Climate Zonation Analysis for Glacier National Park, Rocky Mountain National Park, Great Sand Dunes National Park, Little Bighorn Battlefield National Monument, Grant-Kohrs Ranch National Historic Site, and Florissant Fossil Beds National Monument

Submitted to the National Park Service's Rocky Mountain Network, a division of the Inventory and Monitoring Program

By

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EXECUTIVE SUMMARY

The Rocky Mountain Network (ROMN), which is a division of the National Park Service (NPS) Inventory and Monitoring (I&M) Program, seeks to understand climate status, variability, and trends in its six park units (Glacier National Park, Rocky Mountain National Park, Great Sand Dunes National Park, Little Bighorn Battlefield National Monument, Grant-Kohrs Ranch National Historic Site, and Florissant Fossil Beds National Monument). Averaging weather observations across an entire park would be of little value because it would obscure much of the spatial (place to place) variability among regions. The analysis presented here defines climate zones with consistent seasonal and temporal dynamics. These zones will be treated as reporting units in annual climate status reports. Three statistical techniques were used: (1) Cluster analysis of seasonal weather station data (temperature and precipitation), (2) Principal Components Analysis of long-term monthly variability in temperature and precipitation, and (3) Analysis of snow cover timing to define elevation-based stratification of stations. The zones defined for the larger parks (Glacier, Rocky Mountain, and Great Sand Dunes National Parks) have clear differences in seasonal pattern and long-term variability. Zones defined for the smaller parks (Grant-Kohrs, Little Bighorn Battlefield, and Florissant Fossil Beds) have less practical value. The statistical methods used in this report will always provide dichotomous distinctions, but judgment must be used to determine whether the differences among zones thus defined are climatically meaningful.

INTRODUCTION

The Rocky Mountain Network (ROMN), which is a division of the National Park Service (NPS) Inventory and Monitoring (I&M) Program, seeks to understand climate status, variability, and trends in its six park units (Frakes et al. 2009, Kittell et al. 2010). Climate is a key driver of variability in the other ecological "vital signs" that are monitored by the network (Frakes et al. 2009), and human industrial activity is very likely to cause rapid climate changes in the next century (Solomon et al. 2007). In this context, the goals of the ROMN I&M program are (1) to evaluate variability and trends in key climate parameters and (2) to provide climate data that will contribute to analysis of changes in other ecological vital signs (Frakes et al. 2009).

In topographically complex areas, averaging weather observations across an entire park would be of little value because it would obscure much of the spatial (place to place) variability among regions (Gray 2008). Furthermore, there are likely to be differing temporal (year to year) changes observed among groups of weather stations, and when these changes are in conflict they should be reported separately (Gray 2008). The goal of this report is to define groups of weather stations in and near ROMN park units that have (1) similar average seasonal (month to month) patterns of temperature and precipitation, and (2) similar long-term patterns of variability over the period 1895-2008. An additional analysis of snow cover timing is used in this report to determine whether there is stratification among weather stations according to elevation. Methods used in this report were developed in response to guidelines described in Frakes et al. (2009) and Kittell et al. (2010). They are also being used to define zones in Yellowstone and Grand Teton National Parks (Tercek et al. In review).

The groups of weather stations defined here will function as climate zones that will be used as reporting units in annual climate status reports and in periodic climate trend reports produced by ROMN. This report presents climate zones for Glacier National Park, Rocky Mountain National Park, Great Sand Dunes National Park, Little Bighorn Battlefield National Monument, Grant-Kohrs Ranch National Historic Site, and Florissant Fossil Beds National Monument.

METHODS

Weather Station Selection

Weather stations in and near the ROMN park units were identified by Davey et al. (2006). The analyses in this report include all weather stations within 40 km of ROMN park units that are operated by the National Weather Service Cooperative Observer Program (COOP) and by the Natural Resources Conservation Service SNOTEL network. In a few instances, frequently cited stations located more than 40km from park boundaries were added. Weather stations maintained by other agencies were not included either because they report observations for only a portion of each year, have data that are not commensurate with each other, or have been in operation for a time period that is not sufficient to establish long-term averages (Davey et al. 2006). Station names appear in the figures, see Results.

Cluster Analysis of 1971 – 2000 monthly normals.

Monthly average maximum temperature (Tmax), monthly average minimum temperature (Tmin) and precipitation data were downloaded for the period 1971 – 2000 from the websites of 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/). For each weather station, Diurnal Temperature Range (DTR) and mean temperature (Tmean) were calculated for each month from Tmax and Tmin. Tmax and Tmin often vary at different rates, making them both important to the analysis, but DTR and Tmean were used because they usually show lower correlation with each other, which gives greater power to cluster analysis (Easterling et al. 1997, Vose et al. 2005, Kittell et al. 2010).

For COOP stations, NCDC monthly 1971 – 2000 averages ("normals") were incorporated into the analyses directly from the WRCC web site. In contrast, only precipitation data from the NRCS web site were used. This was done because SNOTEL stations often have poor quality temperature data or missing values that make it impossible to calculate accurate 1971-2000 normals (Kittell et al. 2010). In order to replace the missing temperature data, Tmax and Tmin 1971 – 2000 normals were extracted from the 800m PRISM grid cell occupied by each SNOTEL station. PRISM data do not have the same problems as individual SNOTEL temperature data because the values for each grid cell are interpolated from a network of surrounding stations (Daly et al. 1994, 2001).

Since the goal of the cluster analysis was to group weather stations according to their similarity in seasonal patterns, regardless of the absolute magnitude of the observations or differences among stations in the amount of seasonal variance (Frakes et al. 2009), the data were standardized as z-scores. For each weather station separately, the annual averages for precipitation, DTR, and Tmean were subtracted from their respective monthly values and the results were divided by the annual standard deviations for each variable. Without this transformation, weather stations with large annual variances might dominate the analysis. For example, higher elevation stations might cluster together regardless of their geographic location or whether they have the greatest portion of their precipitation during the same months. The final data matrix had 36 values for each weather station: 12 monthly standardized values each for precipitation, DTR, and Tmean.

Hierarchical Agglomerative Cluster Analysis was performed following the methods of Fovell and Fovell (1993) and Unal et al. (2003). Euclidean distance was the distance metric.

Determining the number of climate zones for each park unit

Three criteria were used to determine the number of climate zones for a park unit:

1. Both Ward's and Average clustering algorithms were used and the results were compared (Unal et al. 2003). If a cluster of weather stations appeared unchanged in dendrograms produced by both algorithms, it was retained. If a cluster contained different weather stations in Ward's vs. Average clustering, it was treated as a polytomy (unstructured group) and a larger cluster of stations 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 membership in both Ward's and Average dendrograms were found. This procedure defined the minimum size of the station clusters that were used as zones.
2. Confidence levels were assigned to each cluster of stations with bootstrapping (Suzuki and Shimodaira 2006). Ten thousand pseudo-replicates of the data set were produced and the nodes in the final dendrogram were labeled with the percentage of pseudo-replicate dendrograms that contained each cluster. Clusters with less than 80% bootstrap support were joined with neighboring clusters.
3. The results for each park unit were inspected for groups of stations that both appeared together in the cluster analysis and varied similarly (loaded on the same PCs) in the Principal Components Analysis. If such groups were found, they were defined as climate zones even if they did not meet the second criterion.

The cluster analysis was performed with the R scripting language (R development core team 2009).

Principal Components Analysis of 1895 – 2008 monthly temperature and precipitation

Data for the Principal Components Analysis (PCA) were extracted from 1895-2008 monthly, 800m resolution, gridded data produced by the PRISM climate group (Daly et al. 2000, http://www.prism.oregonstate.edu/). 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 from Tmax and Tmin. 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.

PRISM data have two advantages over raw weather station data. First, since PRISM data for each grid cell are interpolated by using a network of surrounding stations it is possible to extract time series that extend further back in time than the individual weather stations themselves. Second, PRISM data have been quality checked. As a result, they are less prone to biases such as urban heat island effects, station moves, instrument changes, and incompleteness of record that make long-term analyses of raw weather station data difficult (Daly et al. 2000, 2001).

S-mode PCA was performed using methods adapted from Serrano et al. (1999) and Comrie and Glenn (1998). The data matrix had weather stations occupying the columns and months for a single variable, e.g. precipitation, in the rows. A standard PCA scatter plot of this data would show the separation of months along the first two principal components (PCs), so differences among weather stations instead were interpreted from the loadings. The data were natural-log transformed, scaled (performed on the correlation rather than the covariance matrix), and detrended with linear regression prior to analysis. Varimax rotation was used to prevent the shape of the geographic area being analyzed from affecting the results (Buell 1975, Serrano et al. 1999). Scree plots were examined to determine how many principal components to retain. For every PCA in this analysis, loadings were very similar on the first principal component (PC), usually differing by no more than .05 across all weather stations. Clear distinctions among stations were found on PCs 2 and 3, which typically explained 1 – 15% of the variance.

The data were preprocessed with a script written in Python (www.python.org), and the PCA was performed with the R scripting language (R development core team 2009).

Raster mapping to determine the geographic area with high correlation to weather stations in each zone.

A correlation map was created as an estimate of the geographical area represented by the weather stations in each climate zone. The monthly normals from the cluster analysis data set were averaged across all the weather stations in each newly defined climate zone, to produce 36 monthly values (12 months each for DTR, Tmean, and precipitation). Pearson's correlation coefficients were then calculated between the 36 monthly zone averages and the 36 corresponding values associated with each 800m grid cell in the PRISM 1971 – 2000 monthly normal data set. The correlation values for each climate zone were converted into graphical raster files and a mapped. Grid cells were either colored or not, depending on whether they had correlation values above a threshold value for each zone. Cells with correlations falling below a specific threshold for all climate zones were left uncolored. For each park unit, several alternative maps were produced with greater or smaller correlation thresholds. A final correlation threshold was chosen based on its ability to provide minimal geographic overlap among zones. Lower correlation thresholds created geographically larger zones and greater overlap. Higher correlation thresholds produced isolated climate zones with large intervening white, unclassified areas.

The use of different thresholds for each park unit is justified because the correlation maps are merely a technique for illustrating the *approximate* geographic area associated with each group of weather stations. In other words, the climate zones are formally defined by weather station data, and they consist of groups of weather stations. The correlation maps, in contrast, are merely illustrations. In topographically complex areas like the Rocky Mountains, different statistical techniques can produce maps with differing climate zone boundaries (Tercek et al. In Review).

Analysis of snow cover timing to determine elevation-based strata within climate zones

Snow cover timing was used to estimate the stratification of the weather stations according to elevation. For each weather station, 1971 – 2000 daily snow cover data were downloaded from the NCDC and NRCS web sites (cited above). COOP stations report snow depth only, so the number of days with snow cover greater than zero was used as an estimate of winter length at these sites. SNOTEL stations likewise report snow depth, but snow water equivalent (SWE), a second parameter available from these sites, is often a more accurate indicator of local snow cover. As a result, days with measurable SWE were counted towards winter length at these SNOTEL stations. Station data files were organized according to water year, which runs from October 1st – September 30th of the following year, and analyzed by a script written in Python (www.python.org). The script determined the start and end dates of the winter season with 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 snow cover.
2. To correct for the fact that there are often several isolated snow events in early fall and late spring, winter was not deemed as "started" until the seventh day of snow cover was encountered in the water year. Similarly, winter was not over until the fourteenth consecutive snow free day was encountered.
3. In the COOP station files, data flagged with "2" (invalid data element), "T" (failed internal consistency check), and "U" (failed area consistency check) were replaced with missing values. If any month had more than seven missing values after this replacement, the entire water year was excluded from the analysis.

For each year at each weather station, the first day of winter, last day of winter and length of winter in days were estimated. Mean winter length was then calculated across years. Estimates from stations with fewer than six years of valid data were discarded. In order to assign elevation-based strata to the zones, groups of homogenous mean winter lengths were found with Ryan-Einot-Gabriel-Welsch posthoc tests (Hsu 1996).

RESULTS AND DISCUSSION

Glacier National Park

The cluster analysis of 1971 – 2000 monthly normals defined two climate zones, each containing two subzones. Bootstrap support for all clusters was strong, ranging from 78 to 99% (Fig. 1).

Figure 1. Ward's cluster analysis for weather stations in and near Glacier National Park. Numbers near each node indicate bootstrap confidence, based on 10,000 pseudoreplicates. Dotted lines delineate clusters that have greater than 90% bootstrap support. Climate zones, which were selected according to criteria described in the methods, are labeled on the bottom. The dendrogram based on average clustering contained the same four zones.

A comparison of average precipitation, Diurnal Temperature Range (DTR), and mean temperature (Tmean) values shows that Zones 1a and 1b differed from Zones 2a and 2b primarily because they had a relatively greater proportion of their precipitation in November – January (Fig. 2). Because the data in the cluster analysis were standardized, the station groupings in Fig. 1 were based only on month-to-month variability and not the absolute magnitude of the observations. For example, the fact that Zone 1b had greater precipitation than the others did not affect the analysis (Fig. 2). The cluster analysis was based on standardized (z-score) values, but the data in Fig. 2 are in their original units for ease of interpretation.

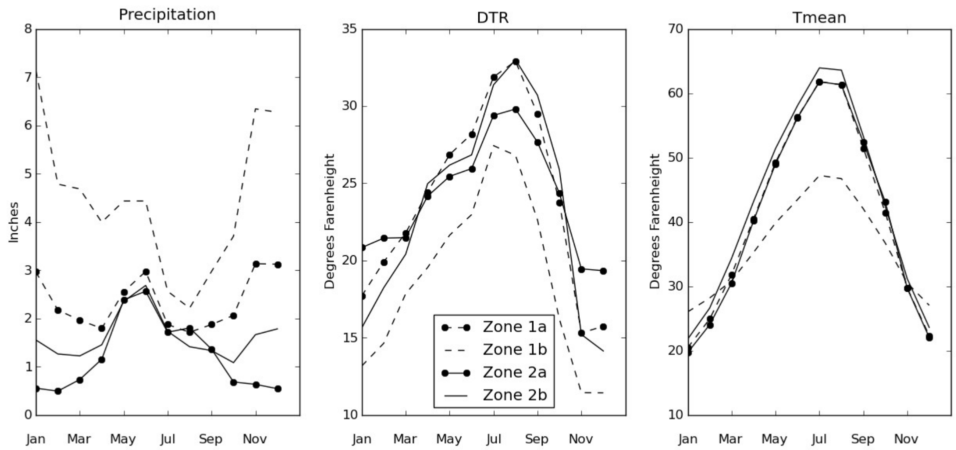

Figure 2. Monthly mean precipitation, diurnal temperature range (DTR), and mean temperature (Tmean) for each climate zone. Means were calculated from 1971-2000 normals from all weather stations in each zone.

All four zones shared similar Tmean and DTR seasonal patterns, but Zone 1b is distinguished by lower amplitude fluctuation in Tmean (Fig. 2). In general, Zone 1 weather stations are located in and near Glacier NP, while Zone 2a and 2b stations are more distant, east and west of the park respectively (map, Fig. 3).

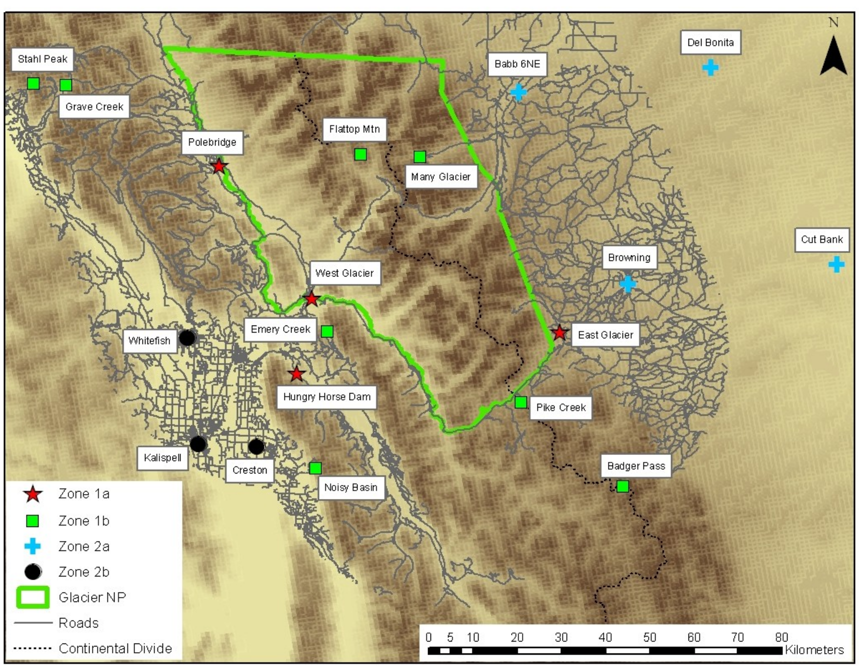

Figure 3. Map showing the locations of the weather stations included in the cluster analysis (Fig. 1). Background shading indicates topographic relief.

The Principal Components Analysis (PCA) of 1895 – 2008 monthly precipitation and Tmean showed a slightly different structure than the cluster analysis. Loadings for all stations were very similar on principal component 1 (PC1) in all four PCAs. For example, loadings on Principal Component 1 (PC1) for the summer precipitation PCA ranged from -.218 to -.247 across all stations. In contrast, loadings on PCs 2 and 3, which explained 1 – 8.4% of the variance, provided clear patterns of distinction among the stations. Loading plots on PCs 2 and 3 show that stations in Zones 1a (red text) and 2b (black text) have similar long-term patterns of variability that are in contrast to zone 2a (green text, Figs. 4,5). One exception to this pattern is the East Glacier station (Zone 1a), which has loadings more similar to Zone 2a stations. Zone 1b stations (blue text in Figs. 4, 5) have mixed patterns of long-term variability and consequently plot among stations from all the other zones.

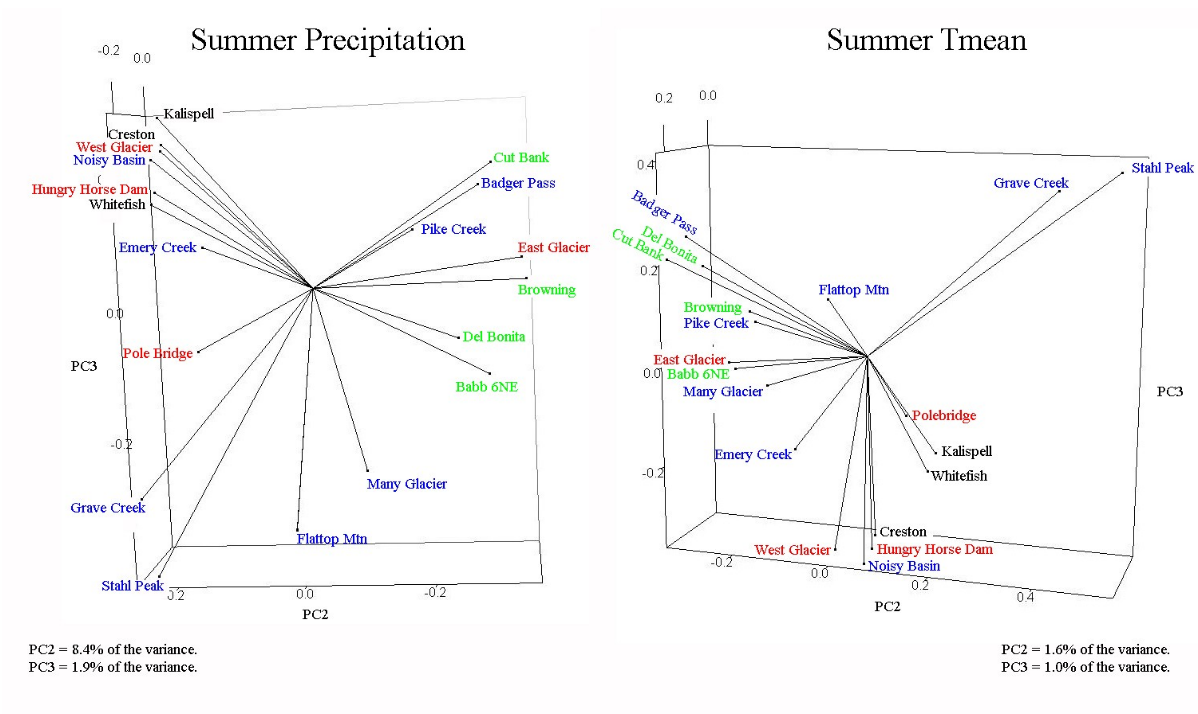

Figure 4. Loading plots of S-mode Principal Components Analysis of 1895 – 2008 summer (June, July, August) precipitation and mean temperature for weather stations in and near Glacier National Park. Colored text indicates zone membership for each station as determined by the cluster analysis of monthly normals. Red = Zone 1a, Blue = Zone 1b, Green = Zone 2a, Black = Zone 2b.

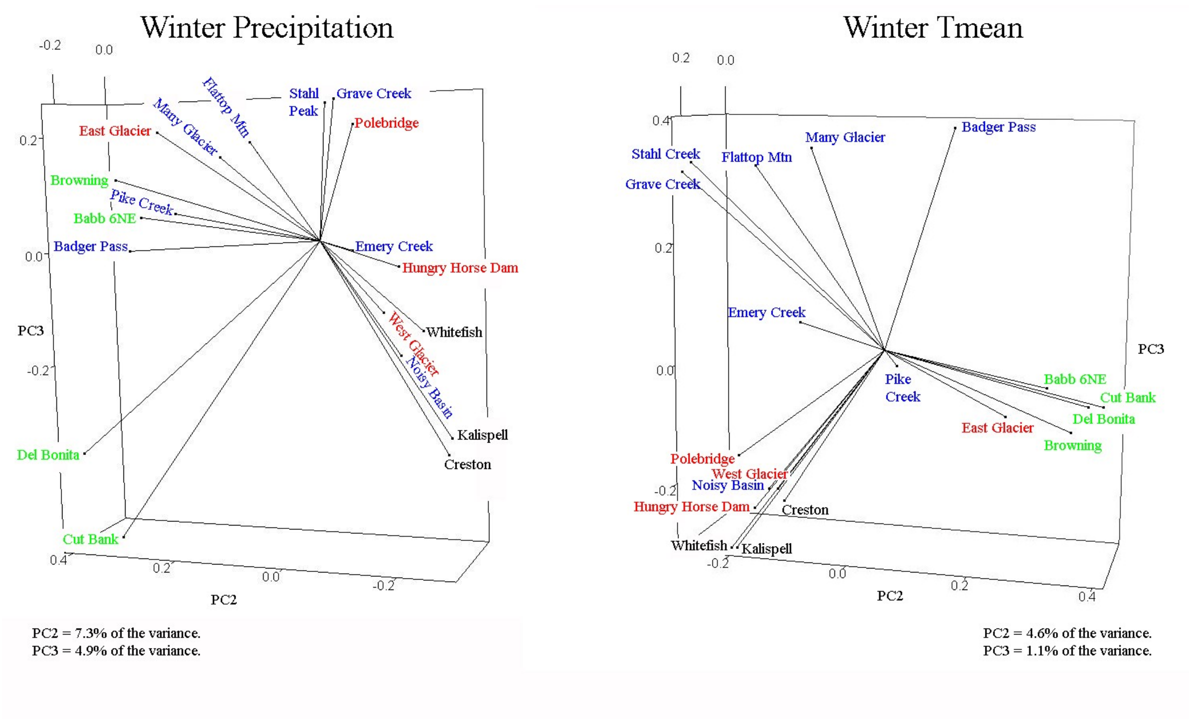

Figure 5. Loading plots of S-mode Principal Components Analysis of 1895 – 2008 winter (December, January, February) precipitation and mean temperature for weather stations in and near Glacier National Park. Colored text indicates zone membership for each station. Red = Zone 1a, Blue = Zone 1b, Green = Zone 2a, Black = Zone 2b.

The correlation map showed good correspondence between the geographic areas that have 0.95 correlation with each set of zone averages and the locations of the weather stations, with the exception of a small area which shows affiliation with Zone 1b east of the park (Fig. 6). White areas in Fig. 6 had correlations below 0.95 for all zones and may be considered as having intermediate seasonal patterns.

The snow cover analysis ranked the weather stations according to mean length of winter season. These subzones may be employed if ROMN wishes to stratify its reporting of snowpack along elevation gradients (Table 1).

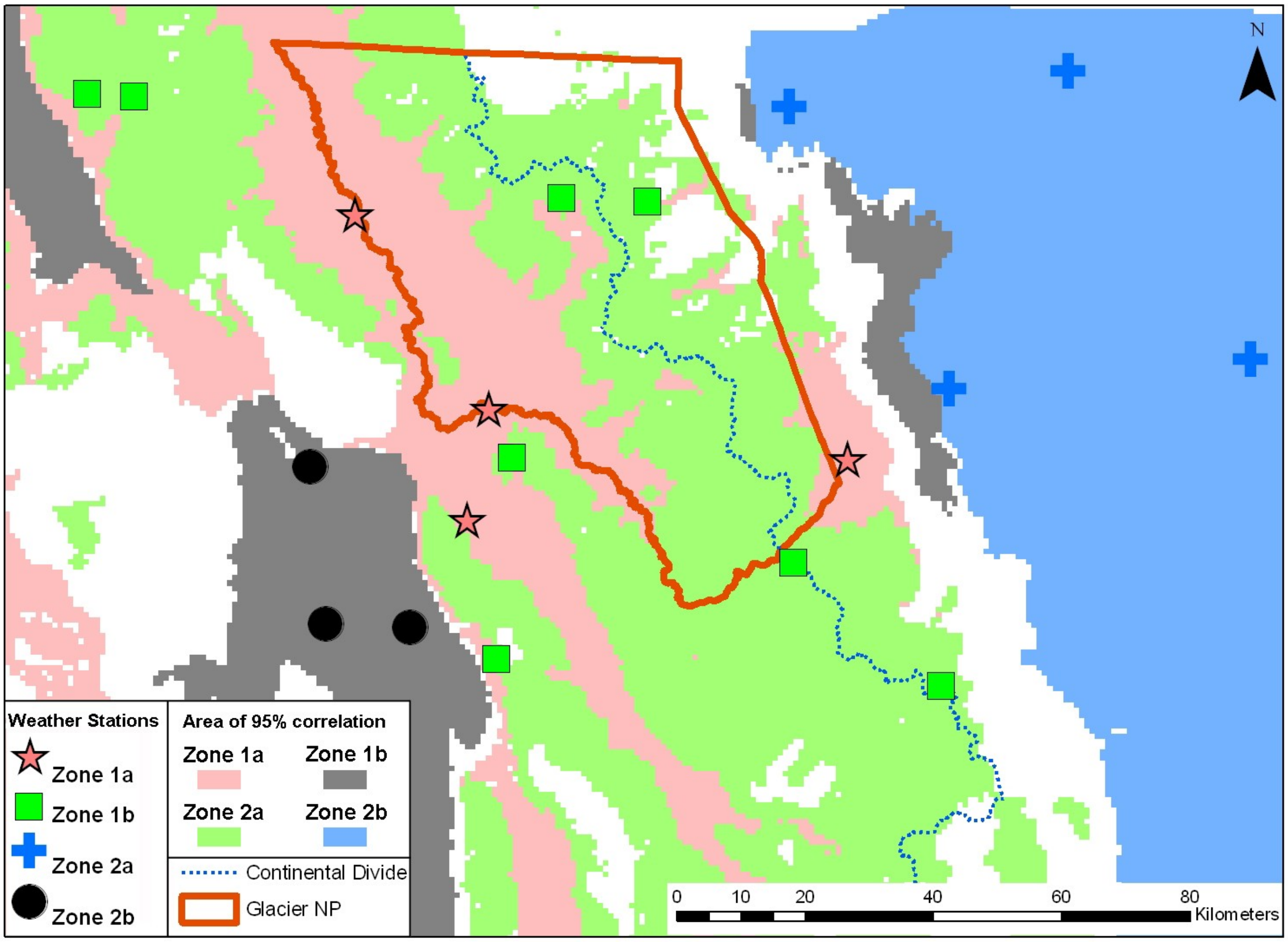

Figure 6. Map showing areas that have 0.95 or greater correlation with weather stations in each climate zone. White areas had correlation below 0.95 for all zones.

Table 1. Classification of weather stations in and near Glacier National Park. "N/A" indicates that there were insufficient data available for an accurate estimate. In such cases, stations were ranked in order of elevation.

ZONE 1A					
STATION NAME	SNOW SUBZONE	MEAN WINTER LENGTH (DAYS)	# Winters Calculated	ELEVATION (m)	STATION TYPE
Hungry Horse Dam	A	108.67	9	963	COOP
West Glacier	A	160.33	24	955	COOP
Polebridge	A	N/A	N/A	1073	COOP
East Glacier	A	190.58	12	1465	COOP
ZONE 1B					
STATION NAME	SNOW SUBZONE	MEAN WINTER LENGTH (DAYS)	# Winters Calculated	ELEVATION (m)	STATION TYPE
Many Glacier	A	178.32	25	1494	SNOTEL
Emery Creek	A	180.84	25	1326	SNOTEL
Grave Creek	A	182.96	26	1311	SNOTEL
Pike Creek	B	213.68	25	1807	SNOTEL
Badger Pass	B	242.74	23	2103	SNOTEL
Noisy Basin	B	250.22	27	1841	SNOTEL
Stahl Peak	B	255.54	26	1838	SNOTEL
Flattop Mtn	B	261.97	30	1920	SNOTEL
ZONE 2A					
STATION NAME	SNOW SUBZONE	MEAN WINTER LENGTH (DAYS)	# Winters Calculated	ELEVATION (m)	STATION TYPE
Cut Bank	A	N/A	N/A	1170	COOP
Babb 6NE	A	N/A	N/A	1311	COOP
Del Bonita	A	N/A	N/A	1322	COOP
Browning	A	N/A	N/A	1335	COOP
ZONE 2B					
STATION NAME	SNOW SUBZONE	MEAN WINTER LENGTH (DAYS)	# Winters Calculated	ELEVATION (m)	STATION TYPE
Creston	A	99.72	25	896	COOP
Kalispell Airport	A	118.89	27	901	COOP
Whitefish	A	136.27	22	945	COOP

Rocky Mountain National Park

The cluster analysis of 1971 – 2000 monthly normals defined two climate zones, one of which contained two subzones. (Fig. 7).

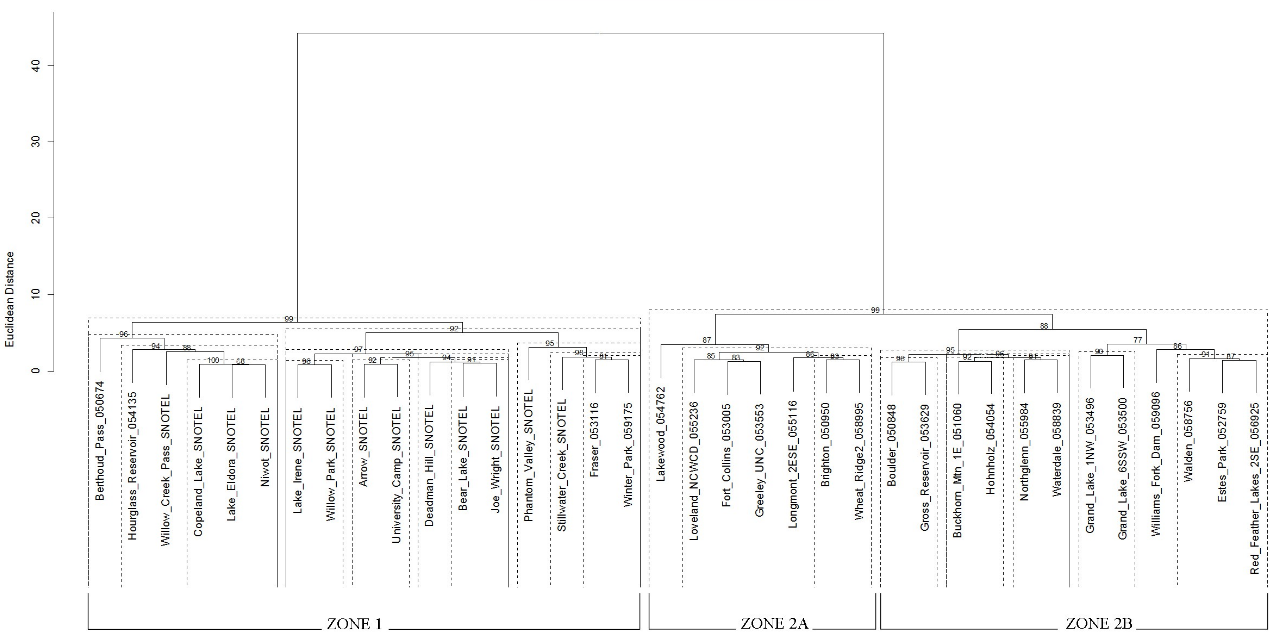

Figure 7. Ward's cluster analysis for weather stations in and near Rocky Mountain National Park. Numbers near each node indicate bootstrap confidence, based on 10,000 pseudoreplicates. Dotted lines delineate clusters that have greater than 90% bootstrap support. Climate zones, which were selected according to criteria described in the methods, are labeled on the bottom. The dendrogram based on average clustering contained the same zones.

A comparison of average precipitation, Diurnal Temperature Range (DTR), and mean temperature (Tmean) values shows that Zone 1 has a relatively greater proportion of its precipitation in the winter and spring, while Zones 2a and 2b have more of their precipitation during May – August (Fig. 8). Zone 2a stations, which are located east of Rocky Mountain NP (map, Fig. 9), have less seasonal variation in DTR. Zone 1 and 2b stations are in or near the park, with Zone 1 stations often at higher elevations than Zone 2b stations.

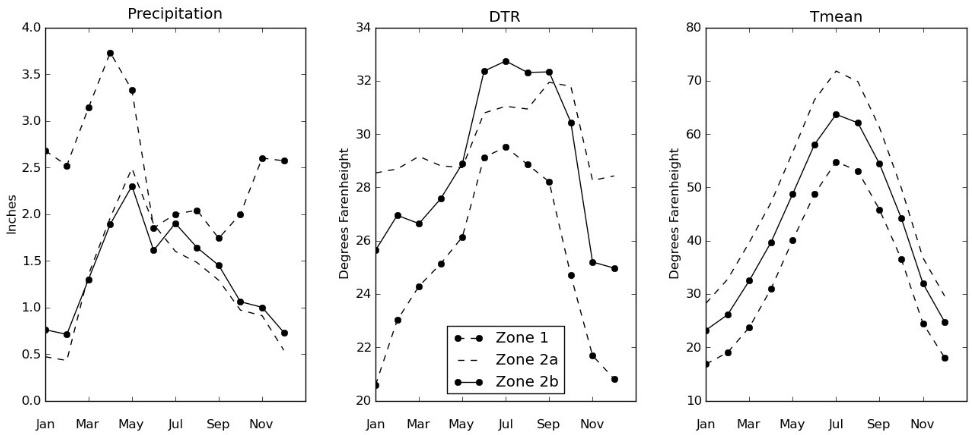

Figure 8. Monthly mean precipitation, diurnal temperature range (DTR), and mean temperature (Tmean) for each climate zone. Means were calculated from 1971-2000 normals from all weather stations in each zone.

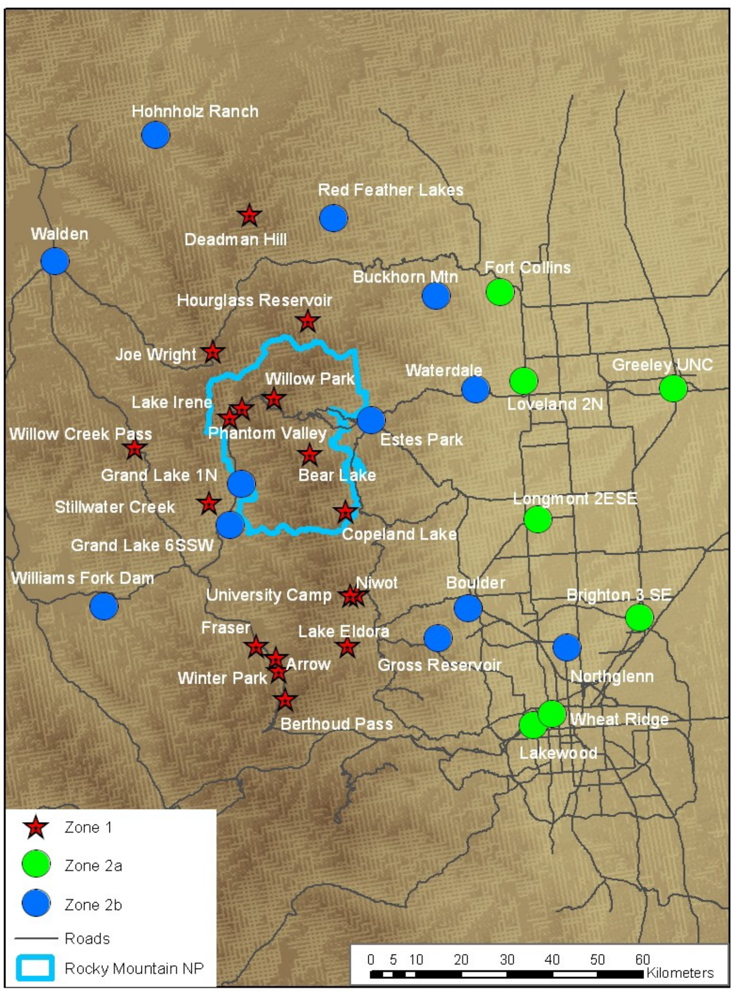

Figure 9. Map showing the locations of the weather stations included in the cluster analysis (Fig. 1). Background shading indicates topographic relief.

Loadings for all Rocky Mountain National Park weather stations were very similar on the first principal component (PC1), and distinctions among stations were found on PCs 2 and 3. In general, the greatest contrast in long-term variability was seen between Zone 1 (green text) and Zone 2a (blue text) stations, which always loaded in the opposite direction on PC2 (Figs. 10,11). Zone 2b stations (black text) were mixed, with some plotting near either Zones 1 or 2a (Figs. 10,11).

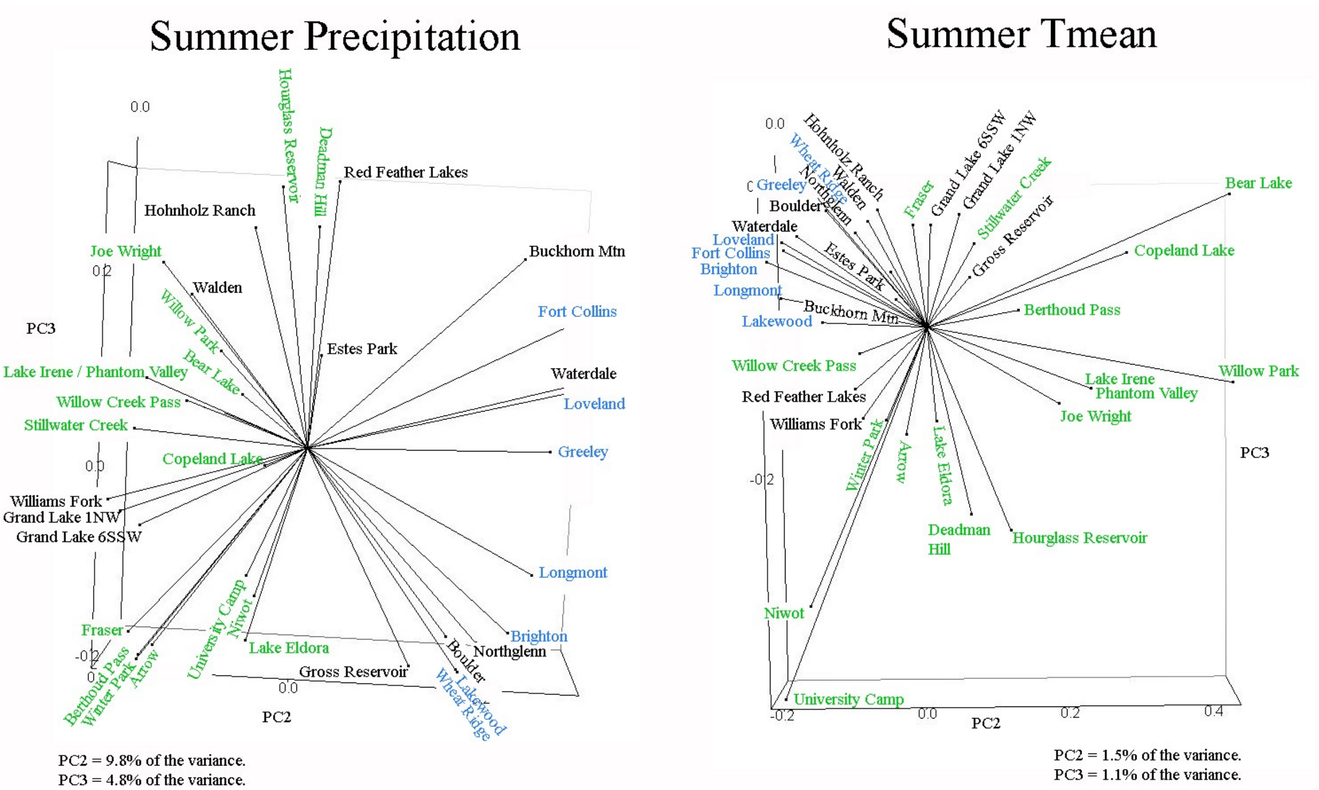

Figure 10. Loading plots of S-mode Principal Components Analysis of 1895 – 2008 summer (June, July, August) precipitation and mean temperature for weather stations in and near Rocky Mountain National Park. Colored text indicates zone membership for each station. Green = Zone 1, Blue = Zone 2a, Black = Zone 2b.

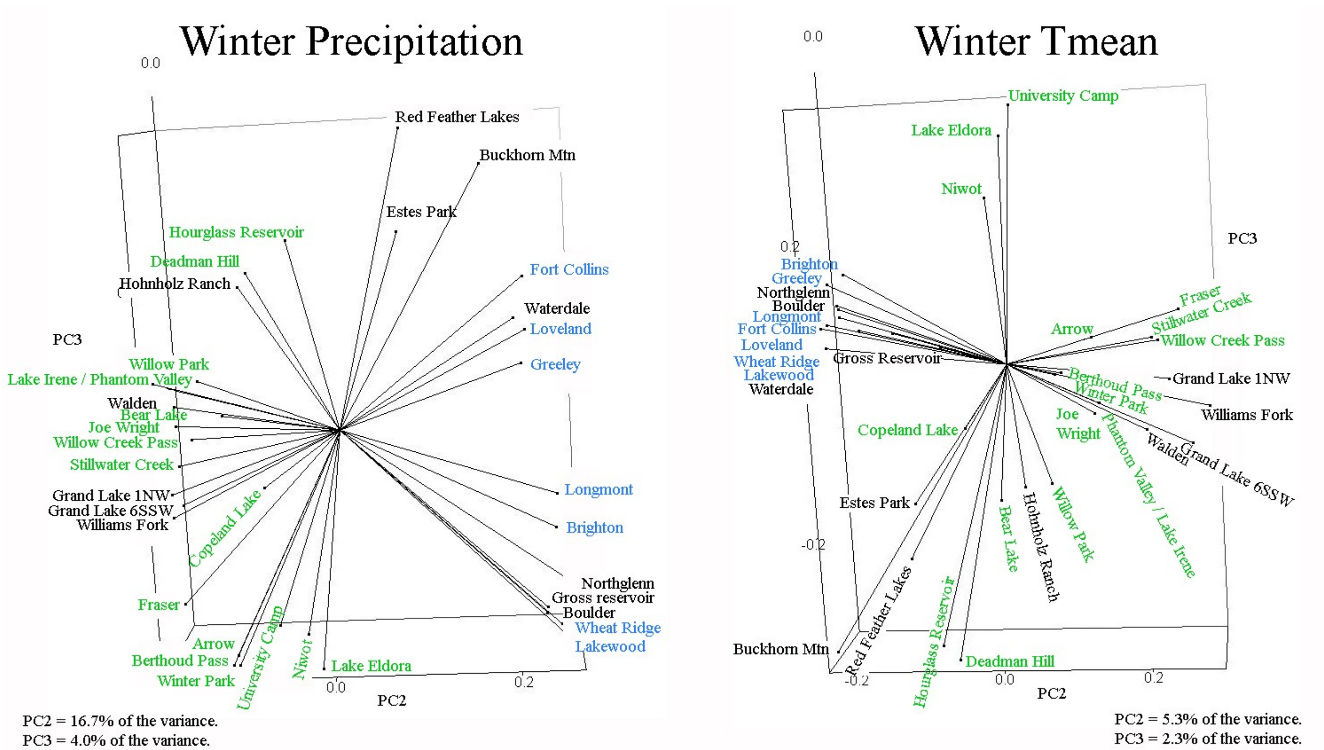

Figure 11. Loading plots of S-mode Principal Components Analysis of 1895 – 2008 winter (December, January, February) precipitation and mean temperature for weather stations in and near Rocky Mountain National Park. Colored text indicates zone membership for each station. Green = Zone 1, Blue = Zone 2a, Black = Zone 2b.

The correlation map (Fig. 12) shows that, for the most part, the zones did not overlap. However, grid cells in the area between the Northglenn and Brighton 3SE weather stations (see Fig. 9) could be classified as either Zone 2a or 2b. They are classified as Zone 2b (blue) in Fig 9, but had correlations above 0.965 for both zones.

A large number of missing values made it impossible to estimate winter length for many of the Zone 2A stations (Table 2). Without more information, all the stations in Zone 2a are considered to have similar winter length and are assigned to the same subzone.

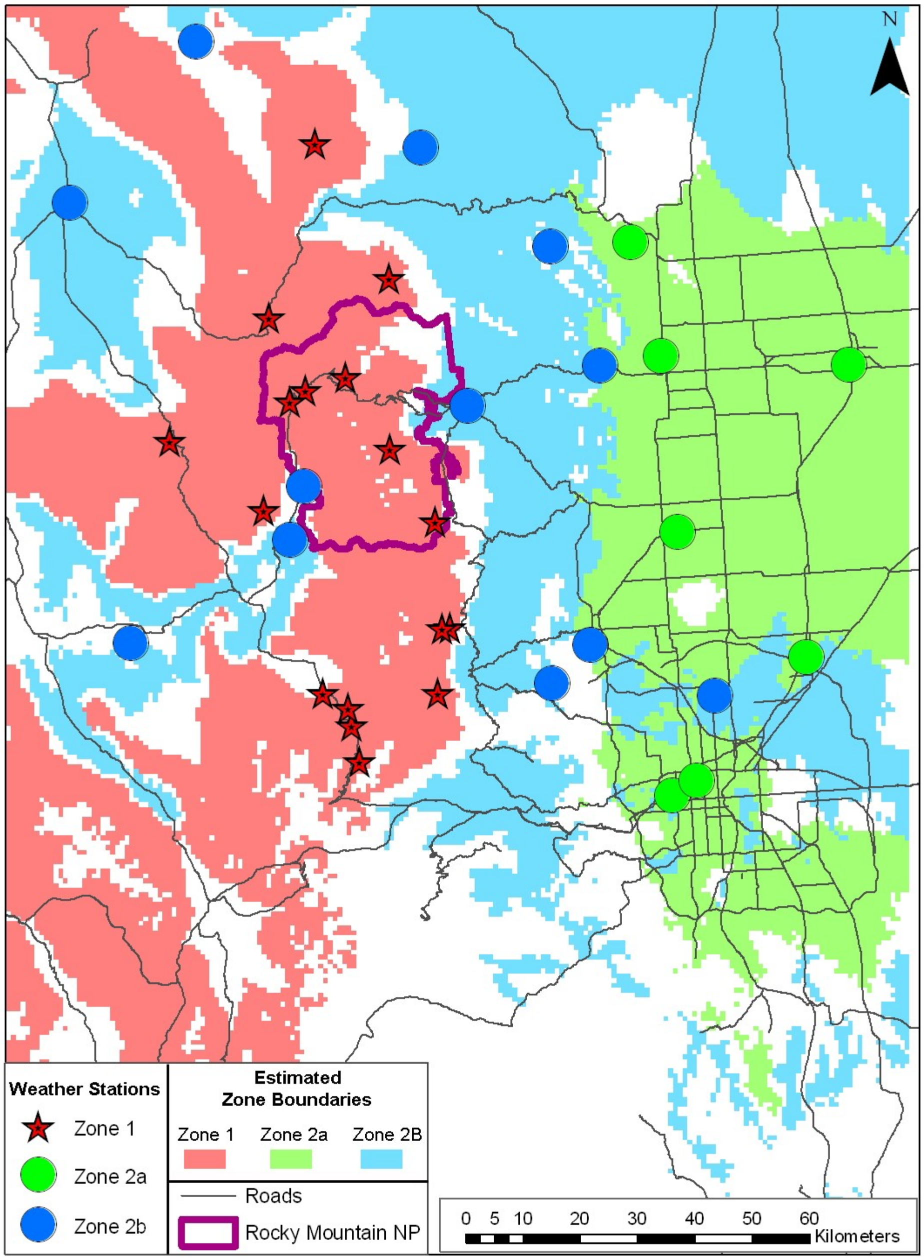

Figure 12. Map showing the geographic area correlated with the weather stations in each zones. Correlation thresholds were chosen to produce non-overlapping boundaries that covered as much of the map as possible. Correlations used were: Zone 1 = 0.9, Zones 2a and 2b = 0.965.

Table 2. Classification of weather stations in and near Rocky Mountain National Park. “N/A” indicates that there were insufficient data available for an accurate estimate. In such cases, stations were ranked in order of elevation.

ZONE 1					
STATION NAME	**SNOW SUBZONE**	**MEAN WINTER LENGTH (DAYS)**	**# Winters Calculated**	**ELEVATION (m)**	**STATION TYPE**
Copeland Lake	A	132.3	20	2621	SNOTEL
Stillwater Creek	B	165.07	15	2658	SNOTEL
Fraser	B	182.6	10	2609	COOP
Phantom Valley	B	186.62	21	2752	SNOTEL
Lake Eldora	B	190.14	22	2957	SNOTEL
Arrow	C	211.78	23	2950	SNOTEL
Winter Park	C	215.39	23	2775	COOP
Willow Creek Pass	C	219.39	23	2908	SNOTEL
Bear Lake	C	219.67	21	2896	SNOTEL
Berthoud Pass	C	N/A	N/A	2957	COOP
Niwot	C	221.57	21	3021	SNOTEL
Willow Park	C	222.86	21	3261	SNOTEL
Hourglass Reservoir	C	225.83	12	2902	COOP
University Camp	C	235.77	22	3139	SNOTEL
Lake Irene	C	236.86	22	3261	SNOTEL
Deadman Hill	C	237.39	23	3115	SNOTEL
Joe Wright	C	239.96	23	3085	SNOTEL
ZONE2A					
STATION NAME	**SNOW SUBZONE**	**MEAN WINTER LENGTH (DAYS)**	**# Winters Calculated**	**ELEVATION (m)**	**STATION TYPE**
Longmont 2ESE	A	56.08	12	1509	COOP
Loveland 2N	A	58.4	10	1548	COOP
Fort Collins 053005	A	76.64	25	1525	COOP
Greeley UNC	A	N/A	N/A	1439	COOP
Brighton	A	N/A	N/A	1515	COOP
Wheat Ridge 2	A	N/A	N/A	1655	COOP
Lakewood	A	N/A	N/A	1719	COOP
ZONE 2B					
STATION NAME	**SNOW SUBZONE**	**MEAN WINTER LENGTH (DAYS)**	**# Winters Calculated**	**ELEVATION (m)**	**STATION TYPE**
Waterdale	A	59.27	11	1594	COOP
Northglenn	A	N/A	N/A	1637	COOP
Boulder 050848	A	96.95	20	1672	COOP
Gross Reservoir	A	114.43	21	2429	COOP
Buckhorn Mtn	B	149.9	10	2256	COOP
Estes Park 052759	B	151.75	8	2280	COOP
Grand Lake 6SSW	B	173.67	6	2526	COOP
Williams Fork Dam	B	177.65	17	2322	COOP
Hohnholz Ranch	B	N/A	N/A	2365	COOP
Walden	B	N/A	N/A	2475	COOP
Red Feather Lakes 2_ESE	B	N/A	N/A	2489	COOP
Grand Lake 1NW	B	188.16	25	2658	COOP

Great Sand Dunes National Park

The cluster analysis of 1971 – 2000 monthly normals defined three climate zones. (Fig. 13).

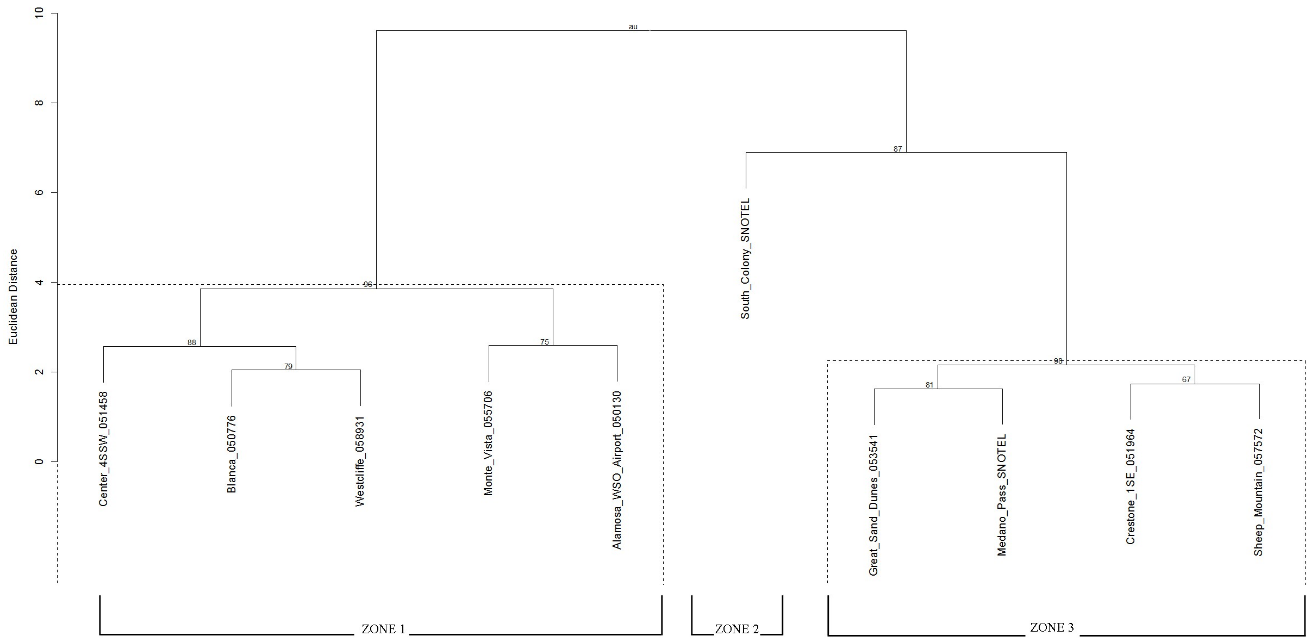

Figure 13. Ward's cluster analysis for weather stations in and near Great Sand Dunes National Park. Numbers near each node indicate bootstrap confidence, based on 10,000 pseudoreplicates. Dotted lines delineate clusters that have greater than 90% bootstrap support. Climate zones, which were selected according to criteria described in the methods, are labeled on the bottom. The dendrogram based on average clustering contained the same zones.

Zone 2, which contains only the South Colony SNOTEL station, is unique in having a relatively even distribution of precipitation throughout the year (Fig. 14). Zones 1 and 3 have peak precipitation during the summer – fall (Fig. 14). Zone 1 is distinguished by its relatively even seasonal DTR pattern (Fig. 14). Zone 1 stations are further from the park than Zone 2 and 3 stations (Fig. 15).

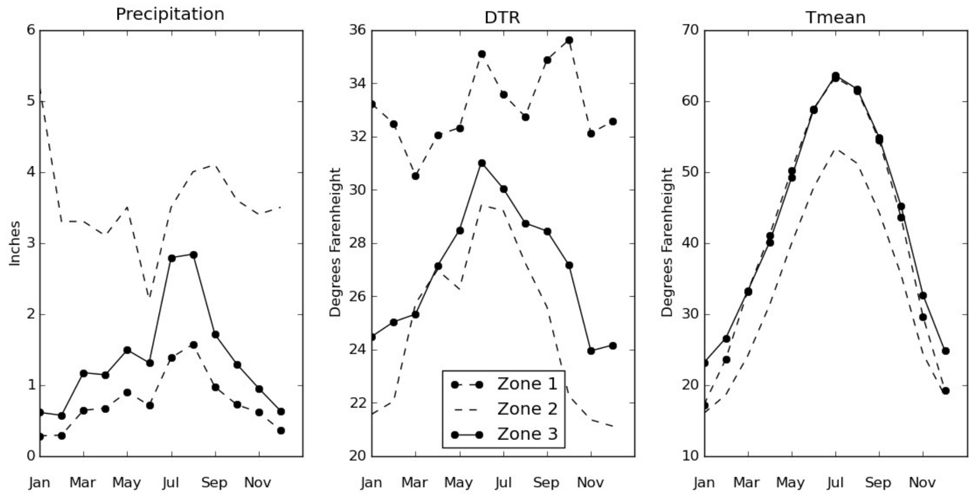

Figure 14. Monthly mean precipitation, diurnal temperature range (DTR), and mean temperature (Tmean) for each climate zone. Means were calculated from 1971-2000 normals from all weather stations in each zone.

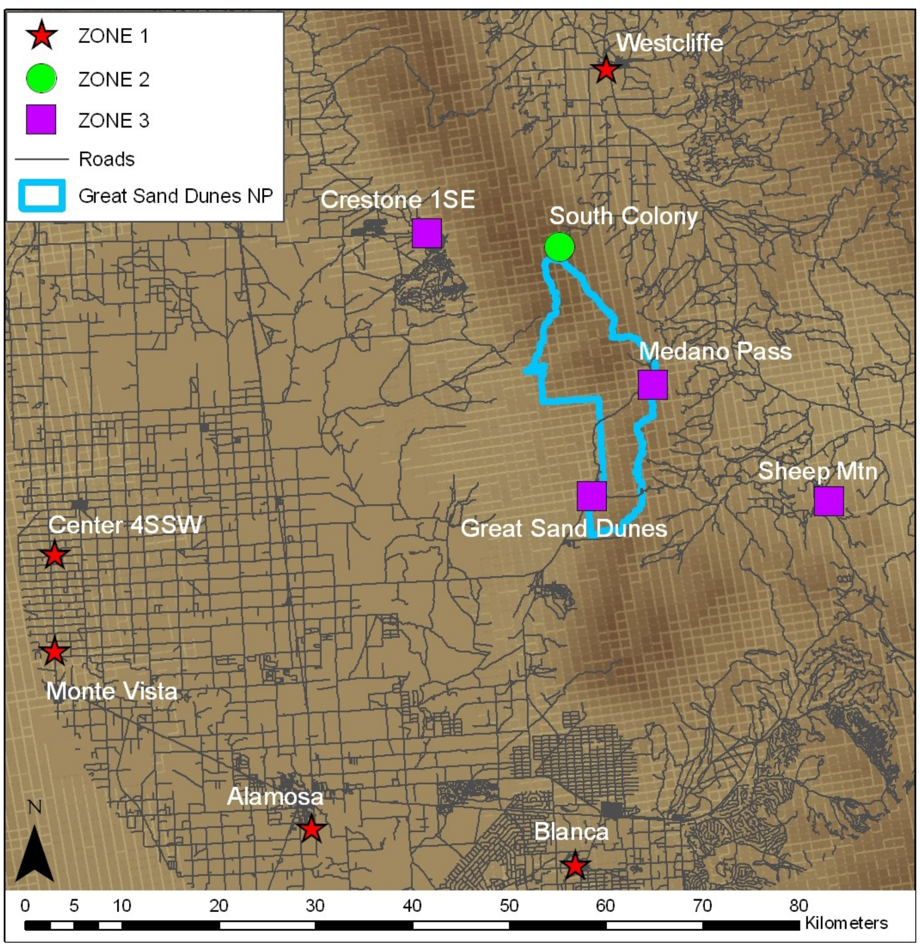

Figure 15. Map showing the location of weather stations included in the analysis. Background shading indicates topography.

The PCAs for Great Sand Dunes National Park (Figs. 16,17) show good separation between stations in Zones 1 and 3. One exception occurs for the Westcliffe station, a Zone 1 station that plots nearer to Zone 3 stations in every PCA except the one conducted on Summer Tmean data (Figs. 16, 17). South Colony, the only station in Zone 2, has patterns of long-term variability that are more similar to Zone 3 than Zone 1 (Figs. 16,17). This agrees with the clustering hierarchy shown in Fig. 13, where Zone 2 is shown to be more similar to Zone 1.

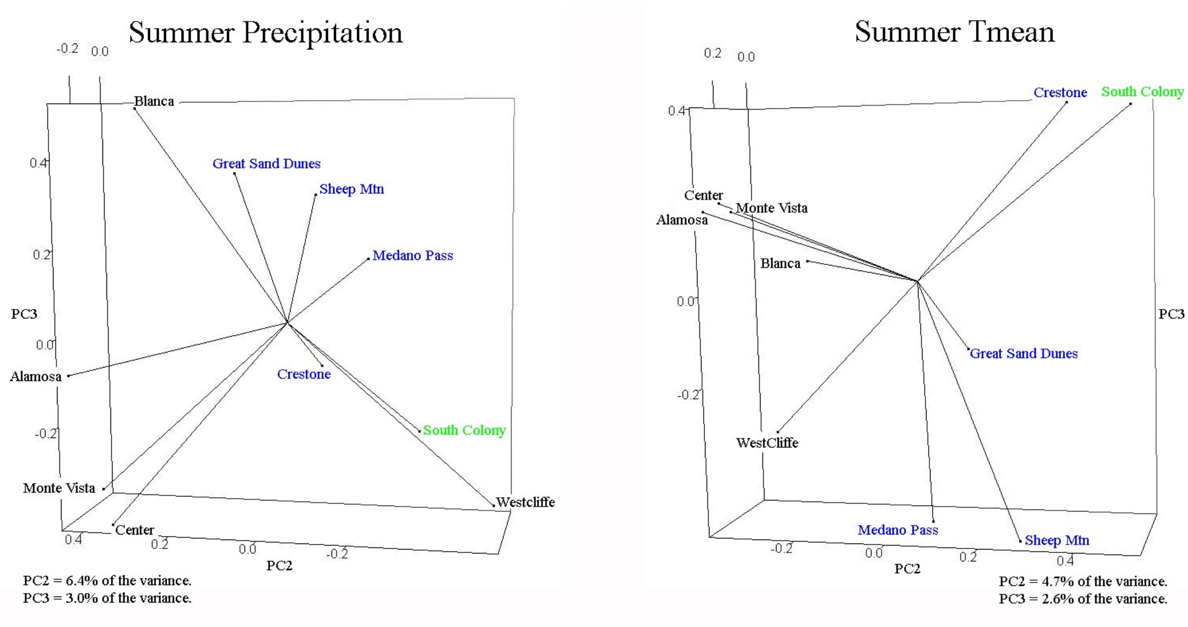

Figure 16. Loading plots of S-mode Principal Components Analysis of 1895 – 2008 summer (June, July, August) precipitation and mean temperature for weather stations in and near Great Sand Dunes National Park. Colored text indicates zone membership for each station. Black = Zone 1, Green = Zone 2, Blue = Zone 3.

The geographic area in and around Great Sand Dunes National Park (GRSA) has relatively low correlation to the weather stations analyzed in this report. This has been illustrated in Fig. 18, which shows the grid cells that have 0.85 or greater correlation to the weather stations in each zone. The use of a relatively low correlation threshold (0.85) has produced significant overlap between Zones 1 and 3 in two areas, however there is still an area within the boundary of GRSA that has not been assigned to any of the three zones (Fig. 18). This white area has less than 0.85 correlation to all three climate zones.

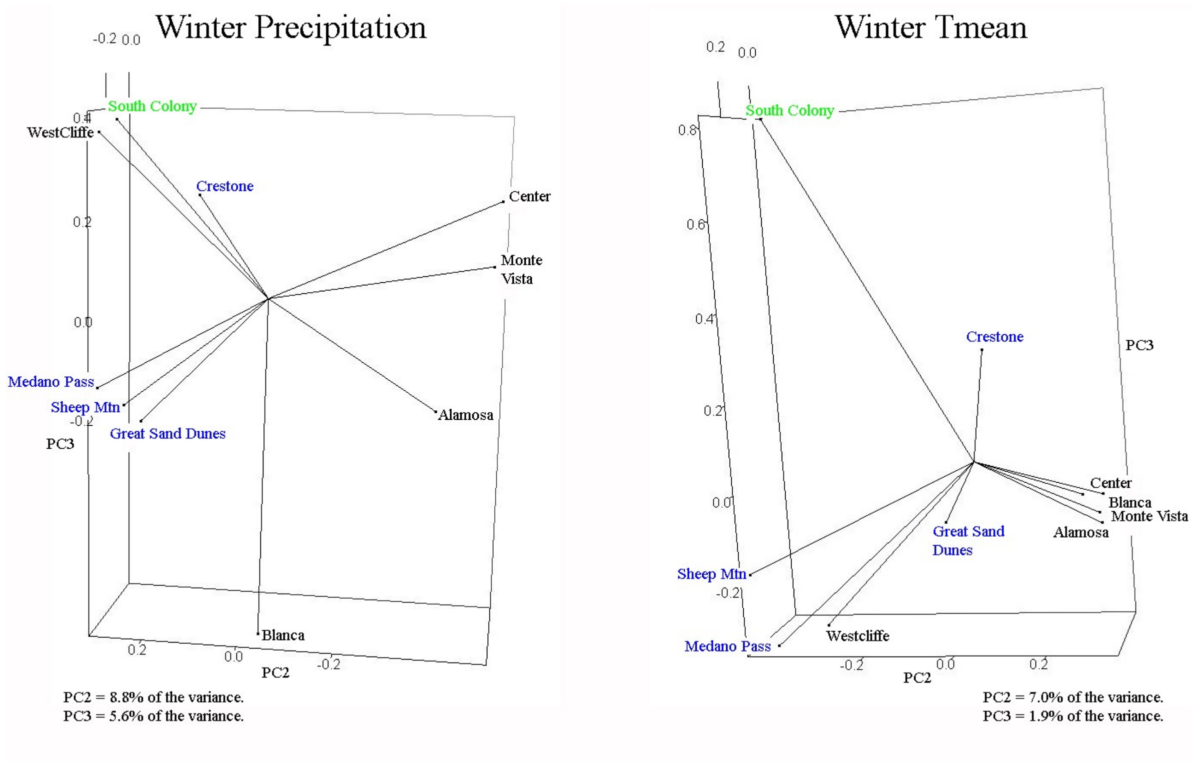

Figure 17. Loading plots of S-mode Principal Components Analysis of 1895 – 2008 winter (December, January, February) precipitation and mean temperature for weather stations in and near Great Sand Dunes National Park. Colored text indicates zone membership for each station. Black = Zone 1, Green = Zone 2, Blue = Zone 3.

Because of the low correlations just mentioned, ROMN may choose to emphasize observations from individual weather stations, such as Medano Pass or Great Sand Dunes. These weather stations are likely to be more representative of the white areas in Fig. 18 than averages calculated across all the weather stations in either Zone 1 or 3.

The results of the snow cover analysis for GRSA appear in Table 3. Because relatively few stations were involved, elevation-based subzones (strata) have not been assigned. Zone 1 weather stations have the shortest winter season. Zone 3 stations have winters of intermediate length, and South Colony (Zone 2) had the longest average winter length.

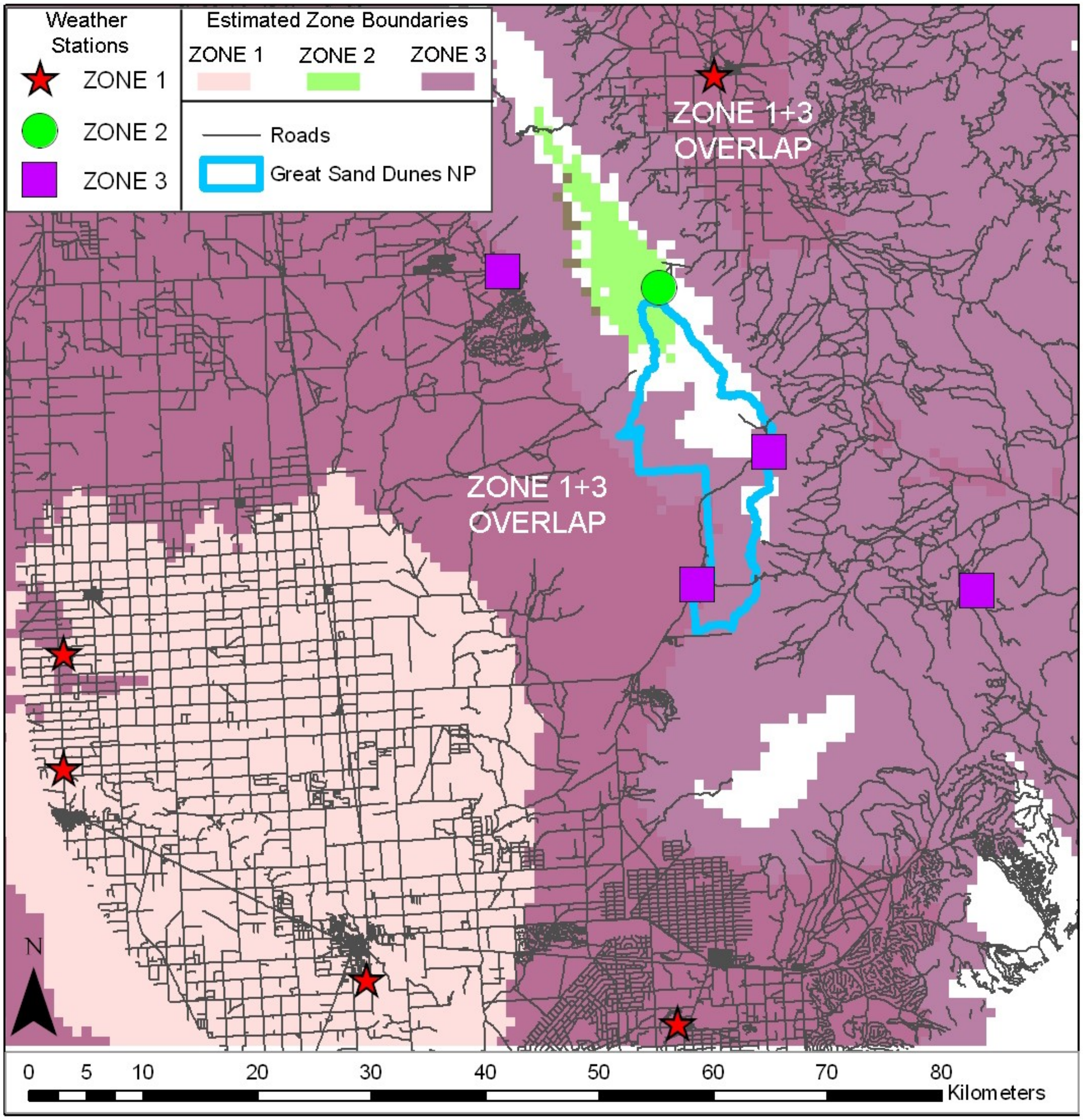

Figure 18. Map showing the geographic areas that have at least 0.85 correlation with the weather stations in each zone. Zones 1 and 3 were made semi-transparent to illustrate the amount that they overlap. The overlapping areas are shaded darker purple and are labeled with white text. White areas on the map have lower than 0.85 correlation with weather stations in any zone.

Table 3. Estimated winter length (days) for weather stations in and near Great Sand Dunes National Park. Stations are arranged in ascending order of winter length. “N/A” indicates that there were insufficient data to obtain an accurate estimate. Stations with insufficient data are arranged in ascending order of elevation.

Station Name	Climate Zone	Elevation (m)	Mean Winter Length (Days)	# Winters Calculated	Station Type
Center 4SSW	1	2339	N/A	5	COOP
Westcliffe	1	2396	62.3	10	COOP
Monte Vista	1	2333	79.36	14	COOP
Alamosa Airport	1	2296	83.67	27	COOP
Blanca	1	2350	N/A	N/A	COOP
Sheep Mtn	1	2363	N/A	N/A	COOP
Crestone 2S	3	2473	86.38	16	COOP
Great Sand Dunes	3	2494	115.22	9	COOP
Medano Pass	3	2932	151.5	6	SNOTEL
South Colony	2	3292	228	10	SNOTEL

Little Bighorn Battlefield National Monument

The cluster analysis of 1971 – 2000 normals defined two climate zones (Fig. 19).

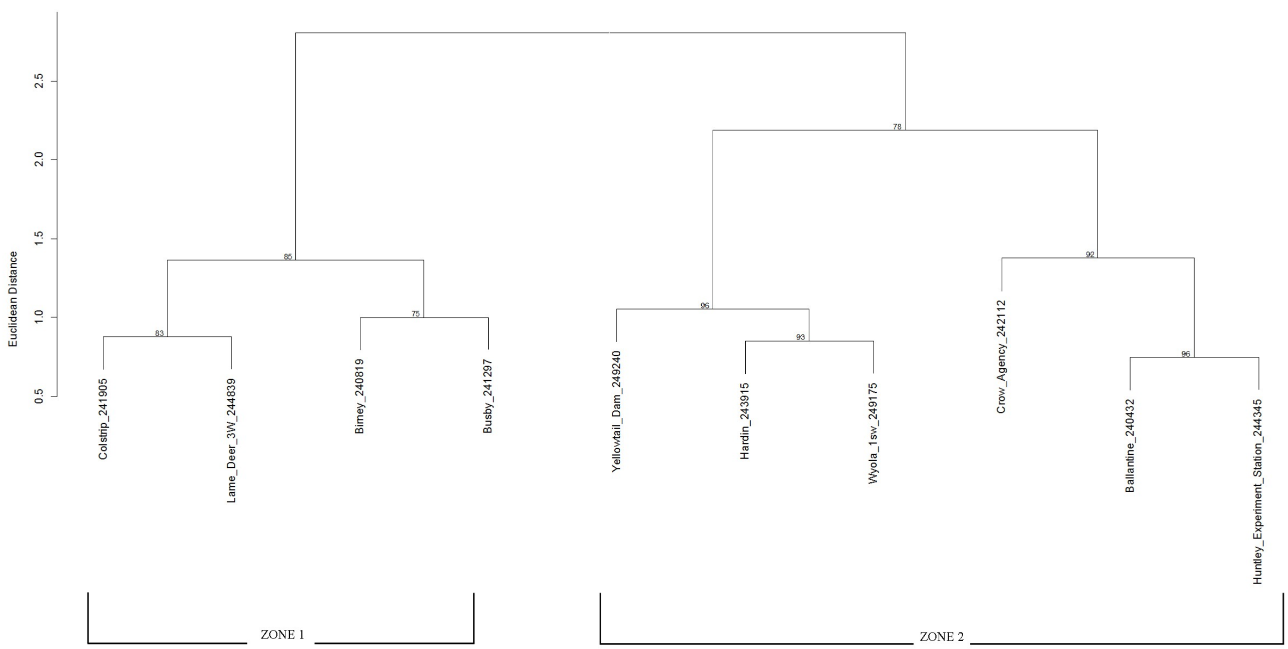

Figure 19. Ward's cluster analysis for weather stations in and near Little Bighorn Battlefield. Numbers near each node indicate bootstrap confidence, based on 10,000 pseudoreplicates. Dotted lines delineate clusters that have greater than 90% bootstrap support. Climate zones, which were selected according to criteria described in the methods, are labeled on the bottom. The dendrogram based on average clustering contained the same zones.

The seasonal patterns for the two zones are very similar (Fig. 20). With the exception of Lame Deer, Zone 1 stations are east of Little Bighorn Battlefield (LIBI) and Zone 2 stations are to the west (Fig. 21). If the climate zones were being defined solely on the basis of the cluster analysis, it might be argued that all the weather stations could be combined into one zone. However, the PCAs of 1895 – 2008 variability show the same separation between Zone 1 and 2 weather stations (Figs. 22, 23). ROMN may detect different long-term patterns in these zones when it conducts the trends analysis specified in the climate protocol (Frakes et al. 2009). Annual climate status reports, in contrast, might be more efficient if they focus on individual weather stations near LIBI (e.g., Lame Deer, Crow Agency, Hardin, Busby) or report combined annual averages for all stations as one zone.

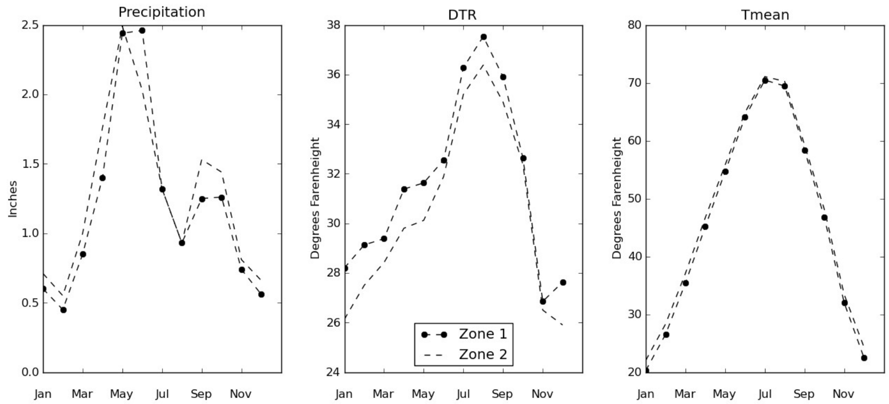

Figure 20. Monthly mean precipitation, diurnal temperature range (DTR), and mean temperature (Tmean) for each climate zone. Means were calculated from 1971-2000 normals from all weather stations in each zone.

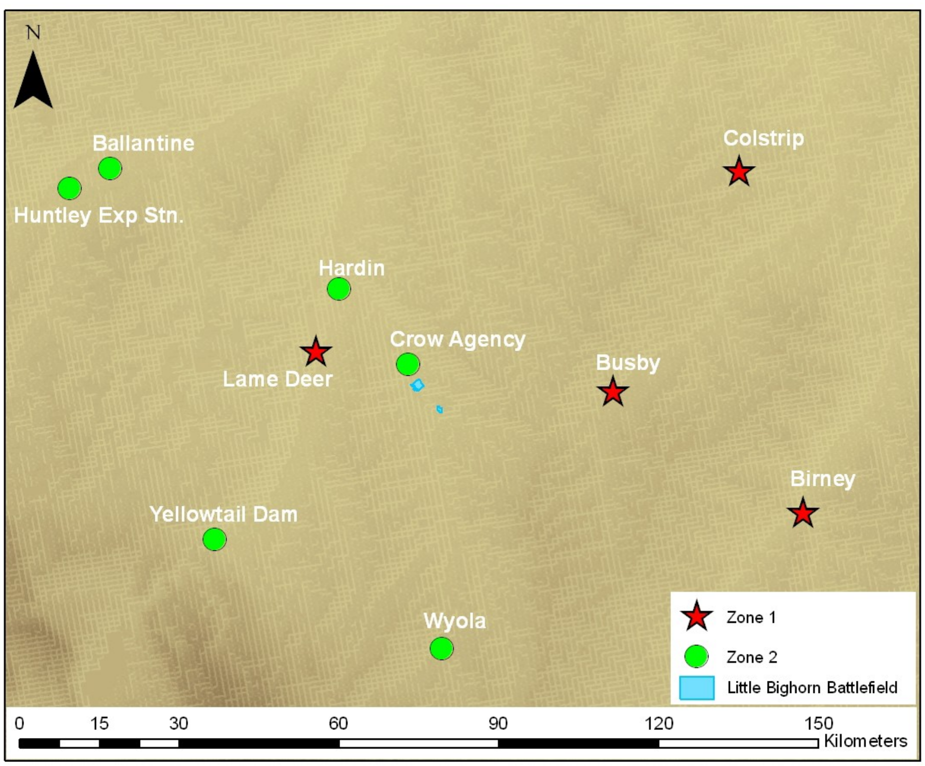

Figure 21. Map showing the location of weather stations included in the analysis. Background shading indicates topography.

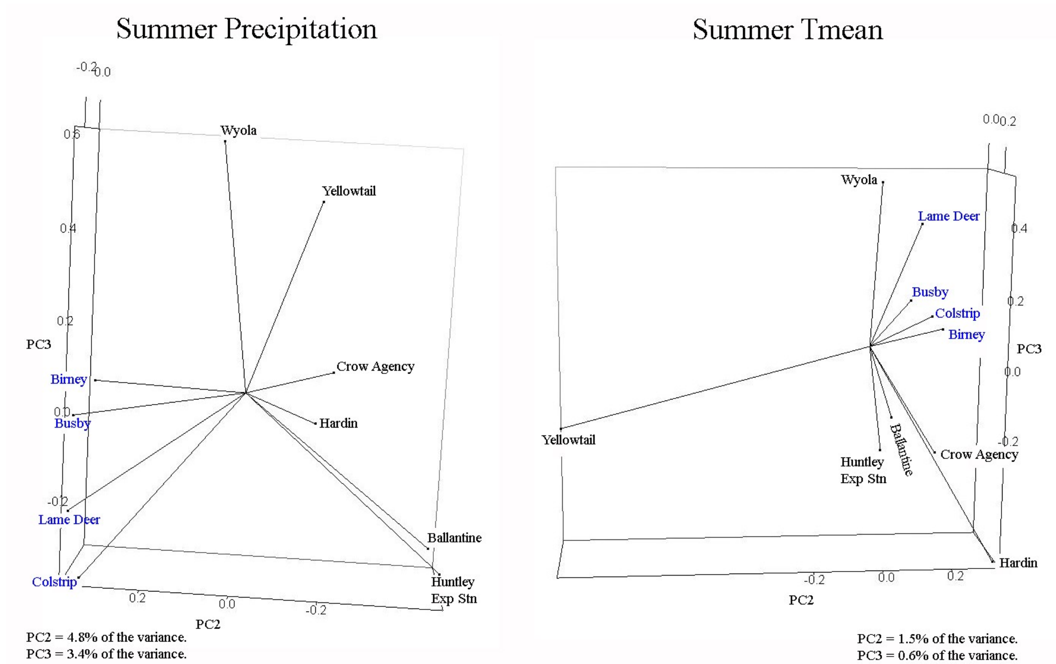

Figure 22. Loading plots of S-mode Principal Components Analysis of 1895 – 2008 summer (June, July August) precipitation and mean temperature for weather stations near Little Bighorn Battlefield. Colored text indicates zone membership for each station. Blue = Zone 1, Black = Zone 2.

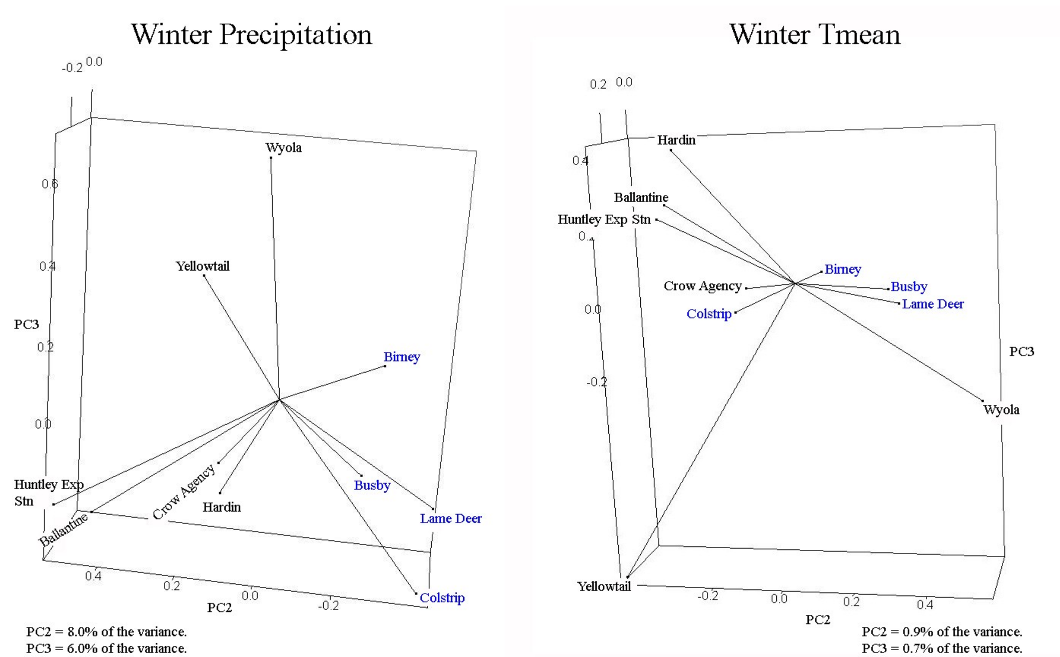

Figure 23. Loading plots of S-mode Principal Components Analysis of 1895 – 2008 winter (December, January, February) precipitation and mean temperature for weather stations near Little Bighorn Battlefield. Colored text indicates zone membership for each station. Blue = Zone 1, Black = Zone 2.

Grant-Kohrs Ranch National Historic Site

The cluster analysis of 1971 – 2000 normals defined two climate zones (Fig. 24).

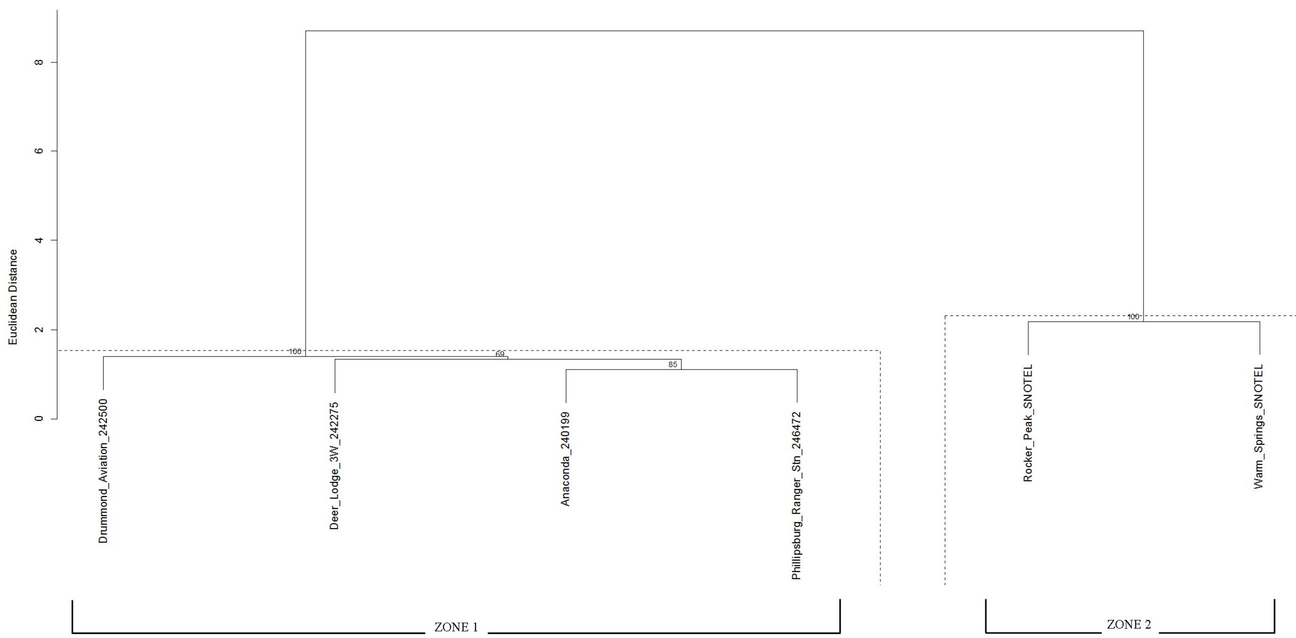

Figure 24. Ward's cluster analysis for weather stations near Grant-Kohrs Ranch. Numbers near each node indicate bootstrap confidence, based on 10,000 pseudoreplicates. Dotted lines delineate clusters that have greater than 90% bootstrap support. Climate zones, which were selected according to criteria described in the methods, are labeled on the bottom. The dendrogram based on average clustering contained the same zones.

The distinction between the two zones coincides with the distinction between COOP vs. SNOTEL stations. Zone 2 stations (the SNOTEL stations) have a greater proportion of precipitation in winter, while Zone 1 stations experience the majority of their precipitation in May - August (Fig. 25). There is no geographic clustering of the stations in each zone (Fig. 26), but the Zone 2 stations are located at higher elevation and have longer winters (Table 4). The PCAs of long-term variability do not show strong separation among the weather stations in the two zones (Figs. 27, 28).

SNOTEL stations are deliberately sited at higher elevations than COOP stations and are designed to better measure snow pack (Davey et al. 2006). ROMN may choose to treat the weather stations for this park as belonging to one climate zone with elevation-based strata that correspond to what are called “zones” in this report.

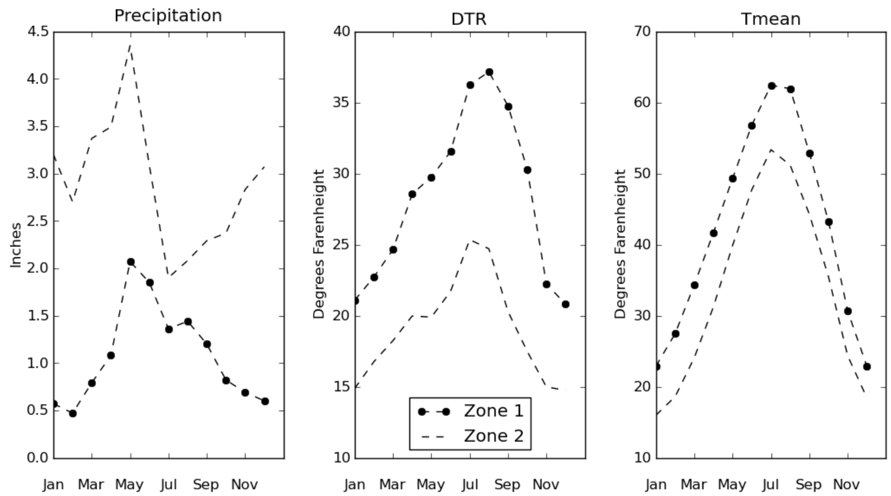

Figure 25. Monthly mean precipitation, diurnal temperature range (DTR), and mean temperature (Tmean) for each climate zone. Means were calculated from 1971-2000 normals from all weather stations in each zone.

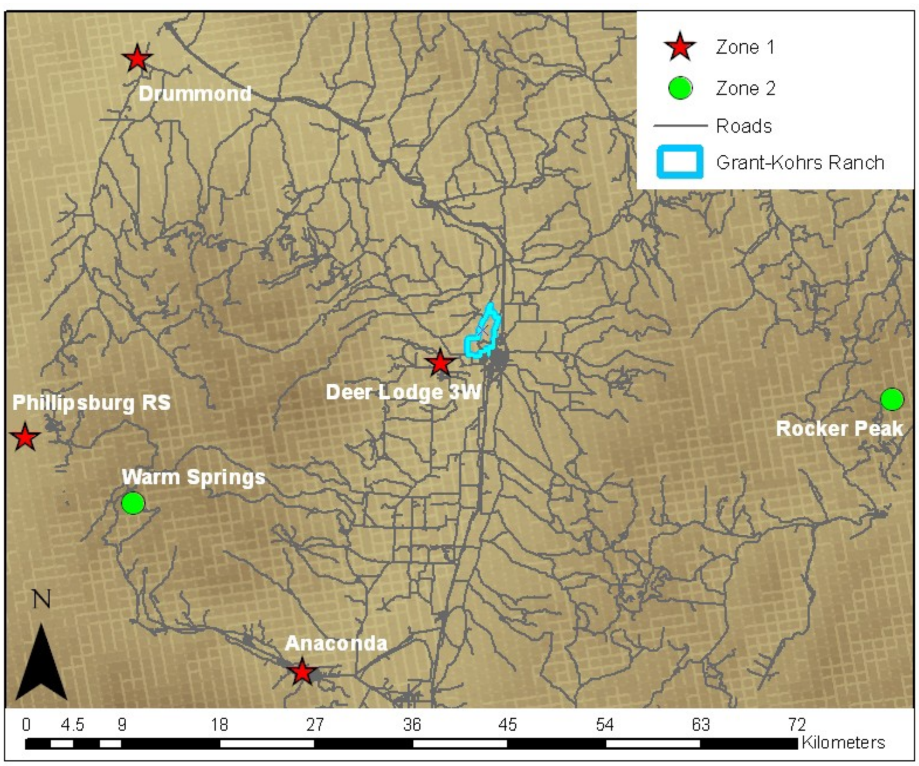

Figure 26. Map showing the location of weather stations included in the analysis. Background shading indicates topography.

Table 4. Estimated winter length (days) for weather stations near Grant-Kohrs Ranch. Stations are arranged in ascending order of winter length. “N/A” indicates that there were insufficient data to obtain an accurate estimate. Stations with insufficient data are arranged in ascending order of elevation.

Station Name	Climate Zone	Elevation (m)	Mean Winter Length (Days)	# Winters Calculated	Station Type
Drummond Aviation	1	1219	94.5	28	COOP
Deer Lodge 3W	1	1478	102.91	11	COOP
Phillipsburg RS	1	1606	N/A	N/A	COOP
Anaconda	1	1609	128.79	14	COOP
Rocker Peak	2	2438	239.45	31	SNOTEL
Warm Springs	2	2377	251.04	24	SNOTEL

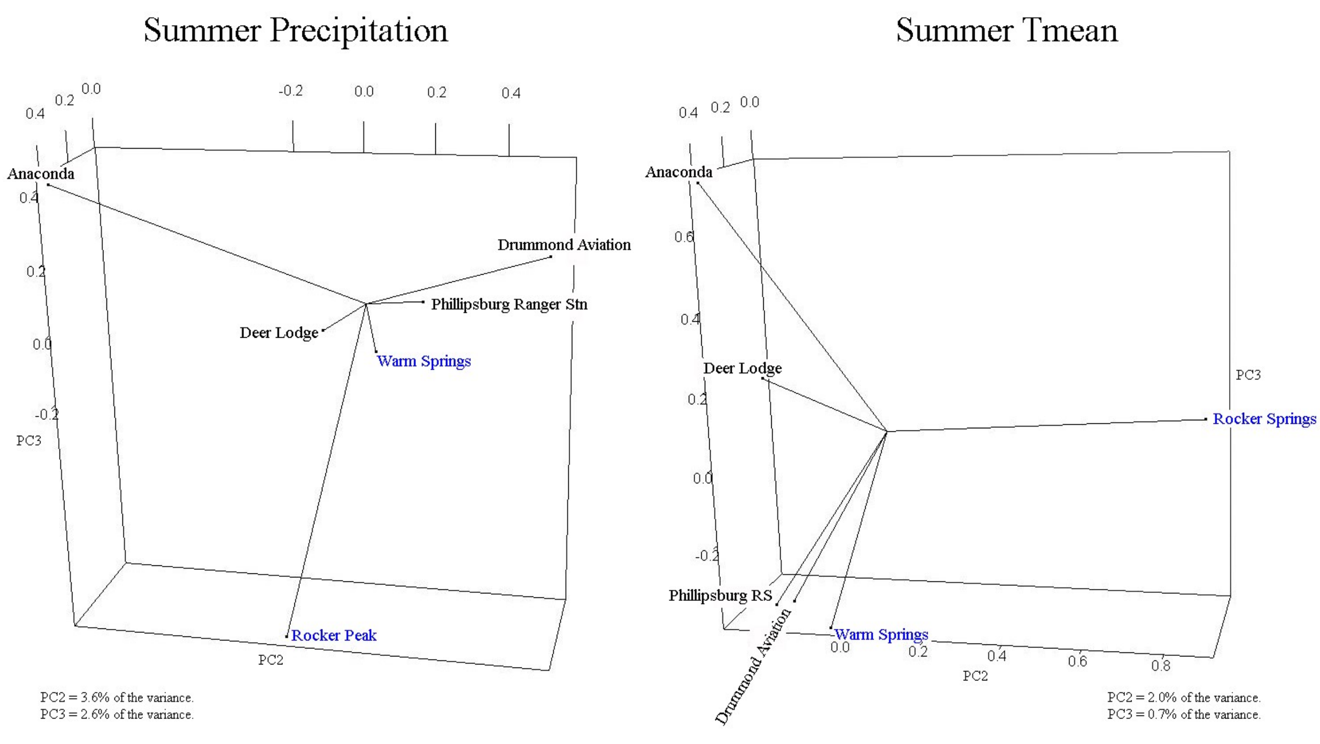

Figure 27. Loading plots of S-mode Principal Components Analysis of 1895 – 2008 summer (June, July, August) precipitation and mean temperature for weather stations near Grant-Kohrs Ranch. Colored text indicates zone membership for each station. Black = Zone 1, Blue = Zone 2.

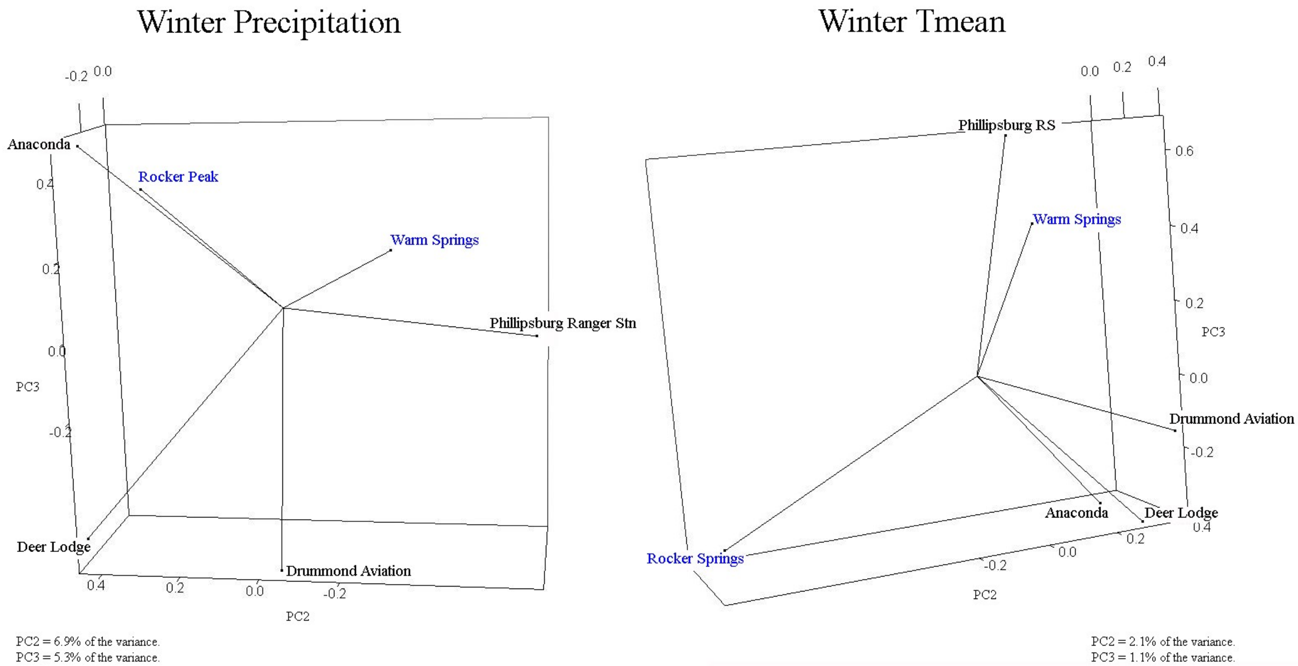

Figure 28. Loading plots of S-mode Principal Components Analysis of 1895 – 2008 winter (December, January, February) precipitation and mean temperature for weather stations near Grant-Kohrs Ranch. Colored text indicates zone membership for each station. Black = Zone 1, Blue = Zone 2.

Florissant Fossil Beds National Monument

The cluster analysis of 1971 – 2000 normals defined two climate zones (Fig. 29).

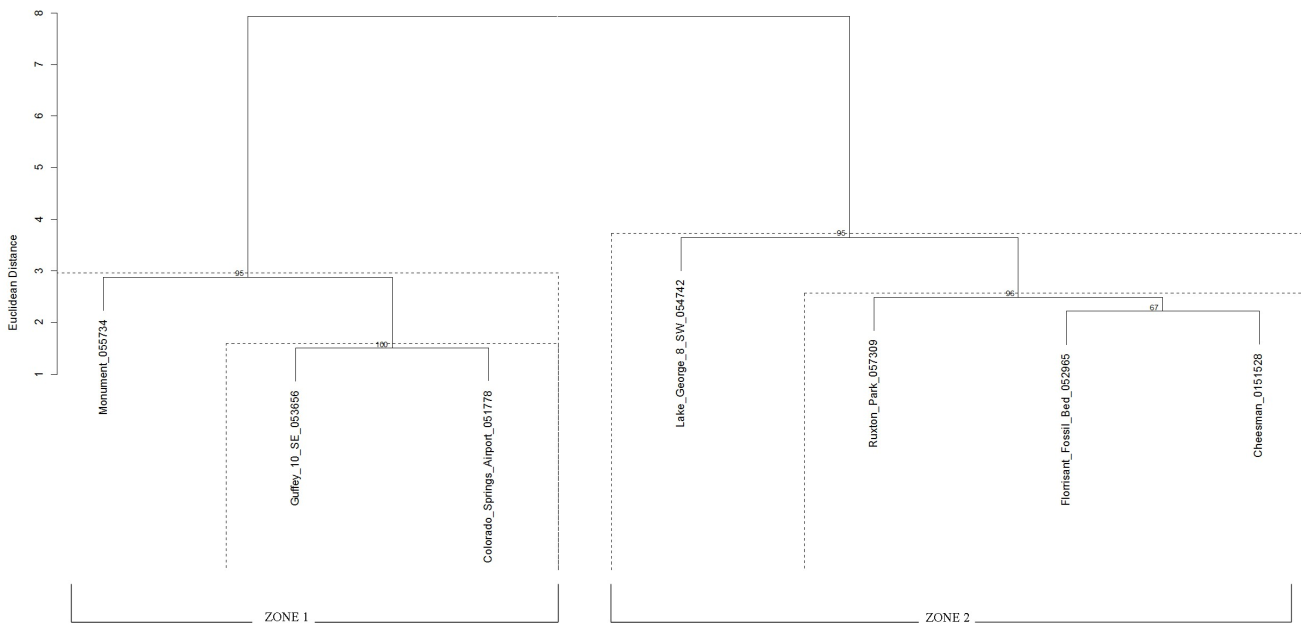

Figure 29. Ward's cluster analysis for weather stations near Florissant Fossil Beds National Monument. Numbers near each node indicate bootstrap confidence, based on 10,000 pseudoreplicates. Dotted lines delineate clusters that have greater than 90% bootstrap support. Climate zones, which were selected according to criteria described in the methods, are labeled on the bottom. The dendrogram based on average clustering contained the same zones.

Zone 1 weather stations have greater DTR during the summer than winter, while Zone 2 stations have relatively great DTR during winter and summer (Fig. 30). Zone 2 stations are generally closer to the national monument than Zone 1 stations (Fig. 31). The PCAs do not provide strong support for the separation of these zones (Figs. 32, 33). Because of the small number of stations involved, mean winter lengths were estimated, but elevation-based subzones were not assigned (Table 5).

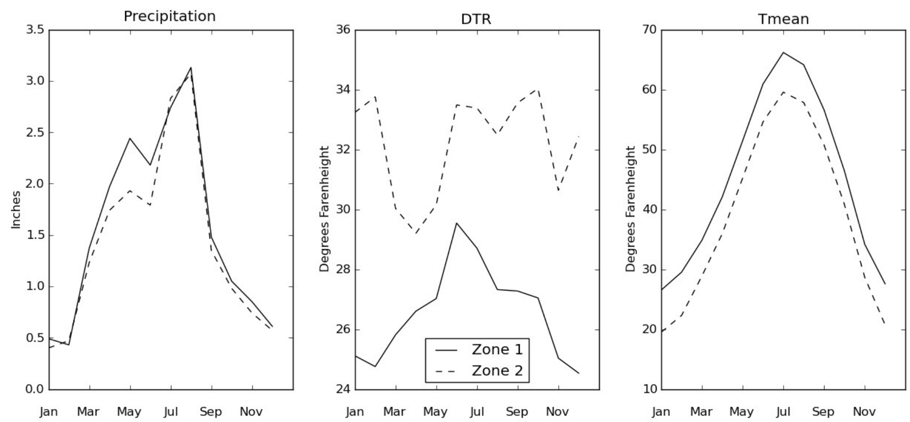

Figure 30. Monthly mean precipitation, diurnal temperature range (DTR), and mean temperature (Tmean) for each climate zone. Means were calculated from 1971-2000 normals from all weather stations in each zone.

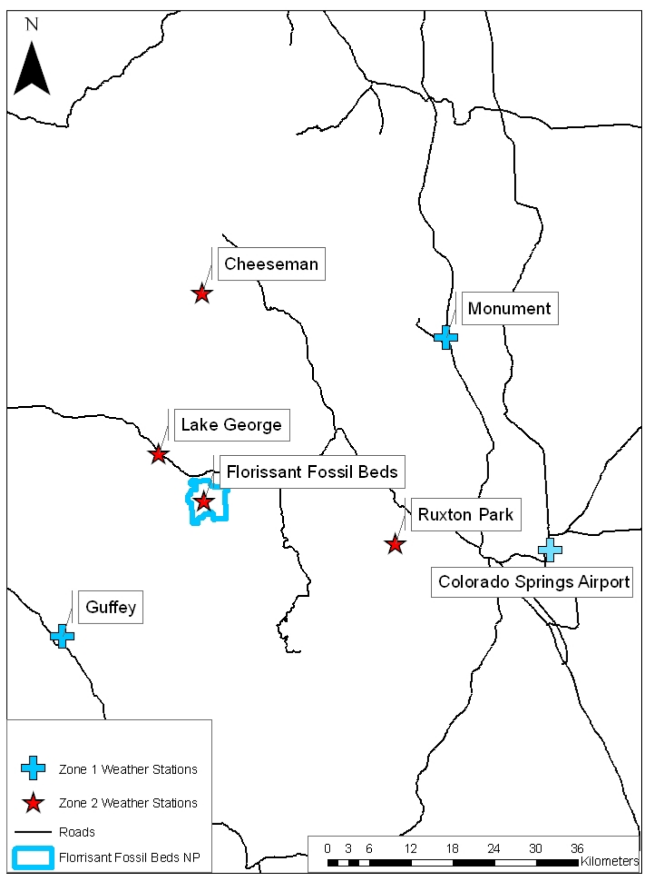

Figure 31. Map showing the location of weather stations included in the analysis.

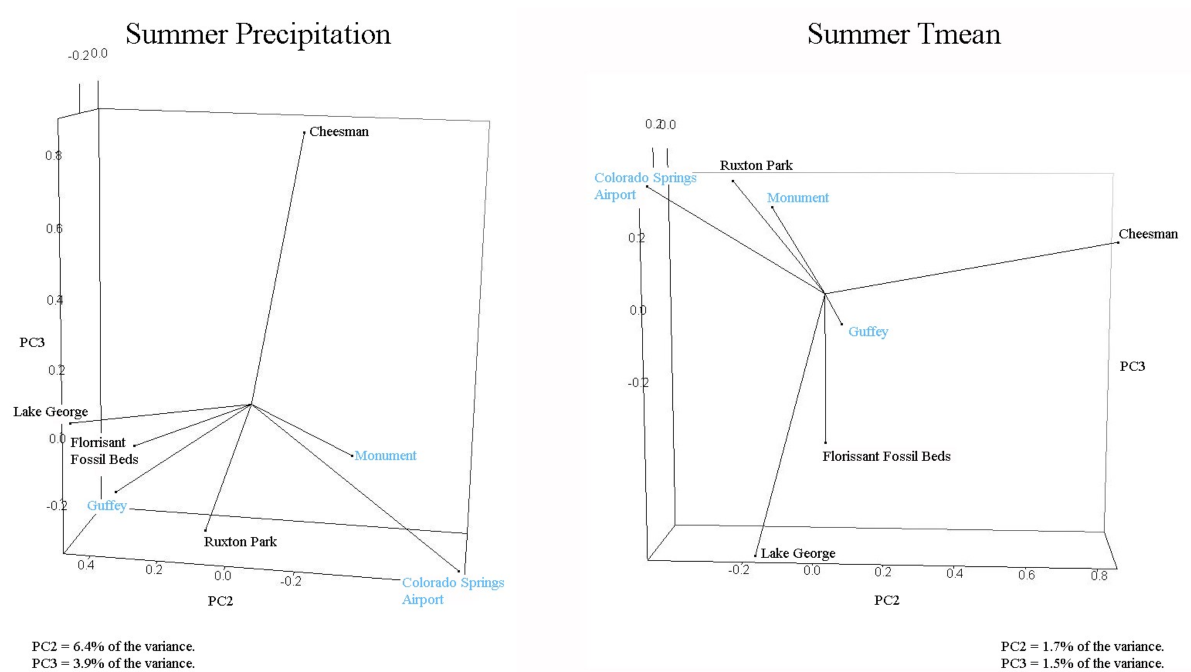

Figure 32. Loading plots of S-mode Principal Components Analysis of 1895 – 2008 summer (June, July, August) precipitation and mean temperature for weather stations near Florissant Fossil Beds National Monument. Colored text indicates zone membership for each station. Blue = Zone 1, Black = Zone 2.

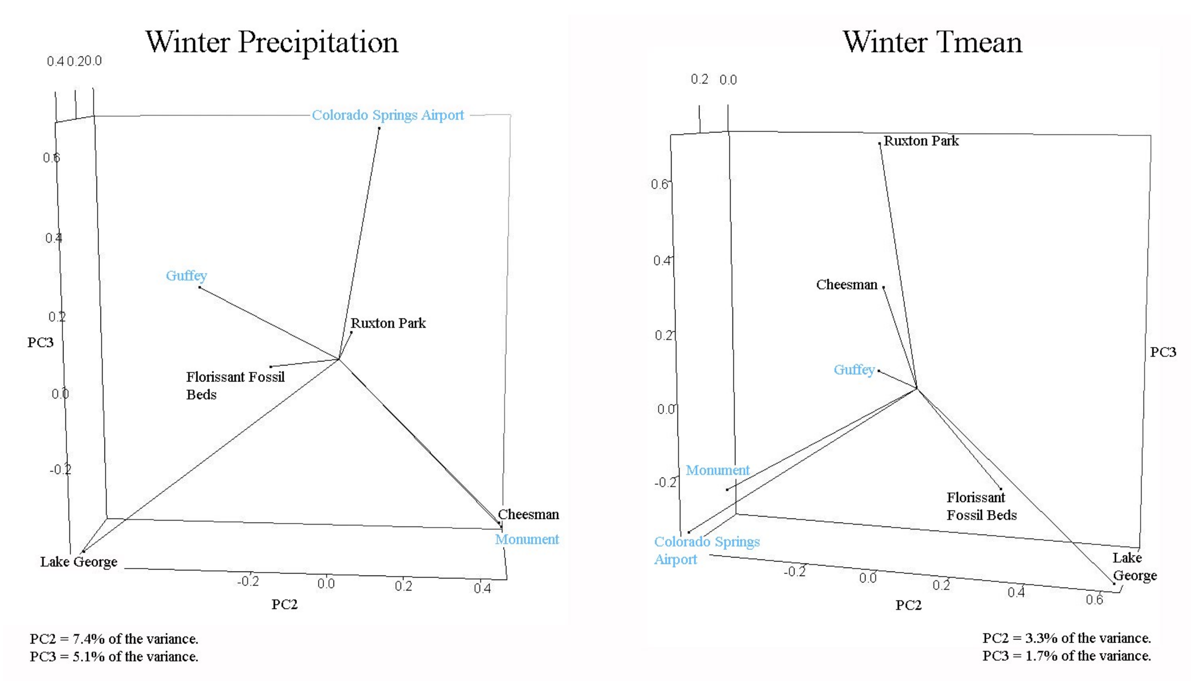

Figure 33. Loading plots of S-mode Principal Components Analysis of 1895 – 2008 winter (December, January, February) precipitation and mean temperature for weather stations near Florissant Fossil beds National Monument. Colored text indicates zone membership for each station. Blue = Zone 1, Black = Zone 2.

Table 5. Estimated winter length (days) for weather stations in and near Florissant Fossil Beds National Monument. Stations are arranged in ascending order of winter length. "N/A" indicates that there were insufficient data to obtain an accurate estimate. Stations with insufficient data are arranged in ascending order of elevation.

Station Name	Climate Zone	Elevation (m)	Mean Winter Length (Days)	# Winters Calculated	Station Type
Colorado Springs Airport	1	1856	56.14	28	COOP
Cheesman	2	2097	72.56	25	COOP
Monument	1	2158	N/A	4	COOP
Guffey 10SE	1	2620	77.9	20	COOP
Lake George 8SW	2	2606	130.88	26	COOP
Ruxton Park	2	2758	174.93	15	COOP

CONCLUSIONS

It is important to bear in mind that the analyses in this report were based either on weather station data or on point estimates derived for the grid cell occupied by a particular weather station. As a result, the climate zones presented in this report are formally defined as groups of weather stations. In contrast, maps depicting the geographic area associated with the weather stations in each zone are intended as less formal illustrations. There are three reasons that these maps should be interpreted with caution. First, the PRISM data used to generate the zone boundaries in the maps are estimates rather than actual observations (Daly et al. 1994, 2000, 2001). Second, different methods of analyzing these PRISM estimates statistically may produce different zone boundaries (Tercek et al. In review). Third, the maps contain only information from the cluster analysis of seasonal data and do not reflect station groupings defined by the principal components analysis (PCA) of long-term variability. The differences between the PCA vs. cluster analyses can be significant. For example, in Glacier National Park, the PCA usually grouped weather stations from zones 1 and 2b as a unit that was opposed to zone 2a stations, and zone 1b stations were mixed throughout all the other zones. In contrast, the cluster analyses defined these four zones (1a,1b,2a,2b) as distinct units (Fig. 1). When ROMN discusses climate zones in their park units, it will be important to distinguish between zones defined for long-term trend analyses (PCA results) vs. those defined in terms of seasonal patterns (cluster analysis results).

The statistical techniques used in this report provide better results when they are applied to relatively large geographic areas. The zones defined for Glacier and Rocky Mountain National Parks show clear differences in seasonal pattern (cluster analysis) and long-term variability (PCAs). Consequently, these zones are suitable for use in ROMN's climate status and trend reports. The zones defined for Great Sand Dunes National Park (GRSA) have different seasonal and long-term patterns, but the geographic areas associated with the weather stations in each zone overlap significantly. Long-term analyses that are scheduled for ROMN (Frakes et al. 2009) may find different trends among the zones defined for GRSA. However, because the geographic area in and near GRSA has low correlation to the averages calculated across all the weather stations in each zone, annual climate status reports might be more useful to park managers if they focus on individual weather stations, such as Great Sand Dunes, Medano Pass, and South Colony. In other words, reporting climate zone averages on an annual basis for GRSA is likely to be less useful than reporting annual averages for individual weather stations.

Because of the small geographic areas involved, there is probably little practical value in implementing the zones defined for Little Bighorn Battlefield (LIBI), Grant-Kohrs Ranch (GRKO), and Florissant Fossil Beds (FLFO), either for annual or long-term trend reports. In the case of LIBI, it may be more expedient to write annual climate reports that focus on nearby weather stations, such as Lame Deer, Hardin, Crow Agency, and Busby. Grant-Kohrs Ranch should probably be viewed as one climate zone that spans an elevation gradient, with SNOTEL stations ("Zone 2") at the higher elevations. Reports written for FLFO might focus only on nearby weather stations, which are labeled as "Zone 2" in this report.

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