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Climate Zone Delineation: Evaluating Approaches for Use in Natural Resource Management

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Abstract Recent efforts by the United States Department of the Interior (DOI) have the potential to make climate zones the basic geographic units guiding monitoring and resource management programs in the western U.S. We evaluated a new National Park Service approach for delineating climate zones that will likely be a model for other DOI agencies. Using the test case of the Greater Yellowstone Area in Wyoming, Montana and Idaho, we conducted three separate analyses, each based on a different dataset. Cluster analysis of 1971–2000 temperature and precipitation normals grouped weather stations according to similarities in seasonal patterns. Principal Components Analysis (PCAs) of 1895–2008 monthly data grouped stations by similarities in long-term variability. Finally, an analysis of snow data further subdivided the zones defined by the other two analyses. The climate zones produced by the cluster analysis and the PCAs were roughly similar to each other, but the differences were significant. The two sets of zones may be useful for different applications. For example, studies that analyze links between climate patterns and the demography of threatened species should focus on the results of the PCAs. The broad similarity among results produced by the different approaches supported the application of these zones in climate-related monitoring and analysis. However, since choices in data and methodology can affect the details of maps depicting zone boundaries, there are practical limitations to their use.

Keywords Climate zonation · National Park Service · Yellowstone National Park · Grand Teton National Park · Climate monitoring · Ecological impacts of climate

Introduction

Many previous studies have described the difficulties associated with basing natural resource monitoring and management programs on political or jurisdictional boundaries (e.g., Knight and Landres 1998). In this context, the United States Department of the Interior has recently begun to shift the focus of multiple management and science programs toward more natural units like watersheds, species home ranges, and ecosystems (National Park Service 2009; National Park Service 2010; U.S. Fish and Wildlife Service 2010). As one example, the U.S. National Park Service (NPS) is developing protocols for monitoring climate in and around its park units that are based on spatial patterns of seasonal and long-term climatic variability rather than land ownership. This approach hinges first and foremost on the identification of relatively homogeneous climate regions or "zones", and these zones will in turn serve as the basis for assessing climate change impacts on water, biological and cultural resources (Frakes and others 2009).

The delineation of climate zones has the potential to influence a wide variety of management decisions

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throughout the national park system. Current efforts include the integration of climate zones into operations in at least 9 national park units including Yellowstone, Glacier, and Rocky Mountain National Parks (Frakes and others 2009; Tercek 2010) as well as the formation of region-wide Landscape Conservation Cooperatives that seek to manage natural resources according to ecological rather than administrative boundaries (Editors of Nature 2011). As one of the first such comprehensive programs of its kind, this NPS effort is likely to serve as a model for other DOI agencies which control over 180 million ha of land in the United States (Department of Interior 2000).

Because climate zones are being proposed for such widespread application in a variety of geographical and ecological contexts, it is important to understand the methods by which they are defined and their potential limitations. As a first test of the methods recently developed by the NPS, the work presented here defines climate zones for the Greater Yellowstone Area (GYA), including Yellowstone and Grand Teton National Parks.

The GYA provides a good test case for the NPS climate zonation methods for at least three reasons. First, the zones will be immediately relevant because this area contains ecological resources of high conservation value that are thought to be vulnerable to climate change. For example, whitebark pine, a key food source for bears, and multiple amphibian species are reportedly at risk of extirpation as a result of a warming and drying climate (Bartlein and others 1997; McMenamin and others 2008; Logan and others 2010). Second, the region's mountainous topography produces a complex climate that varies on relatively fine spatial scales, and this complexity provides a strong challenge for any methods that seek to define areas with homogeneous climate (Shafer and others 2005). Third, in addition to the orographic effects just mentioned, the GYA's climate is further complicated by its location at the boundary of two large scale precipitation regimes. Northern Yellowstone National Park (YNP) typically experiences its highest precipitation during the late spring and early summer months (April, May, June) when continental heating and large-scale convection bring moisture from multiple sources. In contrast, southern YNP and Grand Teton National Park (GTNP) generally have the greatest precipitation in winter months (December, January, February), as a result of westerly storm systems (Whitlock and Bartlein 1993).

We examined the three methods for defining climate zones chosen by the NPS, following a recently proposed NPS climate zonation protocol (Frakes and others 2009). First, weather stations were grouped according to similarity in seasonal pattern with cluster analyses of 1971–2000 monthly temperature and precipitation averages (normals). Second, Principal Components Analyses of 1895–2008 monthly precipitation and temperature data were used to evaluate the degree to which stations could be separated according to patterns of long-term variability. Third, we calculate the average number of days per year with snowcover at each weather station as an estimate of snow season length.

These three types of analysis were designed to look at different aspects of the climate system. It was recognized at the outset that each analysis might produce a different set of climate zones, and that each set of zones would have different practical applications for resource managers. Climate data aggregated from zones produced by the cluster analysis might be used in studies of phenology or the timing of annual life-cycles. Data taken from zones provided by the Principal Component Analyses could be used as covariates in studies that assess the long-term increase or decrease of sensitive species (Frakes and others 2009). The estimates of snowcover duration produced by the third method will be useful for studies of species that have specific snow requirements such as wolverine (Copeland and others 2010) and pika (Beever and others 2010). They also may explain variability in ecological processes affected by snowcover, such as scavenger feeding rates (Wilmers and Getz 2005), elk migration patterns (White and others 2010), and elk herbivory on riparian vegetation (Creel and Christianson 2009).

When possible, our application of these methods included assessments of how robust the results were to changes in variable inputs and statistical algorithms. For example, we used two types of cluster analysis on two variants of the 1971–2000 monthly data; and two different statistical techniques were used to estimate the geographic boundaries associated with the weather stations in each zone. We also used bootstrapping to assign statistical confidence to the results of the cluster analyses.

Our objective was to evaluate the climate zonation methods proposed by the NPS, presenting both their strengths and weaknesses as clearly as possible. In this way, resource managers in other parts of the country, in the NPS as well as in other federal agencies that are considering similar programs, will understand their proper application and limitations.

Methods

A schematic work-flow of our methods appears in Fig. 1.

Cluster Analyses of 1971–2000 Monthly Normals Derived from Weather Station Data

The purpose of the cluster analysis was to group weather stations according to similarity in seasonal pattern. For

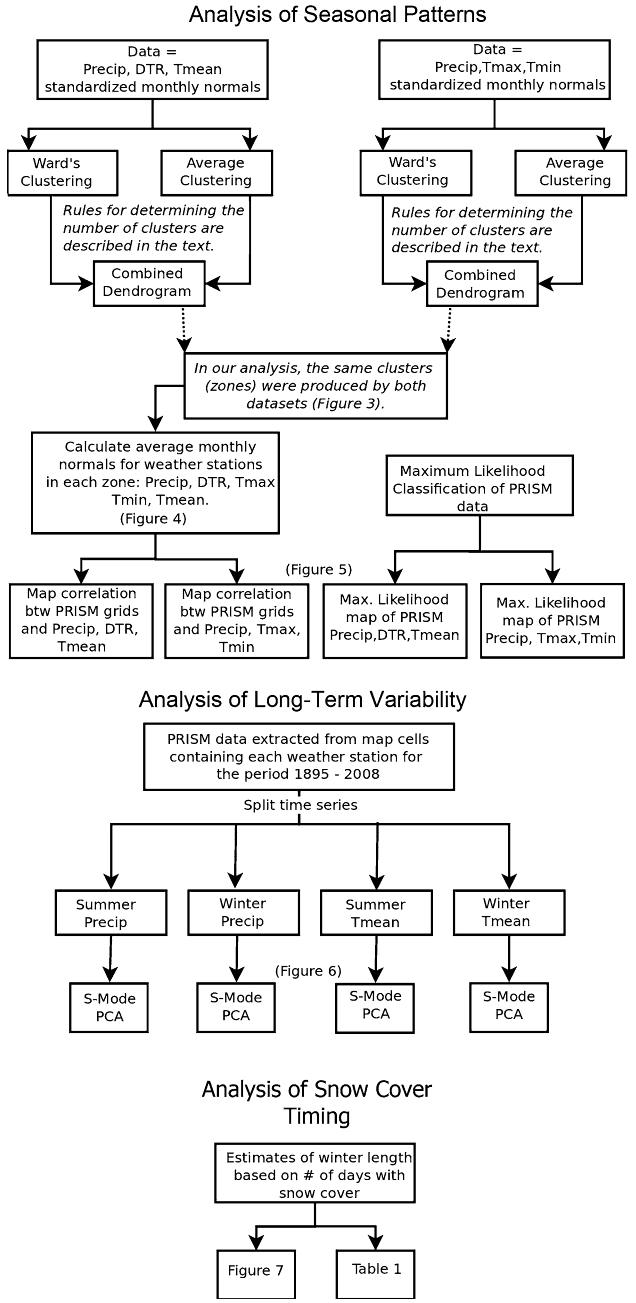


Fig. 1 Schematic diagram depicting the analyses performed in this study and their relationships to each other

example, weather stations that experience a greater proportion of their precipitation in winter months might cluster separately from stations that experience more precipitation in summer. In each data matrix, there were 12 monthly values for each of three climate parameters (described below), creating 36 values for each weather station, each station in a separate row. We included data from every National Weather Service Cooperative Observer (COOP) and Natural Resources Conservation Service Snowpack Telemetry (SNOTEL) station within 40 km of YNP and GTNP that reported 1971–2000 monthly normals (42 stations, Fig. 2, Map). In recent years, new clustering methods have addressed challenges posed by the seasonal structure and autocorrelation inherent in atmospheric time series data (Bengtsson and Cavanaugh 2008; Lund and Li 2009). However, because the cluster analyses here do not rely on time series data, instead using only a matrix of monthly averages (normals), we used more traditional climate clustering methods (Fovell and Fovell 1993; Unal and others 2003) and instead employed bootstrapping (described below) to assess the sensitivity of our results to data artifacts. All cluster analyses calculated the distinctiveness of weather stations in multivariate space with the squared Euclidean Distance metric because it has performed better than alternatives in previous meteorological studies (Fovell and Fovell 1993; Unal and others 2003; Neal and Phillips 2009; Van Cooten and others 2009). Unless noted, all analyses were performed within the R statistical analysis platform (R Development Core Team 2009).

Following the NPS climate zonation protocol, we performed cluster analyses separately on two different datasets and compared the results. The first data matrix chosen by NPS contained monthly precipitation, diurnal temperature range (DTR), and mean temperature (Tmean) values for each weather station. The second matrix contained monthly precipitation, monthly average maximum temperature (Tmax), and monthly average minimum temperature (Tmin). Tmax and Tmin values are often used in ecological studies, but DTR and Tmean usually show lower correlation with each other, which gives greater power to cluster analysis (Easterling and others 1997; Vose and others 2005). Tmax, Tmin, and precipitation data were obtained for the period 1971–2000 from the Western Regional Climate Center (WRCC) (www.wrcc.dri.edu), the Natural Resources Conservation Service (NRCS) (www.wcc.nrcs.usda.gov), and the Parameter-elevation Regressions on Independent Slopes Model (PRISM) Climate Group (http://www.prism.oregonstate.edu/). DTR and Tmean were calculated from monthly Tmax and Tmin normals. For COOP stations, monthly normals were taken directly from the WRCC. In contrast, only precipitation data from NRCS SNOTEL sites were used. This was done because of concerns over the quality and consistency of SNOTEL temperature data (Pederson and others 2010). Unlike SNOTEL temperature data, PRISM data have been subjected to rigorous QC/QA procedures and do not have the same flaws (Daly and others 2005, 2008). Consequently, Tmax and Tmin 1971–2000 normals were extracted from the 800 m (30-arc second) PRISM grid cell closest to each SNOTEL station and used in the cluster data matrix. To ensure that weather stations were clustered according to similarity in seasonal patterns, regardless of the absolute magnitude of the observations or differences among

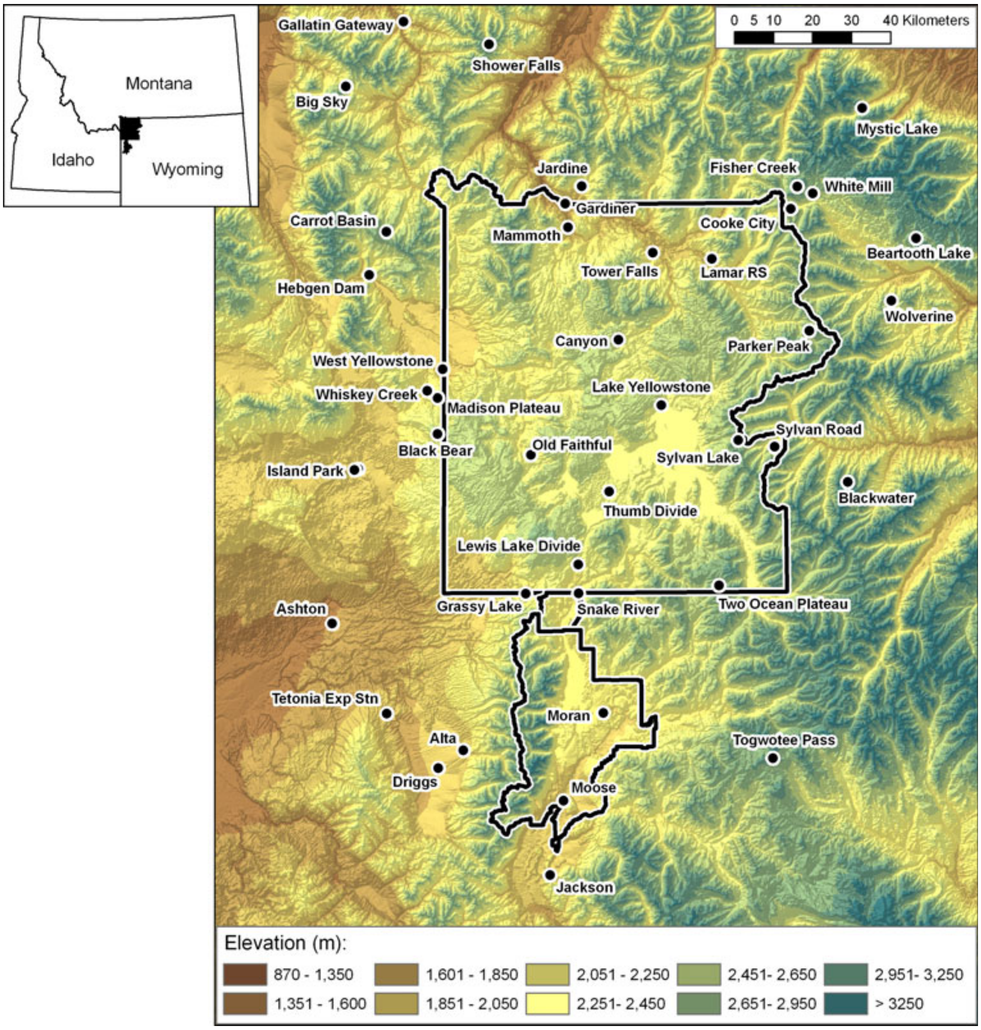


Fig. 2 Map showing weather stations included in the analysis. *Black outlines* show the boundaries of Yellowstone and Grand Teton National Parks, with Yellowstone in the north and Grand Teton in the south

stations in the amount of seasonal variance, the data were converted to z scores, which express values in terms of how many standard deviations they fall above or below the mean.

Determining the Number of Climate Zones to be Retained from the Cluster Analysis

We used three criteria for determining the number of weather stations in a climate zone. First, both Ward's and Average clustering algorithms were used and the results were compared (Unal and others 2003). This resulted in four separate cluster analyses: two types of clustering (Ward's and Average) both performed on two separate data sets (Precipitation, Tmax, Tmin and Precipitation, DTR, Tmean). Ward's clustering uses an Analysis of Variance approach that minimizes the sum of squares within each group of weather stations. Average clustering joins weather stations into successively larger groups in a way that minimizes the average distance between the members of an existing group and any new stations or groups that are added to the existing group (Sheskin 2007). If a cluster of weather stations appeared unchanged in dendrograms produced for the same dataset by both clustering algorithms, it was retained. If a cluster contained different weather stations in Ward's vs. Average clustering for a particular dataset, it was treated as a polytomy (unstructured group) and a larger cluster containing both the polytomy and the cluster of stations most similar to it was examined. Successively larger clusters of stations were examined until groups with the same station membership in both Ward's and Average dendrograms were found. This procedure, which defined the minimum size of the station clusters that were used as zones, was performed separately on the two datasets (Precipitation, DTR, Tmean and Precipitation, Tmax, Tmin). The result was two sets of potential climate zones, one for each dataset, that were compared in order to determine how robust our methods were to changes in variable inputs.

Second, confidence levels were assigned to each cluster of stations with a bootstrapping approach (Suzuki and Shimodaira 2006). Bootstrapping of cluster analysis has been widely used in phylogenetics (Felsenstein 1985; Soltis and Soltis 2003), and Gong and Richman (1995) used bootstrapping methods similar to those presented here for their survey of the strengths and weaknesses provided by several different clustering algorithms in climate studies. For each cluster analysis performed (Ward's and Average clustering each performed on two datasets), the original data set was resampled to produce a new pseudoreplicate dataset, from which a new cluster dendrogram was created. Bootstrap resampling was performed among the columns of the original matrix with replacement, so that the pseudoreplicate datasets differed from the original by having entire columns removed and replaced by a duplicate of an original column. Consequently, data were not mixed among weather stations during resampling, but a particular pseudoreplicate dataset might not contain February precipitation, instead perhaps containing two columns for January precipitation. The resampling procedure was repeated 10,000 times, producing 10,000 pseudoreplicate clustering arrangements. We define bootstrap confidence here as the percentage of times a bootstrap solution splits stations at a parental node (i.e., edge) in a way that was identical to the original classification (Shimodaira 2002). Using this method, the effectiveness of each node could be evaluated, starting at the first agglomeration, and the optimal number of climate classes could be objectively chosen. Clusters chosen by the comparison of Ward's and Average clustering (first criterion for choosing clusters, above) were inspected manually. If any such clusters appeared in less than half of the pseudo-replicate trees, they were merged with successively larger station groups until all station clusters had >50% confidence. We chose this 50% confidence criterion because it is commonly used in the bootstrapping of phylogenetic cluster analyses, where the dendrograms produced are referred to as "majority rule consensus trees" (Felsenstein 1985; Soltis and Soltis 2003). In all cases, the clustering methods used to produce the pseudoreplicate dendrograms were the same as those used in the original dendrogram being assessed. This meant that confidence levels were assigned to the Ward's cluster analyses using bootstrapping with Ward's clustering, and the Average cluster analyses were bootstrapped with Average clustering. All cluster analyses, both bootstrapped and original, used the Euclidean distance metric.

In order to make the results of the cluster analysis more easily comparable to the Principal Components Analysis (described below), we inspected our dendrograms for groups of weather stations that both appeared together in the cluster analysis and varied similarly in the Principal Components Analysis of long-term variability (i.e., loaded on the same principal components). If such groups were found, they were marked on the cluster dendrograms even if they did not have 50% or more bootstrap confidence.

Cluster-Based Mapping of Potential Climate Zones

Correlation maps were used to estimate the geographic boundaries of each climate zone defined by cluster analysis. Monthly normals were averaged across every weather station in each zone defined by cluster analysis. This was performed separately for the precipitation, Tmax, Tmin and the precipitation, DTR, Tmean data sets, resulting in two sets of 36 monthly values for each zone. Pearson's correlation coefficients were then calculated between the 36 monthly zone averages (36 separate values for each zone) and the 36 corresponding values associated with each 800 m (30-arc second) grid cell in the PRISM 1971–2000 monthly normal data set (Daly and others 2000, 2005, 2008). This produced two gridded maps, one for each data set. Each grid cell was assigned colors that indicated which zones were correlated at level $r = 0.93$ or greater. If a cell had $r \geq 0.93$ for more than one zone, it was assigned more than one color, to illustrate the overlap among the zones. After experimentation with a range of correlation thresholds (0.7–0.99), 0.93 was chosen because it provided climate zone boundaries that were geographically near each other for most of their perimeter without overlapping. All correlation thresholds produced zone maps centered on the weather stations classified into each zone by the cluster analyses. However, higher thresholds produced geographically smaller zones with large, unclassified areas between them. Lower correlation thresholds produced a high degree of overlap among zones because many grid cells had correlations exceeding the threshold for more than one zone.

Maximum Likelihood Classification Analysis of PRISM Grid Cells

In order to determine how robust our estimated zone boundaries were to changes in statistical method, we created an alternative set of classification maps. Rather than extrapolating from weather station data as just described, we used a direct classification of gridded map data with Maximum likelihood Classification (MLC; Jensen and others 2009; Tso and Mather 2009). Since the cluster analyses described above had produced four climate zones, we constrained our MLC to produce four zones—or classes of map cells—as well. The PRISM data (described above, Daly and others 2000, 2005, 2008) used in this analysis consisted of 800 m (30 arc-second) map cells covering the entire Greater Yellowstone Area. There were two separate analyses: in order to make a direct comparison to our cluster analyses, each map cell contained either 1971–2000 normals for precipitation, Tmax, Tmin, or normals for precipitation, Tmean and DTR. For each dataset separately, we computed the variance–covariance matrices and then used an isodata clustering algorithm (ArcGIS 9.3 with spatial analyst, ESRI Corporation, Redlands, California) that created four sets of discrete variance–covariance signatures, one for each of the climate zones to be delineated. The data for each map cell (1971–2000 normals) were then compared to each of the four class signatures, and each cell's zone membership was assigned according to which of the four signatures produced the greatest maximum likelihood value (Jensen and others 2009; Tso and Mather 2009). Two final MLC zone maps were created: one for cell classifications based on precipitation, Tmax, Tmin, and one for precipitation, Tmean and DTR.

Principal Components Analysis of 1895–2008 Monthly Temperature and Precipitation

Unlike the cluster analyses, which used *1971–2000 average values for each month of the year*, the Principal Components Analyses (PCAs) were performed on data matrices that contained *values for each month during the period 1895–2008* (the longest time period available). Instead of analyzing seasonal pattern, as in the cluster analysis, the PCAs were designed to assess the degree to which stations could be grouped according to patterns of variability that evolve over the timespan of years and decades. Data for the PCAs were extracted from monthly 1895–2008 PRISM estimates (Daly and others 2000, 2005, 2008). Specifically, monthly time series for Tmax, Tmin, and precipitation were extracted from the grid cells occupied by each weather station. Tmean for each station was calculated by arithmetically averaging Tmax and Tmin. In order to test for the possibility that summer and winter might vary independently, each precipitation and Tmean time series was split into separate summer (June, July, August) and winter (December, January, February) time series. This resulted in four separate data sets for analysis: winter precipitation, summer precipitation, winter Tmean, and summer Tmean.

In the context of this particular analysis, PRISM estimates have two major advantages and one potential disadvantage relative to raw weather station data. First, since PRISM values for each grid cell are interpolated from a network of surrounding stations, it is possible to extract time series that extend further back in time than many of the individual weather station records. Second, this same interpolation process results in continuous time series where all missing data points have been in-filled via a rigorous statistical process that incorporates QC/QA procedures not included in available COOP records (Daly and others 2000, 2005, 2008). Despite these advantages, it is important to consider the fact that the number of weather stations on which PRISM interpolation was based changed throughout the time period of the dataset, with fewer weather stations contributing to older PRISM estimates. In order to test this potentially confusing influence of station density, we performed additional PCAs using the methods described below on raw weather station observations from 1968–2008, which was the longest time period common to all stations.

S-mode PCA was performed using methods adapted from Serrano and others (1999) and Comrie and Glenn (1998). The data matrix had values for each weather station in separate columns and months for a single climate variable, e.g. precipitation, in the rows. Differences among weather stations were interpreted from the loadings. In order to balance the magnitude of the variance among stations, so that stations were not grouped because they had a large degree of variability but instead because they exhibited similarities in patterns over time, the data were natural-log transformed and scaled (performed on the correlation rather than the covariance matrix). Because long-term trends in the data might mask PCA's ability to detect similarities among stations with respect to other patterns of interest (e.g., cyclic phenomena such as El Nino), the data were detrended with linear regression prior to analysis, i.e., the PCA was performed on the residuals of a linear regression between the climate parameter of interest and time. Plots of regression residuals against fitted values were examined to confirm that no higher order (i.e., non-linear) relationships existed between time and temperature or precipitation. Varimax rotation was used to prevent the shape of the geographic area being analyzed from affecting the results (Buell 1975; Serrano and others 1999). Scree plots were examined to determine how many principal components to retain.

Estimates of the Average Number of Days Per Year with Snowcover at Each Weather Station

We estimated the average number of days per year with persistent snow cover at each weather station. The goals were to develop a relative ranking of stations with respect to snowcover duration within each climate zone, and to determine the strength of the relationship between snowcover duration and station elevation. For each COOP and SNOTEL station, 1971–2000 daily snowcover data were obtained from the NCDC or NRCS, respectively. COOP stations report snow depth only, so the number of days with snowcover greater than zero was used at these sites. SNOTELs likewise report snow depth, but snow water equivalent (SWE), a second parameter available from these sites, is often a more accurate indicator of local snowcover (Pederson and others 2010). As a result, days with measurable SWE were counted at these SNOTEL stations. Station data files were organized according to water year

(October–September), and analyzed using a script written in Scientific Python (http://www.scipy.org/). The script determined the start and end dates of the snow season according to the following rule set:

1. To correct for the fact that SNOTEL stations record SWE in tenths of inches, but COOP stations do not record a measurement until snow depth exceeds one inch, SNOTEL data were not considered greater than zero until they exceeded 0.5 inches SWE. All non-zero COOP snow depth values were counted as days with snowcover. The threshold of 0.5 inches SWE represents a snow density of 50% water when compared to the COOP measurements, which approximates an extreme upper limit for the Rocky Mountains of 45% reported by Halfpenny and Ozanne (1989) rounded to the nearest tenth inch. Experiments with alternative thresholds ranging from 0–0.5 inches SWE did not change the relative ranking of stations, but higher thresholds produced shorter estimated snowcover duration for all of the SNOTEL stations in the analysis.
2. To correct for the fact that there are often several isolated snow events in early fall and late spring, snowcover was not deemed to have started until the seventh day of snow cover, consecutive or not, was encountered in the water year. Snowcover was not considered over until the fourteenth consecutive snow free day was encountered. These threshold values were determined by experimentation. Reducing the number of snow days/snow free days on either end of the snow season increased the likelihood that isolated late spring or early fall storms would be included in the estimates of snowcover duration. Without these buffers, all weather stations had snowcover duration estimates very close to an entire water year in length. Increasing the length of these buffers beyond the thresholds chosen did not change the relative ranking of stations, but merely shortened all the estimates of snowcover duration.
3. In the COOP station files, data flagged by the National Climatic Data Center as invalid, having failed internal consistency checks, or having failed area-based consistency checks were treated as missing values (Gleason 2002). If any month had more than seven missing values, the entire water year was excluded from the analysis.

For each water year at each weather station, the first day of snowcover, last day of snowcover, and snowcover duration in days were estimated. Mean snowcover duration was then calculated across years. Snowcover duration estimates for stations with fewer than 4 years of valid data during 1971–2000 were discarded.

Results

Cluster and Maximum Likelihood Classification Analysis

The cluster analysis of 1971–2000 monthly climate normals identified two climate zones, each containing two subzones. The four resulting subzones were designated 1, 1a, 2, and 2a (Fig. 3), all referred to as “zones” hereafter. The list of stations included within each of these zones was the same when the cluster analyses were performed on data matrices containing precipitation, DTR, and Tmean vs. precipitation, Tmax, Tmin. As described in the methods, the minimum size of the station clusters selected as zones was determined by comparing dendrograms produced by Ward’s vs. average clustering. Consequently, station membership within each zone was the same for Ward’s vs. Average clustering, but there were slight differences in the individual pairing of stations within the zones (average clustering dendrograms are not shown). For example, even though the list of stations for zone 1 was the same in Ward’s vs. Average clustering, within this zone the dendrogram for Average clustering placed the Gardiner weather station directly next to the Yellowstone Park station, instead of pairing Tower Falls with Yellowstone Park, as shown in Fig. 3. For this reason, each zone was treated as a polytomous (unstructured) group of weather stations.

Weather stations in zone 1 experienced the majority of their precipitation in May–July, and zone 1a stations had a prominent precipitation peak only in May (Fig. 4). Zones 2 and 2a had the least amount of precipitation during July–October, and zone 2a had a more pronounced dip in average DTR during May than the other zones. The differences among zones were poorly defined for Tmean, Tmax, and Tmin (Fig. 4). Note that the data used in the cluster analyses were standardized, but untransformed values are presented in Fig. 4 for ease of interpretation.

Even though stations in zones 1 and 1a had closely related seasonal patterns (Figs. 3, 4), they were widely separated geographically, in the north and southwest of the GYA respectively (Fig. 2). Stations in zones 2 and 2a segregated roughly east–west, with the exception of the Shower Falls SNOTEL station, which is located in the north, amidst zone 1 stations (map, Fig. 2). When areas with climates most similar to zone 1 stations were mapped, this zone was shown to coincide closely with the “Northern Range” of Yellowstone National Park (Fig. 5, left panels), a lower elevation area often recognized as an ecological unit with distinct vegetation (National Research Council 2002). Despite the clear geographic separation of the weather stations in zones 2 and 2a, when mapped to the broader geographic region these zones had a high degree of overlap, indicated by the darker green areas in Fig. 5, left panels.

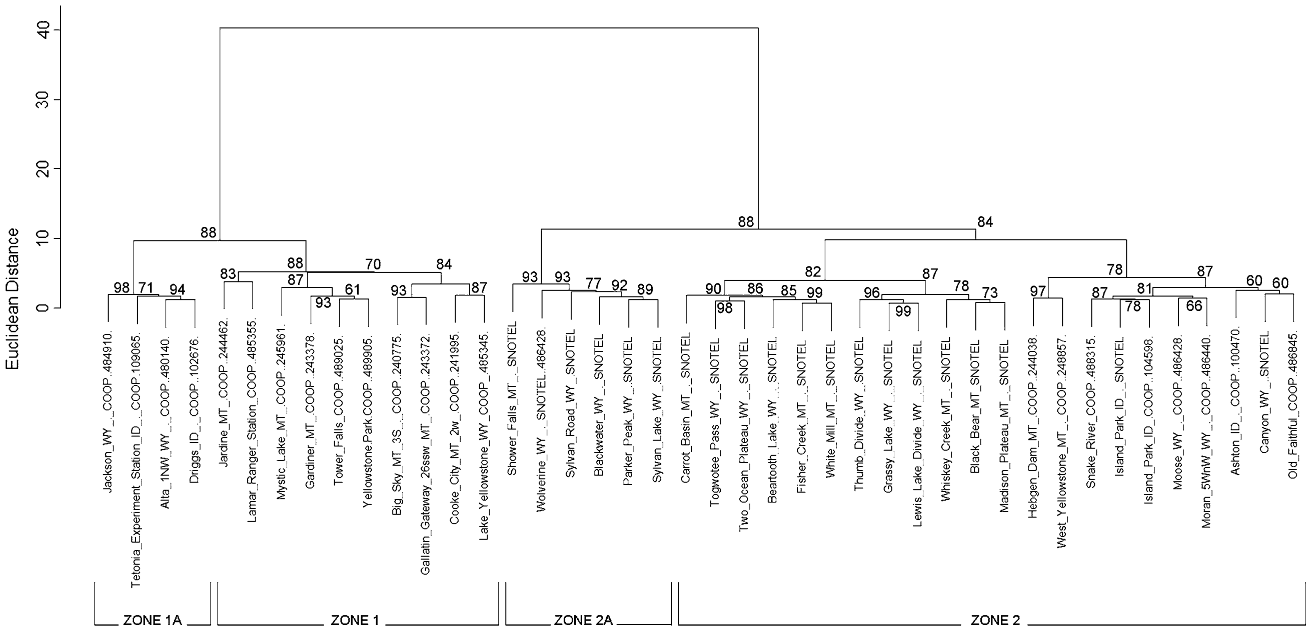


Fig. 3 Ward's cluster analyses of 1971–2000 monthly temperature and precipitation normals for weather stations in and near Yellowstone and Grand Teton National Parks. *Numbers* at *each node* indicate bootstrap confidence. The results shown here were obtained from a data matrix containing precipitation, diurnal temperature range, and mean temperature data. All cluster analyses performed during this study contained the same groups of stations (zones)

The maximum likelihood classification (MLC) of PRISM grids produced estimated zone boundaries that were roughly similar to those from the station-based analyses (Fig. 5), but they also differed in important ways. The orographic effect of the Teton Range appeared clearly in the MLC grid-based analyses as a north-south division that runs the length of Grand Teton National Park. Zone 1 was not as clearly defined in the MLC analyses and did not correspond as closely to the Northern Range of Yellowstone. Of the four climate zone maps (Fig. 5), the MLC of precipitation, Tmax, Tmin was also unique in not delineating an anomalous area around the Lake Yellowstone weather station in central Yellowstone National Park. In the station-based correlation maps (left panels, Fig. 5), this area appeared not to have any clear affiliation with any of the zones, though it did have highest correlation (90–92%) with zone 1.

Principal Components Analysis (PCA)

Four PCAs were performed on monthly data for the period 1895–2008. Precipitation and mean temperature (Tmean) were both analyzed separately for summer (June, July, August) and winter (December, January, February). In all four analyses, the first principal component (PC 1) explained 72–95% of the variance within the dataset, but provided no clear distinctions among weather stations. Within each analysis, the loadings of weather stations on PC 1 were all very similar. For example, winter precipitation, which had the greatest range in loading values on PC 1, had a minimum value of −0.06 and a maximum value of −0.17. Loadings within the other three PCAs differed by no more than 0.03 on PC 1 across all weather stations, and all weather stations loaded with the same sign on PC1 within all four analyses. Following the PCA, scatterplots and time series graphs (not shown) confirmed the loadings on PC1 just described. Most of the variability in 1895–2008 dataset, which was captured by PC1, occurred from month to month instead of among stations. All the weather stations varied similarly over much of the time series. It was only for small time periods that differences in variability were seen among stations. Consequently, this smaller portion of the variance that existed among stations was captured by PCs 2 and 3.

PCs 2 and 3 in all four analyses explained only 1–9% of the variance among months, but they provided interpretable separation among weather stations (Fig. 6). Even though the cluster analysis and the PCAs were based on different datasets and had different goals (i.e., analysis of seasonal variability for cluster analysis and long-term variability for PCAs), there was some agreement between the two analyses. Weather stations classified as zone 1 by the cluster analysis (red text in Fig. 6) often loaded in the opposite direction from weather stations classified as zone 2 by the cluster analysis (black text in Fig. 6) on PC2. Zone 1a weather stations (blue text in Fig. 6) often loaded similarly to zone 2 weather stations (Fig. 6), a pattern that stands in contrast to their closer association with zone 1 weather stations in the cluster analysis (Fig. 3). Stations classified

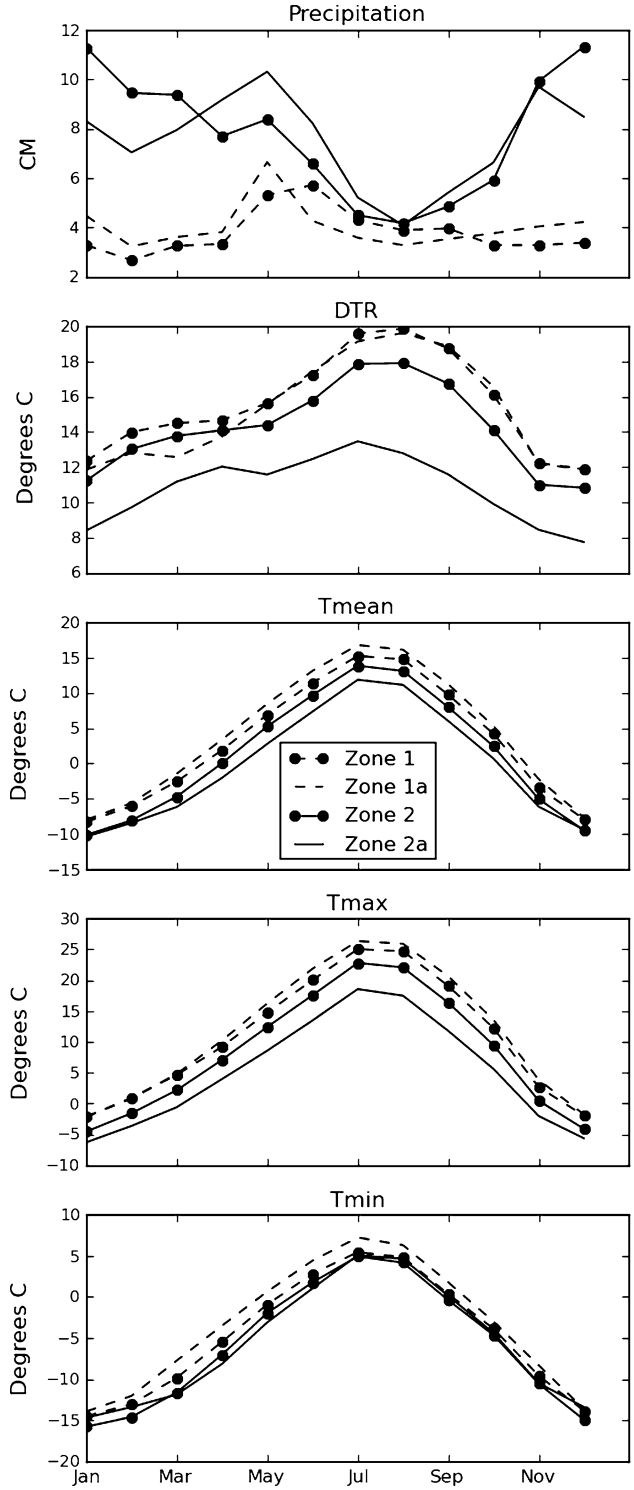


Fig. 4 Average monthly precipitation, diurnal temperature range, mean temperature, average maximum temperature, and average minimum temperature for weather stations in climate zones defined by cluster analysis (Fig. 1). Values were calculated as the mean of 1971–2000 monthly normals for all stations in each zone. The data used in the cluster analysis were standardized as *z* scores, but untransformed values are shown here for ease of interpretation

as zone 2a by the cluster analysis (green text) loaded with zone 1 weather stations during the summer months and with zone 2 weather stations during the winter (Fig. 6).

There were significant differences between the results of the cluster analysis and the PCA. The Fisher Creek, White Mill, Beartooth Lake, Canyon, and Carrot Basin stations were classified as zone 2 by cluster analysis (Fig. 3) but loaded more closely with zone 1 in some or all of the PCAs. The Shower Falls SNOTEL station loaded with zone 1 stations (Fig. 6), but the cluster analysis classified this station as zone 2a (Fig. 3).

PCAs performed on weather station data, rather than PRISM extracted values for each station, for the period 1968–2008 (which is the longest time period common to all stations) showed substantially the same patterns shown here.

Ranking of Weather Stations Based on Snow Cover

The snowcover duration, defined as the number of days per year with consistent snowcover, showed a strong linear relationship to weather station elevation (Fig. 7, linear regression for all stations $R^2 = 0.607$, $P < 0.001$). Though not as strong, relationships between elevation and the first day of snowcover ($R^2 = 0.368$, $P < 0.001$) and the last day of snowcover ($R^2 = 0.554, P < 0.001$) were also significant.

Discussion

The Greater Yellowstone Area Test Case

Given that the climate zonation methods evaluated here will likely be the basis for a wide variety of scientific research and resource management decisions throughout western US national parks and beyond, it is critical that we understand their suitability and potential limitations. In addition to the results presented here for Yellowstone and Grand Teton National Parks, the NPS has already adopted these climate zonation methods for Glacier, Rocky Mountain, and Great Sand Dunes National Parks, along with 4 other smaller park units (Frakes and others 2009; Tercek 2010). Similar efforts are likely to be a part of the emerging US Department of Interior's Landscape Conservation Cooperative and Climate Science Center programs (U.S. Fish and Wildlife Service 2010).

Generally speaking, the results show that the NPS climate zonation techniques are robust across the complex terrain of the GYA, and that they likely provide valuable information related to the spatial characteristics of regional climates. The results of the cluster analysis were not changed by different algorithms (Ward's vs. Average Clustering) or by changes in data inputs (use of DTR and

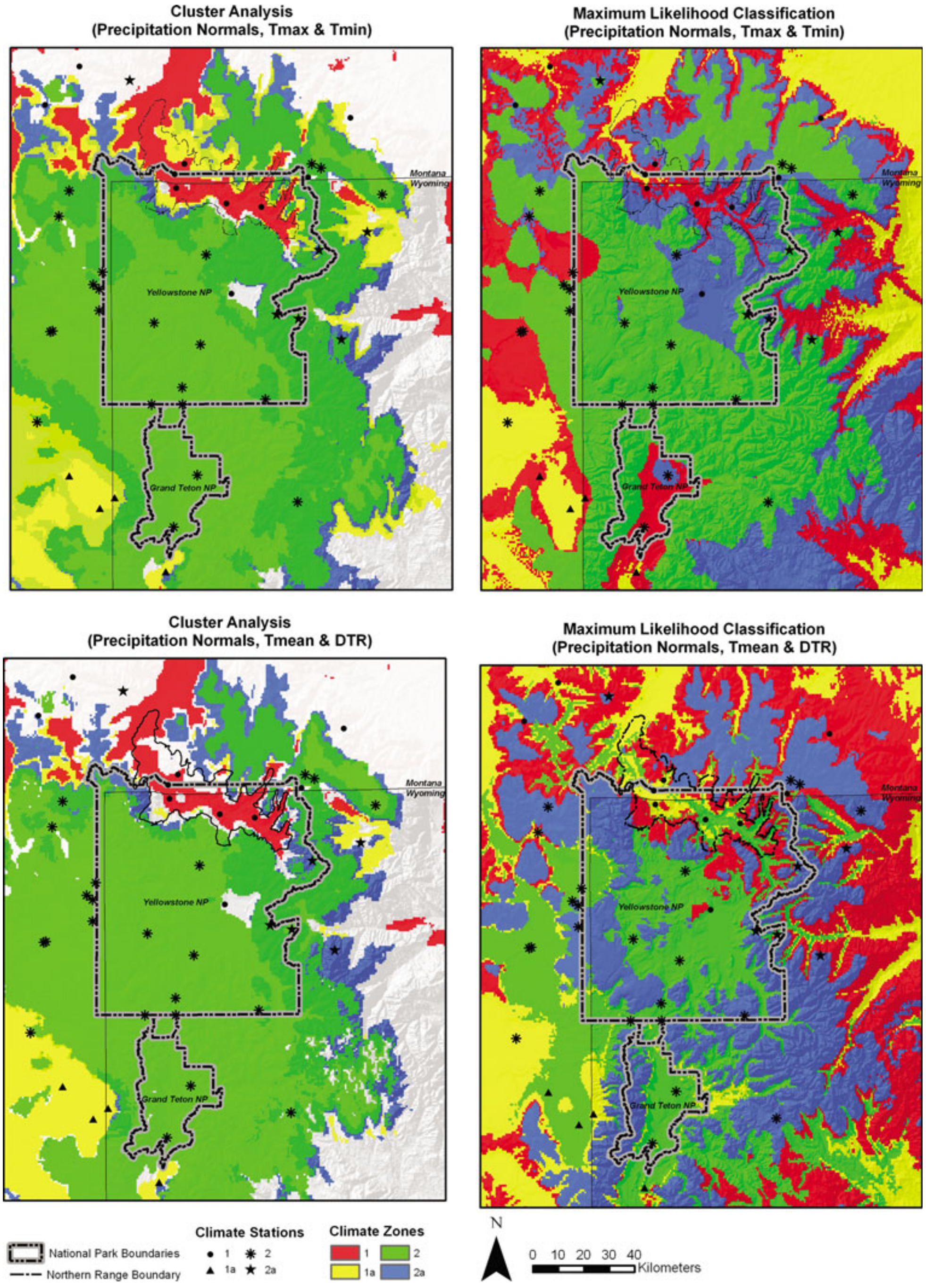


Fig. 5 Maps showing the location of weather stations classified by cluster analysis (Fig. 1) and estimated climate zone boundaries. *Left*: zone boundaries are calculated as the geographic areas that have ≥0.93 correlation with weather stations in each cluster-based zone. Zone boundaries are semi-transparent to illustrate the degree of overlap. For example, *darker green areas* show overlap between zones 2 and 2a, while *lighter green areas* represent zone 2a alone. *White areas* have <0.93 correlation with weather stations in all climate zones. *Right*: zone boundaries are calculated using maximum-likelihood classification of PRISM grid cells. National park boundaries indicated on the map encompass both Yellowstone NP in the north and Grand Teton NP in the south. There is no overlap of zones produced by the maximum-likelihood classification in the *right*. The northern range is a recognized ecological unit that corresponds well with zone 1 in the *left*

Tmean rather than Tmax and Tmin). Furthermore, the proposed zones are in line with previous analyses of regional climate variability in the GYA (described below), and zones generally match classifications based on ecological parameters.

The four groups of weather stations defined by cluster analysis formed geographically coherent zones, and they generally agreed with previous climatological studies conducted in the GYA. Weather stations in zones 1 and 1a had similar seasonal patterns (monthly normals), despite being located at opposite ends of the study area (Figs. 2–4), while stations in zones 2 and 2a were divided into roughly eastern and western groupings (Figs. 2–4). Zone 1 weather stations were located in or near the northern range of Yellowstone National Park (Fig. 5), which is a recognized ecological unit containing distinct vegetation, as well as being the winter home of Yellowstone's northern elk herd (National Research Council 2002). In addition, zone 1, which experiences the greatest portion of its annual precipitation during the summer (Fig. 4), roughly corresponds

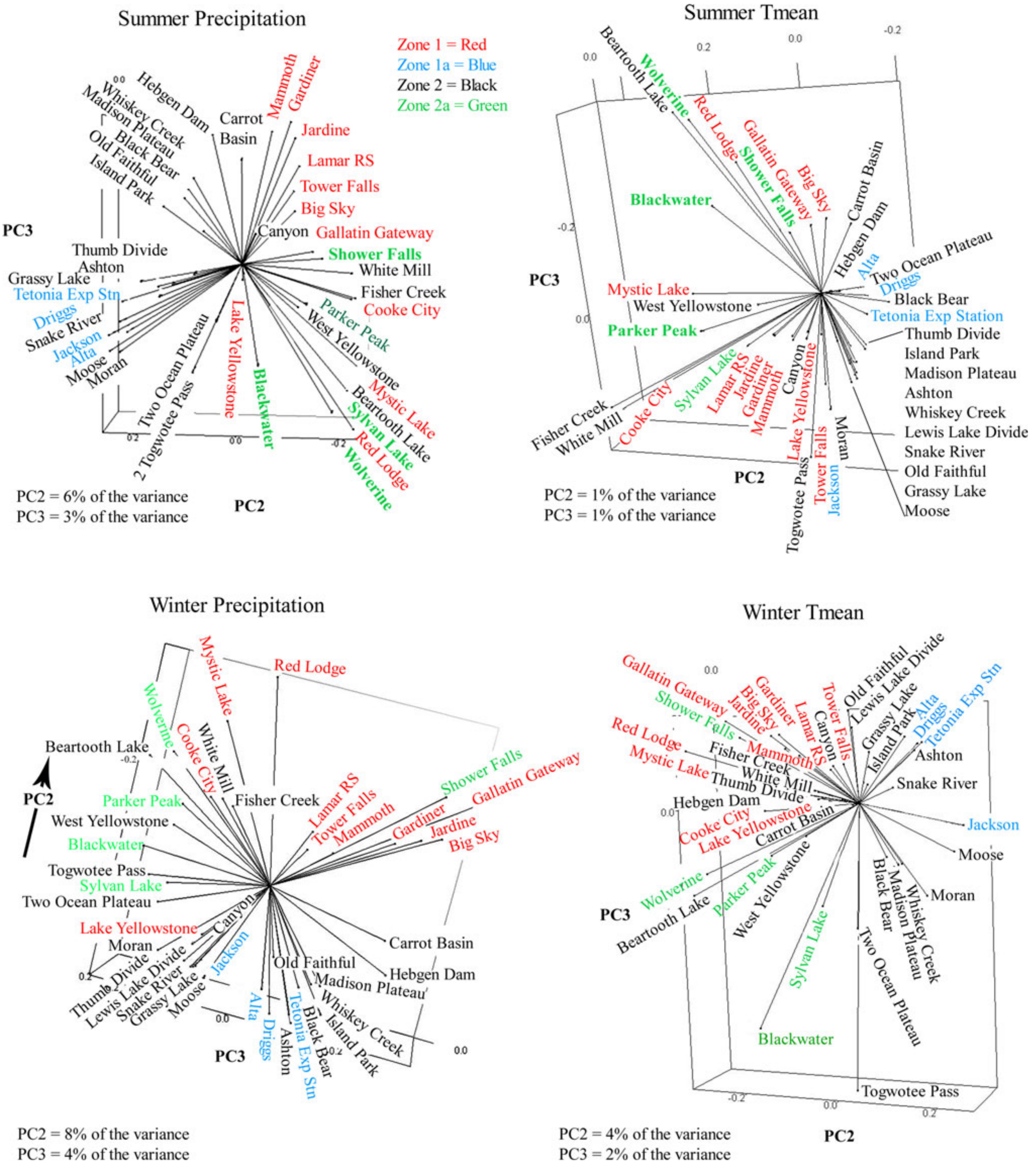
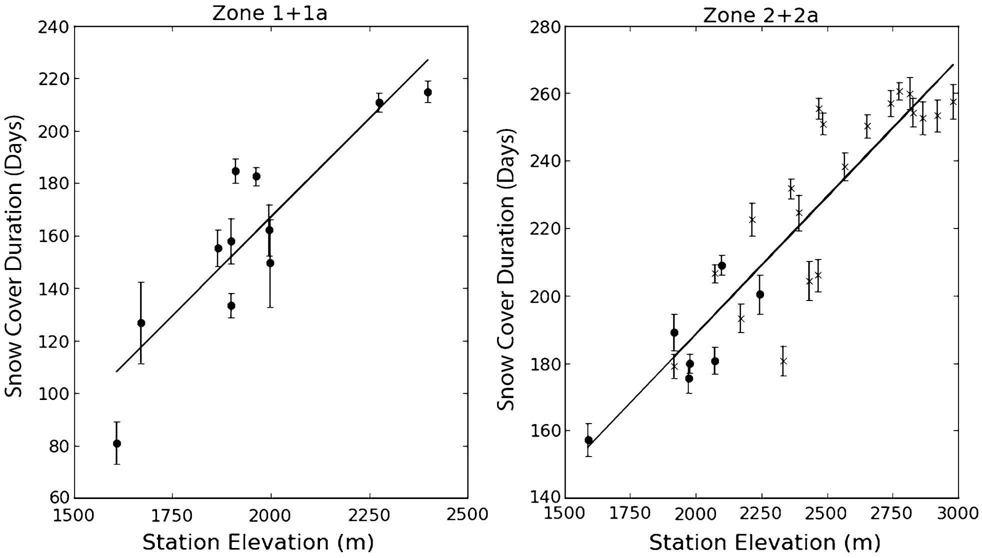


Fig. 6 Loading plots for S-mode principal components analysis of 1895–2008 monthly precipitation and mean temperature. The original time series were divided into summer (June, July, August) and winter (December, January, February). *Text color* for each weather station indicates the zone assigned to each weather station by cluster analysis (Fig. 1)

to the northern "summer wet" zone described by Whitlock and Bartlein (1993) and Huerta and others (2009). Similarly, the "winter wet" zone described by those authors approximates the combination of zones 2 and 2a presented here. The east–west segregation of our zones 2 and 2a is reminiscent of the two climate zones described by Despain (1987), but the boundaries of these zones do not correspond to the continental divide, as suggested by that author.

Fig. 7 The relationship between weather station elevation and mean snowcover duration. *Circles* represent COOP stations. *X*'s represent SNOTEL stations. *Bars* indicate one standard error. *Lines* were fitted with linear regression



Since weather stations represent only discrete points on the landscape, we used two different techniques to estimate the geographic areas represented by the weather stations in the climate zones defined by cluster analysis (Fig. 5). Because cluster analysis formally defined climate zones in terms of *weather stations*, it was possible for the *geographic areas* represented by two groups of stations to have a degree of overlap. This occurred in central and eastern Yellowstone, where some areas had seasonal patterns that correlated strongly with weather stations in both zones 2 and 2a (Fig. 5). Even though weather stations in zones 2 and 2a were distinct enough to group separately in the cluster analysis (Fig. 3), their seasonal patterns did not differ as much from each other as they did from the patterns in the other two zones (Fig. 4). The similarity between zones 2 and 2a was also confirmed by the MLC mapping analysis. If the constraint of 4 zones was removed, zones 2 and 2a were merged, leaving only 3 zones (not shown). Were it not for the fact that zone 2a weather stations exhibited a seasonal switching of allegiance between north and south in the PCAs (described below), we might have merged the stations in zones 2 and 2a. However, the fact that zone 2a stations both clustered separately and exhibited unique behavior in the PCAs justified their retention as separate zones.

The grid-based maximum likelihood (ML) analysis' depiction of climate zone boundaries may be superior to correlation-based mapping methods because it did not produce any overlaps. By classifying each map cell individually rather than with respect to their correlation with point based stations, the ML produced a markedly more heterogeneous depiction of climate zone boundaries, particularly along the axis of the Teton Range and in the lower elevations of Yellowstone's northern range (Fig. 5). It is important to realize that the maps shown in Fig. 5 are merely illustrative estimates of the climate zone boundaries and that different boundaries can be produced by alternative statistical techniques. Moreover, the maps in Fig. 5 present boundary estimates that are based on seasonal patterns alone. They do not include information from the 1895–2008 dataset, which was analyzed using PCA.

Unlike the cluster analysis, which grouped weather stations according to similarity of seasonal patterns in average monthly temperature and precipitation, our Principal Components Analysis (PCA) used a data matrix that contained temperature and precipitation values for every month during the period 1895–2008. These tests grouped weather stations according to patterns of variability that span years and decades. Though the results of the PCA and cluster analyses agree to some extent, there were important differences. For example, PCA (Fig. 6) grouped stations that cluster analysis (Fig. 3) classified as zone 1a with the geographically nearby (Figs. 2, 5) zone 2 weather stations, instead of the more distant zone 1 stations. Weather stations classified as zone 2a by the cluster analysis showed mixed allegiance in the PCA, having loadings similar to stations classified as zone 1 by the cluster analysis in the summer and to stations classified as zone 2 by the cluster analysis in the winter (Fig. 6). This suggests that high elevation sites in eastern Yellowstone exhibit long-term (year to year) patterns of variability that are similar to the northern range of Yellowstone in the summer months (June, July, August) and the southern parts of Yellowstone in winter (December, January, February).

Several benchmark weather stations and stations of significant regional interest (*sensu* Gray 2008) were classified differently depending on whether seasonal pattern (cluster analysis) or long-term variability (PCA) was considered. This should serve as caution to anyone seeking to choose stations that are representative of each climate zone. For example, the Fisher Creek, White Mill, and Beartooth Lake stations classified as zone 2 in the cluster analysis but plotted closer to zone 1 in the PCAs (Figs. 3, 6). The Canyon, Carrot Basin, West Yellowstone, and Hebgen Dam weather stations had the opposite pattern, grouping with zone 2 in the cluster analysis but associating with zone 1 stations in some or all of the PCAs. When aggregating data from these stations into zones for ecological analysis, workers should be careful to distinguish between applications that require similar seasonal patterns vs. similar patterns of long-term variability. If long-term variability is needed for, e.g., analyzing the linkages between climatic patterns and the demography of sensitive species, then the results of the PCAs (Fig. 6) are likely more appropriate than either the cluster analysis or the classification map boundaries shown in Fig. 5.

The climate zones defined here do not contain the same proportion of COOP vs. SNOTEL stations. Zones 1 and 1a contain only COOP stations, zone 2 contains more than half SNOTEL stations, and zone 2a contains only SNOTEL stations (Fig. 7; Table 1). Though this may in part be due to differences in instrumentation among these data collection platforms, we suggest that station siting plays a strong role as well. SNOTEL stations are consistently sited at higher elevations (Fig. 7; Table 1), and some parts of the GYA, such as zone 2a, contain nothing but SNOTELs. Furthermore, since the weather stations in our analyses show geographic coherence rather than a scattered pattern associated solely with station type (Fig. 5), it is quite likely that our zones reflect regional climate processes rather than data collection or network-related artifacts.

The National Park Service Inventory and Monitoring program has recently expressed interest in adding additional climate stations within our study area. We anticipate that any future changes in weather station density may necessitate reevaluation of these climate zonation techniques. The addition of new stations would not only improve the fine-scale resolution of our climate zones, but it would clarify the classification of geographic areas that currently have relatively low correlation to surrounding weather stations, such as the region near Lake Yellowstone (white region in left panels, Fig. 5). Likewise the loss of stations might limit the use of these zones in NPS applications. We also recognize that our zones merely summarize present conditions. Climatic boundaries in the Greater Yellowstone Area have changed in the past (Whitlock and Bartlein 1993), and future changes may be both rapid and dramatic (Bartlein and others 1997; Williams and others 2007).

Caveats for the Use of the Climate Zones Presented Here in Natural Resource Management

The maps depicting estimated climate zone boundaries (Fig. 5) are the least robust of all the analyses presented in this study, and they should be used with caution. Even though the station-based cluster analyses (Fig. 3) were robust to changes in algorithm and variable inputs, different methods of zone extrapolation from weather station data (maximum likelihood and correlation) produced different climate zone boundaries, and the grid-based maximum likelihood methods created maps containing complex spatial patterns that, in a practical sense, might be extremely difficult to apply as part of ecological monitoring or management efforts. It is also important to bear in mind that these maps (Fig. 5) contain only information from the cluster analyses of seasonal data. They do not reflect patterns found in the long-term datasets, which were analyzed by PCA (Fig. 6). For this reason, ecological studies that employ the climate zones presented here would benefit from a focus on the classification of weather stations (Figs. 3, 6; Table 1) rather than the maps depicting geographic areas associated with each zone (Fig. 5), and if the application of zones described in this study is for the analysis of long-term trends, workers should use only the results of the PCAs (Fig. 6) rather than the cluster analysis and associated zone maps in Fig. 5.

The results of our PCAs suggest that weather stations in the Greater Yellowstone Area (GYA) had broadly similar patterns of variability during 1895–2008. Loadings for all stations were very similar on the first principal component of all four PCAs, and significant differences among stations were found only on the second and third principal components, which represented only 1–9% of the variance. Though this portion of the variance is small, the fact that the results of the PCA agree in general terms with both the cluster analysis (see in particular the color-coded text in Fig. 6) and with climate studies based on ecological indicators (e.g., Whitlock and Bartlein 1993) suggests that the loading patterns on PCs 2 and 3 are indicative of real climatological patterns rather than noise. Future application of these PCA methods to larger geographic areas may reveal stronger differences among weather stations. In the meantime, workers that apply the results presented here to ecological studies should be mindful that long-term (1895–2008) patterns differ to a relatively small degree among weather stations in the GYA.

The estimates of snowcover duration in Table 1 are useful to the extent that they provide a list of weather stations arranged in order from short to long, and groups of stations with similar snowcover duration might be used to create smaller divisions within the zones defined by other methods. However, it is important to note that the average number of snowcover days calculated for a weather station (Table 1) is dependent on our specialized definition of when snowcover begins and ends. In order to account for the fact that most weather stations have isolated snow storms throughout the year we defined the start of

Table 1 Snowcover duration, as determined by the mean number of days per year with snow cover during 1971–2000, at weather stations in and near Yellowstone and Grand Teton National Parks

Station name	Snow cover (days)	*N*	Elevation (m)	Station type
Climate zones 1 and 1a				
Gardiner	81	4	1,608	COOP
Gallatin Gateway 10SSW	126.86	7	1,670	COOP
Jackson	133.42	12	1,899	COOP
Lamar Ranger Station	N/A	2	1,998	COOP
Driggs	155.25	4	1,865	COOP
Tetonia Exp. Station	N/A	0	1,881	COOP
Yellowstone Pk. (Mammoth)	158	18	1,899	COOP
Jardine	N/A	0	1,966	COOP
Mystic Lake	162.07	28	1,995	COOP
Alta 1nw	182.63	27	1,962	COOP
Tower Falls	184.64	14	1,910	COOP
Big Sky 3s	N/A	0	2,012	COOP
Cooke City 2w	210.81	16	2,274	COOP
Lake Yellowstone	214.89	19	2,399	COOP
Climate zones 2 and 2a				
Ashton	157.16	19	1,589	COOP
Moose	175.55	20	1,972	COOP
Island Park	179.16	15	1,917	COOP
Hebgen Dam	179.88	24	1,978	COOP
Wolverine	180.71	21	2,332	SNOTEL
Moran 5WNW	180.75	20	2,072	COOP
Island Park	189.2	19	1,917	SNOTEL
West Yellowstone	N/A	0	2,030	COOP
Sylvan Road	193.36	14	2,170	SNOTEL
Old Faithful	200.36	14	2,243	COOP
Thumb Divide	204.43	14	2,432	SNOTEL
Canyon	206.05	21	2,466	SNOTEL
Whiskey Creek	206.53	30	2,073	SNOTEL
Snake River	209.04	24	2,098	COOP
Grassy Lake	222.57	21	2,214	SNOTEL
Lewis Lake Divide	224.57	21	2,393	SNOTEL
Madison Plateau	231.74	30	2,362	SNOTEL
Sylvan Lake	238.29	21	2,566	SNOTEL
White Mill	250.25	28	2,652	SNOTEL
Black Bear	250.97	30	2,484	SNOTEL
Parker Peak	252.75	20	2,865	SNOTEL
Togwotee Pass	253.33	21	2,920	SNOTEL
Beartooth Lake	254.29	21	2,827	SNOTEL
Shower Falls	255.48	30	2,469	SNOTEL
Carrot Basin	257.03	30	2,743	SNOTEL
Blackwater	257.55	20	2,981	SNOTEL
Two Ocean Plateau	259.95	21	2,816	SNOTEL
Fisher Creek	260.61	30	2,774	SNOTEL

N number of years used to obtain the estimate. N/A indicates that there were insufficient data for an accurate estimate. Climate zone designations are taken from the cluster analysis of seasonal data (Fig. 3)

snowcover as the seventh snow event of the water year and the end of snowcover as the date at which 14 consecutive snow free days had been recorded. Without these 7/14 day buffers on either end of the snow season, virtually every weather station had snow season that lasted for the entire water year. When we increased the length of these buffers and re-ran our analysis, the rank order of stations did not change, but the estimated snowcover duration for each station did change. Our results provide a ranking of snowcover that correlates well with station elevation (Fig. 7), but length of snowcover during any given year at a particular weather station may differ from the values presented in Table 1 by several weeks.

Overall this study suggests that the proposed climate zonation techniques be viewed as one tool among many for guiding decisions related to the monitoring and management of natural resources. They should not be used as a sole source of information to guide resource monitoring and management decisions. For example, NPS researchers might integrate information on climate zones with knowledge of critical elk habitat when selecting locations to study climate change impacts on migration corridors. That said, when carefully applied, climate zones may provide an initial foundation for monitoring, analysis and reporting of climate variability and change. Moreover, such zonation exercises could prove to be extremely valuable for identifying gaps in legacy monitoring networks and as one source of guidance for informing further development of weather, climate and hydrologic monitoring programs.

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