflow annual timing vars –Table 1*	Annual	as USGS for Seasonal Baseline Comparison	as for USGS Seasonal Baseline Comparison	as USGS for Seasonal Baseline Comparison	as USGS for Seasonal Baseline Comparison	as USGS for Seasonal Baseline Comparison	as USGS for Seasonal Baseline Comparison	N/A	Descriptive: compare annual values to longterm **variability →**	
	Longterm Trends	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	Descriptive: compare selected key month/seasonal /annual values to longterm **trends →**	Append current year value to longterm plots by year from *Trends Report* trend analyses **– w/o updating trendline**
	Teleconnections	as for Interannual Variability + Circulation Indices (Accept source QC)	as for Interannual Variability **– *except:* aggregate to seasonal /annual**	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	Descriptive→	Update station & circulation values in plots from *Trends Report* teleconnection analyses

(b) Climate Variability and Trends Report

Report	*Objective Temporal or Spatial Frames*	*Input*			*Network Dataset Product*	*Quality Control and Correction* (Processing Order →)					*Analyses*	*Graphics*
		Datasets	*Timestep*	*Continuous[1] Record Length*		*Data Errors, Biases, Outliers, Multiday Obs*	*Inhomogeneities*		*Completeness*			
							Known	*Unknown*	*For Source = Dailies*	*For Source = Monthlies*		
Variability & Trends	***Multiyear Analyses***	***Temporal Analysis Stations***			***High-Quality Final***						***Stations By Zone[2]***	
Variability & Trends – Multiyear Analyses	***Daily Event Structure***	COOP *Tn, Tx, ppt* *(+daily derived vars –Table 1)*	Daily	≥ 30 y – Including Report Year	**Daily Dataset (Final) – Temporal Analysis Stations**	**Apply High QC** (Fig 5) = • Numerical & visual checks • Consult forms and observer[15] • Manual removal • **Multiday obs omitted**	**Apply High QC** (Fig 5) = Detect and correct based on station histories	**Apply High QC** (Fig 5) = Detect and correct	Missing values **not** infilled	N/A	**Frequency distribution change analysis – Extreme value analysis**	Box plots & frequency distribution graphics
											Trend analysis of daily event parameters	By-year plot of daily event parameters – w/ trend line
		USGS official release[16] – *Streamflow*	Daily	as for Daily COOP	as for Daily COOP (Final Dataset)	as for Daily COOP – •Check data gone from provisional to official •Consult observer[16]	as for Daily COOP	as for Daily COOP	as for Daily COOP	N/A	Descriptive	Hydrograph plot by day
											Peak/Min Flow/Center of Mass: **change in timing analysis**	By-year timeseries plots
	Interannual Variability	COOP *Tn, Tx, ppt* *(+monthly derived vars – Table 1)*	**Use *dailies* whenever available** – Aggregate to months, seasons, annual	≥ 40 y – **Operation over 1971-2000 normals period** – Including Report Year	**Monthly-Seasonal-Annual Dataset (Final) – Temporal Analysis Stations** (includes integrative & timing vars)	as for Daily COOP *except -* •**Multiday obs parsed (ppt) or omitted then *infilled***	as for Daily COOP	as for Daily COOP	**Apply High QC** **Missing values infilled**	*If only monthlies available* – Accept source QC, document missing months Attach caveats to results	Descriptive→	By-year timeseries plots – **w/ smoothing function**
											Spectral / wavelet analysis	**Spectral / wavelet diagrams**

[15] Contact the appropriate data managers at USGS/NRCS – great resource for discovering potential bugs or shortcomings of the snow/flow datasets.
[16] As NRSC SNOTEL & USGS stream gauge data considered provisional long after they are released via the internet[8], check that datasets have gone from provisional to official.

Report	*Objective Temporal or Spatial Frames*	*Input*			*Network Dataset Product*	*Quality Control and Correction* (Processing Order →)					*Analyses*	*Graphics*
						Data Errors, Biases, Outliers, Multiday Obs	*Inhomogeneities*		*Completeness*			
		Datasets	*Timestep*	*Continuous*[1] *Record Length*			*Known*	*Unknown*	*For Source = Dailies*	*For Source = Monthlies*		
Variability & Trends – Multiyear Analyses		SNOTEL[16] *1 Jan & 1 Apr SWE* *(+annual derived vars – Table 1)*	Annual values	~≥ 25 y – Including Report Year	as Monthly COOP (Final Dataset)	as for Daily USGS	as for Daily USGS	as for Daily USGS	as for Daily USGS	N/A	as Monthly COOP	as Monthly COOP
		USGS[16] *Streamflow*	Dailies: • Aggregate to months • Derive annual vars – Table 1	as for USGS Daily dataset	as Monthly COOP (Final Dataset)	as for Daily USGS	as for Daily USGS	as for Daily USGS	as for Daily USGS	N/A		
	Decadal Regime Shifts	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability + **~≥50 y([17])**	***Regime-shift subset of*** Monthly-Seasonal-Annual Dataset (Final)	as for Interannual Variability	**Correct only with great care** – will affect shift detection	**Ignore possibility of artificial inhomogeneities** not supported by stn histories or other data. Attach caveats to results	as for Interannual Variability	as for Interannual Variability	**Regime shift detection**	By-year plots **– w/ regime shifts shown**
	Longterm Trends	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	**Trend analysis**	By-year plots

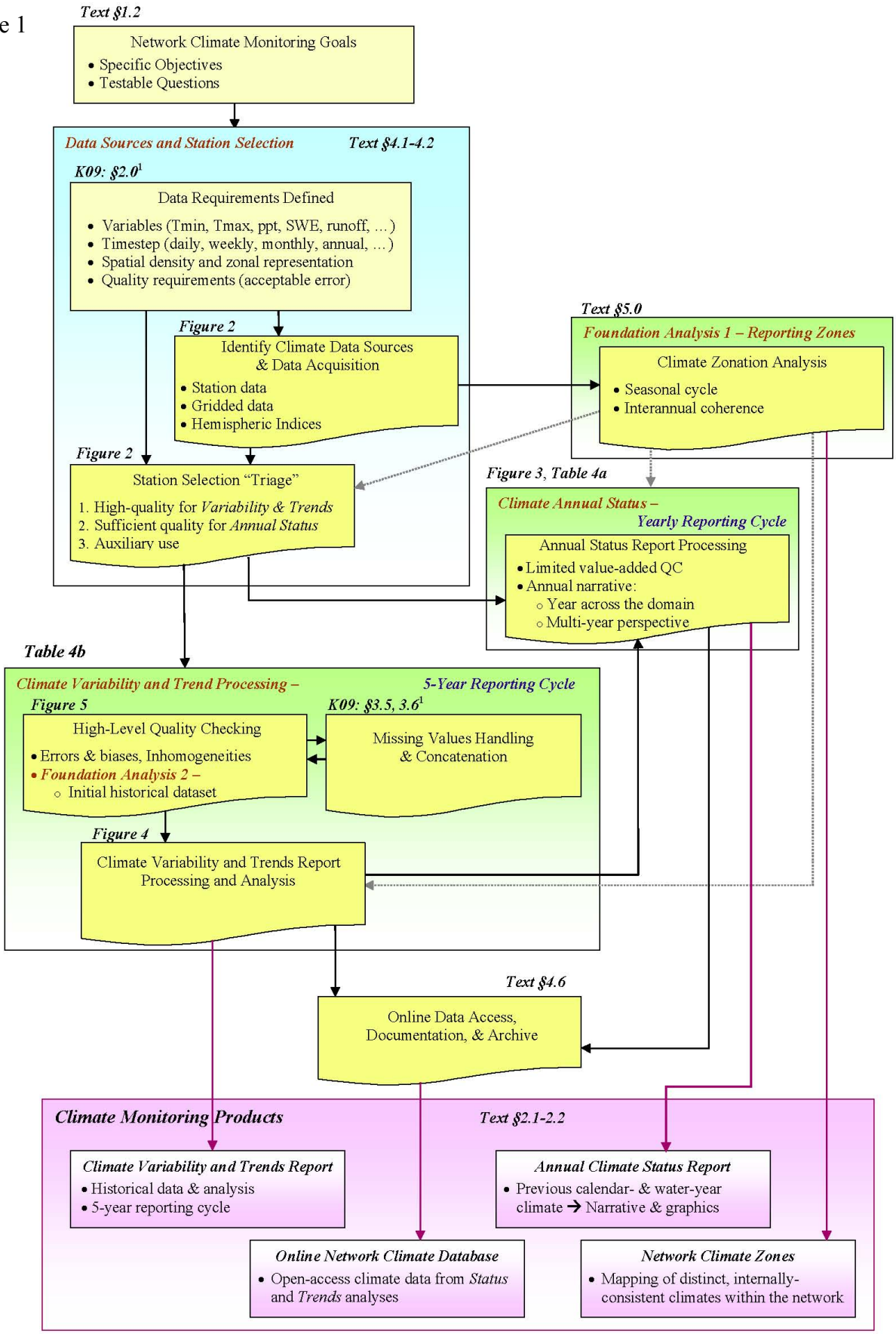
[17] The longer period for regime shift analyses is to limit analyses to records most likely to capture multidecadal shifts. Nonetheless, 50 years is an arbitrary cutoff and can be relaxed.

Report	*Objective Temporal or Spatial Frames*	*Input*			*Network Dataset Product*	*Quality Control and Correction* (Processing Order →)					*Analyses*	*Graphics*
		Datasets	*Timestep*	*Continuous*[1] *Record Length*		*Data Errors, Biases, Outliers, Multiday Obs*	*Inhomogeneities* *Known*	*Inhomogeneities* *Unknown*	*Completeness* *For Source = Dailies*	*Completeness* *For Source = Monthlies*		
	Teleconnections	as for Interannual Variability + **Circulation Indices** (Accept source QC)	as Interannual Variability (aggregate to seasonal + annual)	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	Descriptive	By-year plots **– w/ circ index**
											Cross-correlation analysis	**Lag/lead correlation diagrams**
											Cross-spectral/ wavelet analysis	**Spectral / wavelet diagrams**
Variability & Trends	***Regional Analyses***	***Spatiotemporal Analysis Data***			***High-Quality Final***						***Climate Zones to Regional***	
Regional Analyses	***Regional Coherence*** – Gridded data	***Gridded data*** **PRISM** final release: *Tn, Tx, Td, ppt*	Monthly	since 1895	**Monthly-Seasonal-Annual Dataset – Gridded Data** PRISM cutout for region	Accept source QC	Accept source QC	Accept source QC	N/A	Accept source QC	Descriptive: climate zone & park-wide – geography & averages	Maps & by-year plots w/ smoothing functions & trendlines
											Spatial autocorrelation analysis – incl/ domain's vicinity	**Correlation maps**[18] **/ semivariogram maps**
		Gridded data SNODAS – variables as for SNOTEL	Annual values	since Apr 2003	as for PRISM SNODAS cutout	as for PRISM	as for PRISM	as for PRISM	Accept source QC	N/A	as for PRISM – including of aerial snowpack extent	as for PRISM
	– Station data	**Station data –** as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	as for Interannual Variability	N/A	Spatial autocorrelation analysis – incl/ domain's vicinity	Correlation / semivariogram maps

[18] QC of PRISM is optimized for spatial consistency over temporal consistency (§2.6.2): statistical interpretation of correlation maps must be made with this caution in mind.

Figure 1. Network Climate Monitoring Protocol Framework – Processing Overview

Figure 1

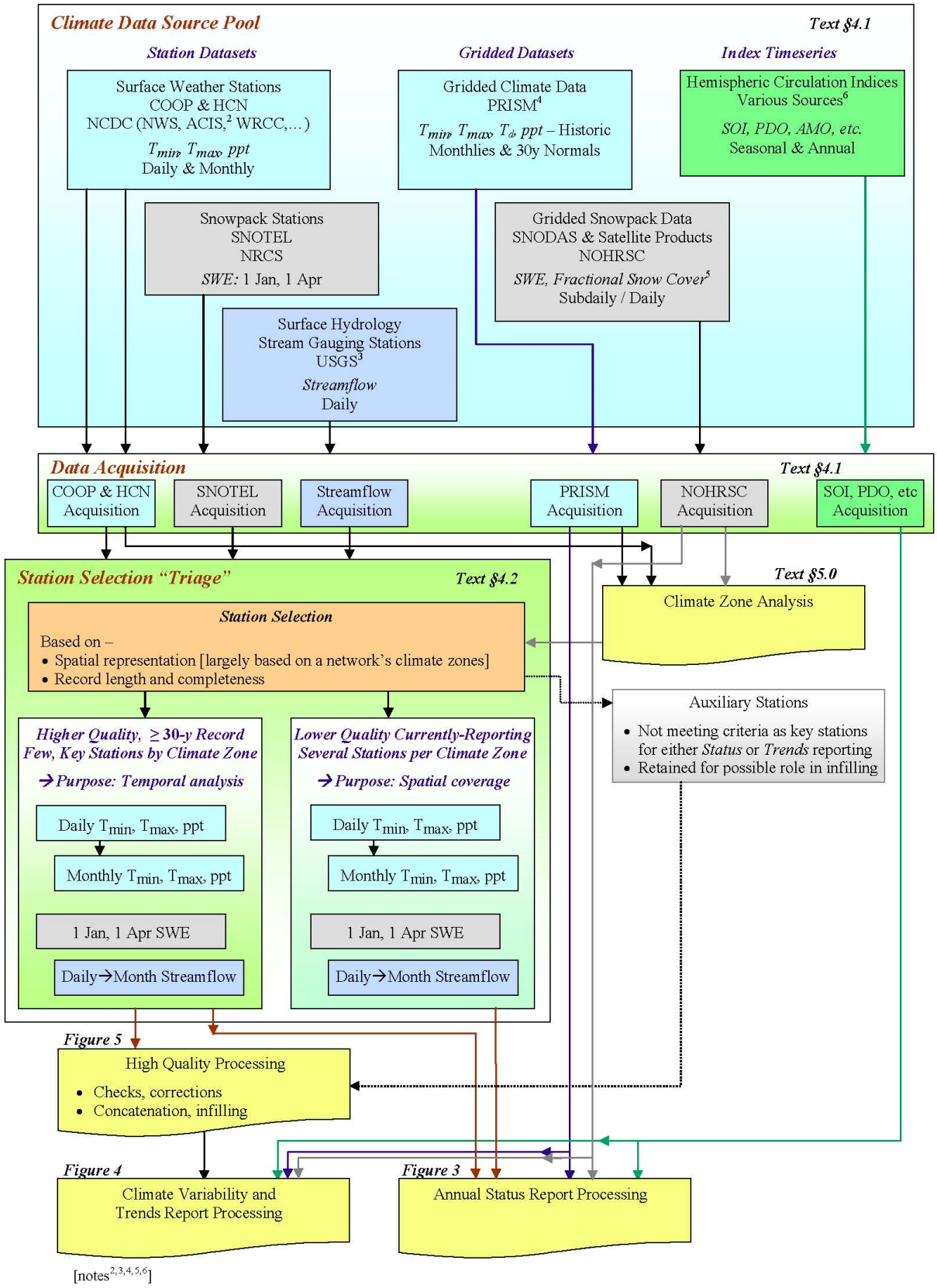


[notes[1]]

[1] K09 = See methods described in Kittel (2009a) "*The Development and Analysis of Climate Datasets*" – listed by section (§)

Figure 2

Figure 2. Climate Data Sources, Acquisition, & Station Selection – Processing Framework



[2] ACIS http://www.rcc-acis.org/

[3] Sources for streamflow – [Is there a source GRYN & ROMN already using?] http://water.usgs.gov/waterwatch/ real-time streamflow; http://water.usgs.gov/GIS/metadata/usgswrd/XML/realstx.xml.

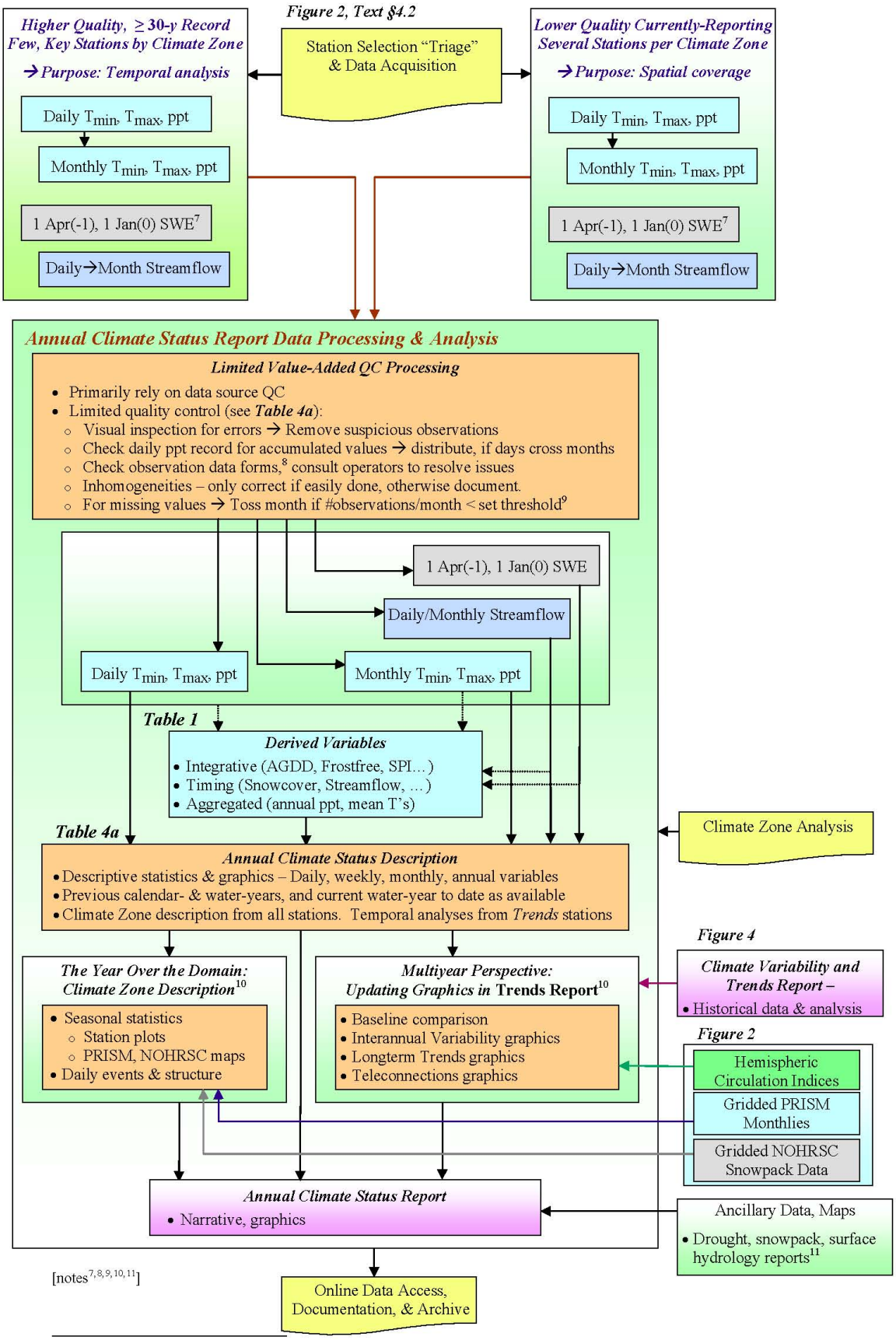
[4] PRISM: http://www.prism.oregonstate.edu/

[5] SNODAS SWE is 6 hourly, Fractional Snow Cover is daily (NOHRSC 2004). See text §5.3 (and related footnotes) for source and additional information.

[6] For sources, refer to Kittel (2009a), Table 4.

Figure 3

Figure 3. Annual Climate Status Report – Processing Framework



[7] Index is for year relative to year *Annual Report* is being compiled: (0) = current year, (-1) = previous year

[8] COOP weather station data are recorded on B-91 forms available from, e.g., state climatologists.

[9] Setting missing thresholds: PRISM uses 85% of observations present (~5 missing days/month). Other example schemes are no more than 3 missing days for precipitation, 5 days for temperature (Kittel 2009a).

[10] See Table 4a for descriptive statistics and graphics by objective and variable. These tasks build on data and analyses from the previous 5-yr cycle *Trends Report* (Figure 4). Annual updates are provisional, based on data available with minimum QC when *Annual Reports* are being prepared. *Annual Reports* involve limited analysis; full analysis is revisited with high level of QC on 5-yr cycle (see Figure 5).

[11] e.g., as used in Gray's (2008) report: *Greater Yellowstone Network: Climate of 2007*

Figure 4

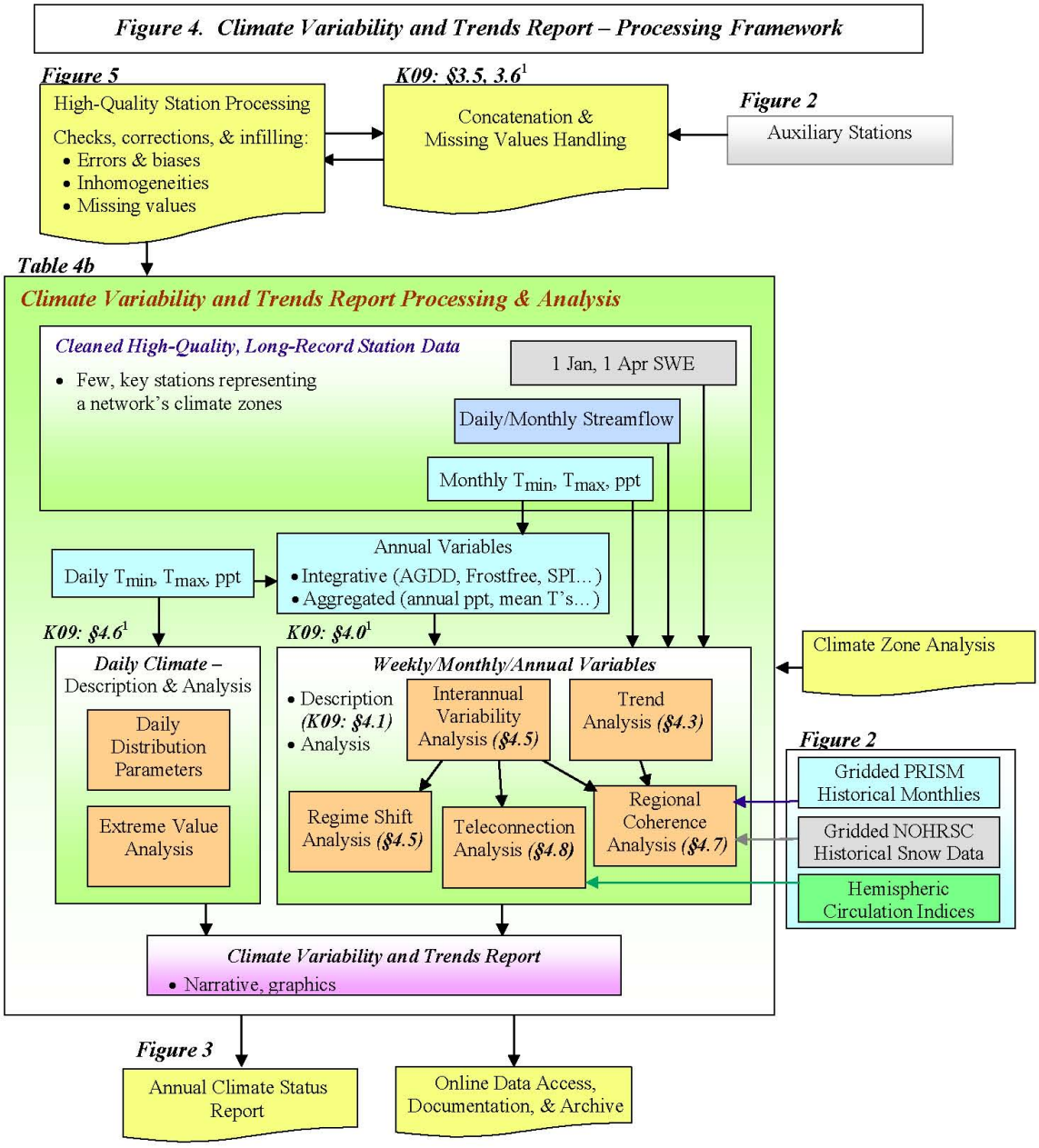
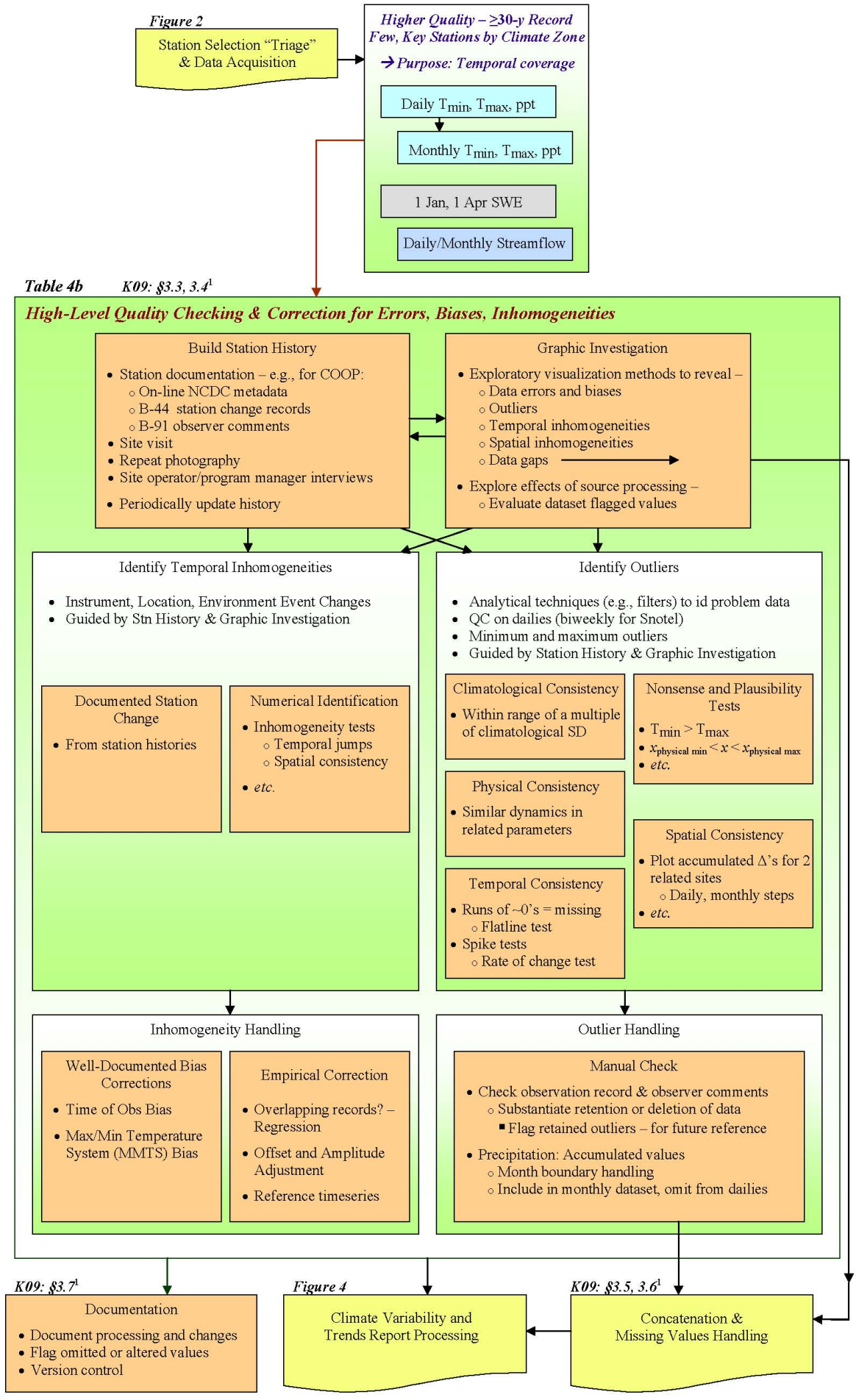


Figure 4. Climate Variability and Trends Report – Processing Framework
Figure 5
High-Quality Station Processing
Checks, corrections, & infilling:
• Errors & biases
• Inhomogeneities
• Missing values
K09: §3.5, 3.6[1]
Concatenation & Missing Values Handling
Figure 2
Auxiliary Stations
Table 4b
Climate Variability and Trends Report Processing & Analysis
Cleaned High-Quality, Long-Record Station Data
• Few, key stations representing a network's climate zones
1 Jan, 1 Apr SWE
Daily/Monthly Streamflow
Monthly Tmin, Tmax, ppt
Daily Tmin, Tmax, ppt
Annual Variables
• Integrative (AGDD, Frostfree, SPI…)
• Aggregated (annual ppt, mean T's…)
K09: §4.6[1]
K09: §4.0[1]
Climate Zone Analysis
Daily Climate – Description & Analysis
Daily Distribution Parameters
Extreme Value Analysis
Weekly/Monthly/Annual Variables
• Description (K09: §4.1)
• Analysis
Interannual Variability Analysis (§4.5)
Trend Analysis (§4.3)
Regime Shift Analysis (§4.5)
Teleconnection Analysis (§4.8)
Regional Coherence Analysis (§4.7)
Figure 2
Gridded PRISM Historical Monthlies
Gridded NOHRSC Historical Snow Data
Hemispheric Circulation Indices
Climate Variability and Trends Report
• Narrative, graphics
Figure 3
Annual Climate Status Report
Online Data Access, Documentation, & Archive

Figure 5

Figure 5. High-Level QC – Processing Framework



Appendices

Appendix A. Workshop Participant Contact Information

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Appendix B. GRYN and RMNO Climate Goals and Objectives

(source: Frakes et al. 2009)

1.1.1 Goals

There are two goals of this protocol:

- To assemble climate covariate data for use in the analysis of other NPS Vital Signs. This protocol will facilitate the acquisition and analysis of climate data at various spatial and temporal scales to inform variations in key surface biophysical processes. Select spatial scales include points (stations) and climate regions, while key temporal scales include daily, monthly, and annual.

- As a vital sign, to determine variations and changes in key climate variables relative to an established baseline. This protocol will be used to analyze intra- (i.e., daily and monthly) and inter-annual (i.e., short- and long-term) variations and changes in key climate variables and to interpret results in light of hemispheric processes that influence local climate variability.

Measurable climate variables particularly relevant to surface biophysical processes include:

- Direct climate measures: temperature, precipitation, and snow
- Integration of multiple climate measures: drought and river flow/surface hydrology
- Indices of large-scale atmospheric variations

1.1.2 Objectives

The following specific monitoring objectives have been developed to meet the climate monitoring goals stated above.

OBJECTIVE 1: Temperature – Determine the status, trends, and periodicity in daily, monthly, and annual temperature, at the scale of points, climate regions and parks.

Proposed variables and methodologies:

- Minimum, maximum, and mean monthly temperatures and departures from an established baseline
- Number of growing degree days per year, number of frost free days per year, and timing of first and last frosts
- Intra- and inter-annual variability and trend analyses and interpretation from the perspective of:
    - Regional coherence
    - Hemispheric teleconnections – including the El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO), and Atlantic Multi-Decadal Oscillation (AMO)
    - Global trends

OBJECTIVE 2: Precipitation – Determine the status, trends and periodicity in daily, monthly and annual accumulated precipitation, including extremes, at the scale of points, climate regions and parks.

Proposed variables and methodologies:

- Minimum, maximum, mean total accumulated precipitation and departures from an established baseline
- Frequency of precipitation events that exceed an established threshold

- Intra- and inter-annual variability and trend analyses and interpretation from the perspective of:
    - Regional coherence
    - Hemispheric teleconnections – including the ENSO, PDO, NAO, and AMO
    - Global trends

OBJECTIVE 3: Drought – Determine the status, trends, and periodicity in monthly and annual drought at the scale of climate divisions

Proposed variables and methodologies:

- Frequency and duration of drought beyond an established threshold
- Intra- and Inter-annual variability and trend analyses and interpretation from the perspective of:
    - Regional coherence
    - Hemispheric teleconnections – including the ENSO, PDO, NAO, and AMO
    - Global trends

OBJECTIVE 4: Snowpack – Determine the status, trend, and periodicity in daily, monthly and annual snow cover and snow water equivalent at the scale of points, climate zones and parks.

Proposed variables and methodologies:

- Amount and timing of peak snow water equivalent (SWE) and snow density
- Number of days with snow cover, aerial extent, and timing of snowmelt and ice on/off lakes
- Frequency of extreme snow cover/SWE events beyond a defined threshold
- Intra- and Inter-annual variability and trend analyses and interpretation from the perspective of:
    - Regional coherence
    - Hemispheric teleconnections – including the ENSO, PDO, NAO, and AMO
    - Global trends

OBJECTIVE 5: Surface Hydrology – Determine the status, trends, and periodicity in daily, monthly and annual stream flow at the major watershed level.

Proposed variables and methodologies:

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