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Development of Alternate Climate Divisions for Colorado Based on Gridded Data

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The official climate divisions for the contiguous United States are used for a wide range of purposes, including ongoing climate monitoring, and through NOAA's long-standing nClimDiv dataset. In Colorado, the climate divisions are based around the basins of the large rivers that flow out of the state. However, considering the complex topography and climate of the state, these divisions do not always represent key climate variations and changes. This study builds upon an approach first developed by Wolter and Allured to establish alternate climate divisions that more closely reflect observed climate variability across Colorado. Hierarchical cluster analysis is applied to gridded temperature and precipitation data (NOAA's nClimGrid) from 1950-2021 to identify areas with similar climate variability, then manual inspection is used to establish 11 divisions. These resulting divisions are being used in an updated state-level climate change assessment. The method is flexible and uses open-source tools that could be extended to other regions or datasets.

1. Introduction

The contiguous United States is divided into 344 climate divisions (Figure 1), which have a history dating back to the early 20th century (Guttman and Quayle 1996). The current divisions were established in the 1950s, and in the western US largely align with river drainage basins. These divisions have been used extensively for analysis of climate variability and change, and for real-time climate monitoring. One such example is NOAA's nClimDiv dataset (Vose et al. 2014a), which for many years has served as a "flagship" monthly climate dataset for the United States. Prior to 2013, divisional averages for temperature and precipitation were calculated using averages of station observations, primarily from the Cooperative Observer program (Guttman and Quayle 1996). More recently, NCEI has developed a gridded climate dataset (nClimGrid; Vose et al. 2014b) for the CONUS that better represents spatial variations and complex terrain, and nClimDiv now reflects averages of nClimGrid over the climate divisions. Climate divisions remain an important method of representing climate in the CONUS, including through NCEI's monthly maps and Climate at a Glance tool (NOAA 2023).

The existing climate divisions have numerous limitations, however. As noted by Guttman and Quayle (1996), the divisions were created with factors other than climate in mind, including river basins and crops, and they may not reflect actual climate variations across each state. The number of divisions per state varies, with some large states having up to ten divisions, but others, including Colorado, having only five. Guttman and Quayle (1996) pointed specifically to the climate division covering all of western Colorado, noting that "An example of a division that is likely to be inhomogeneous for most applications is the Colorado Drainage Division." This limitation has been apparent in routine climate monitoring activities at the Colorado Climate Center, an example of which is presented in section 4.

The limitations associated with the existing climate divisions, especially in the complex terrain of the western US, were also pointed out by Wolter and Allured (2007). To address these problems, they applied hierarchical cluster analysis to seasonal temperature and precipitation observations at stations across the CONUS. Their analysis produced a set of alternate climate divisions (Figure 2) that is based on observed climate variability, rather than on geographic or political boundaries. Marston and Ellis (2021) applied related methods to delineate regions of the US with similar precipitation variability. Although the Wolter and Allured (2007) climate divisions have not attained wide use in official national products, they have been employed in state-level climate assessments (e.g., Lukas et al. 2014).

This study extends Wolter and Allured (2007)'s work, by applying a similar method to gridded temperature and

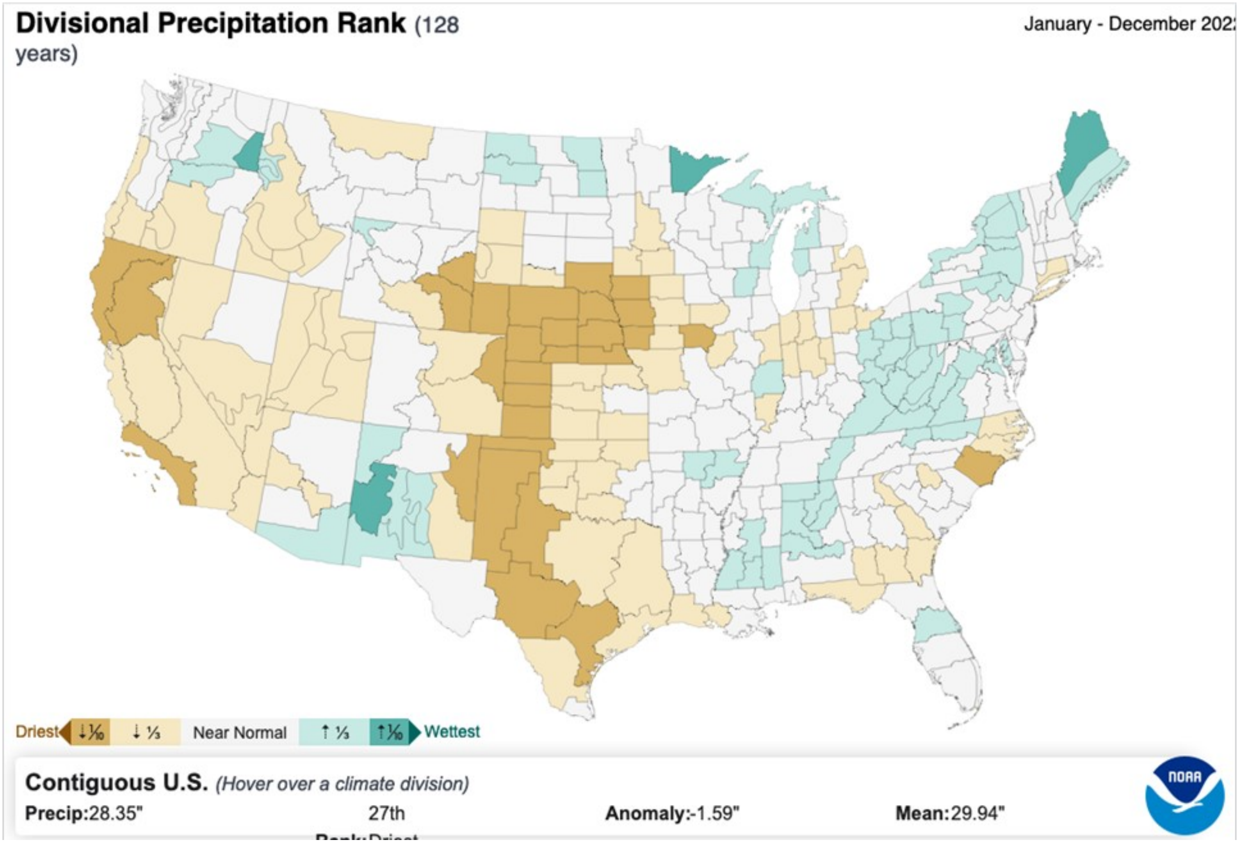

FIGURE 1: Precipitation rankings for calendar year 2022, showing the 344 climate divisions across the CONUS. Obtained from https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/divisional/mapping/110/pcp/202212/12/rank

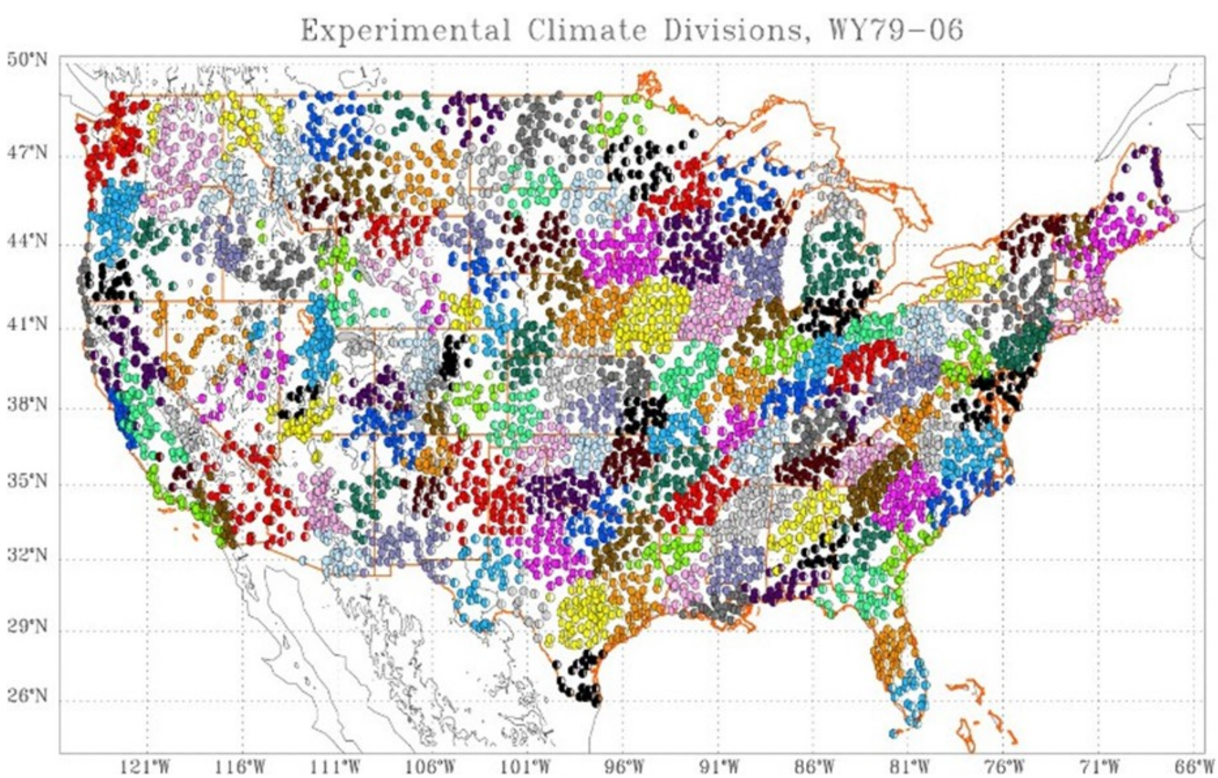

FIGURE 2: Experimental climate divisions based on temperature and precipitation station data. Each dot is a COOP station and a cluster of dots of the same color represents a new climate division. Reproduced from Wolter and Allured (2007).

precipitation data, specifically the nClimGrid dataset (Vose et al. 2014b). Gridded climate data have the advantage of being spatially and temporally continuous, so the difficulties associated with missing data and varying station density are avoided. Alternate climate divisions are developed for the state of Colorado, for use in monitoring of climate variability and change at scales larger than counties, that are more representative than the existing climate divisions for the state.

Section 2 provides a description of the data and method, and the results follow in section 3. Section 4 presents some applications of the alternate divisions, sensitivity tests are presented in section 5, and section 6 concludes the manuscript.

2. Method

As in Wolter and Allured (2007), the purpose of this work is to define climate divisions that reflect areas with similar *climate variability*. In other words, locations that tend to be, for example, warmer or drier than average during the same months. They do not necessarily represent locations with similar *climates*—in Colorado, these would mostly just be defined by elevation (higher elevations colder and wetter, lower elevations warmer and drier.) Instead, we focus here on locations that are affected by similar weather patterns and thus vary together.

Monthly nClimGrid average temperature and precipitation data, available on a 4-km latitude/longitude grid, were obtained in April 2022 and subset to the state of Colorado (37–41°N latitude, 102–109°W longitude) and the years 1895-2021. Given initial testing, and knowledge that the station record in Colorado is more complete after the 1940s, the primary analysis uses nClimGrid from 1950-2021. This is an array of 170×98 grid points, with 864 timesteps for each variable. Sensitivity to the number of years included in the analysis are presented in section 5.

Anomalies with respect to the 1950-1999 mean were calculated for each monthly average temperature and precipitation value. Following Wolter and Allured (2007), both temperature and precipitation anomalies were used in the analysis. The arrays for each variable were reshaped into one with 864 rows (one for each time) and 16660 columns (one for each grid point). The correlation matrix (i.e., the correlation between each time series column in these arrays and each other time series) was calculated for each variable.

The correlation r was converted to a squared Euclidean distance $d^2 = 2(1-r)$ for each variable, and then the sum of those distances was used as a combined distance for the two variables (temperature and precipitation). Then, following

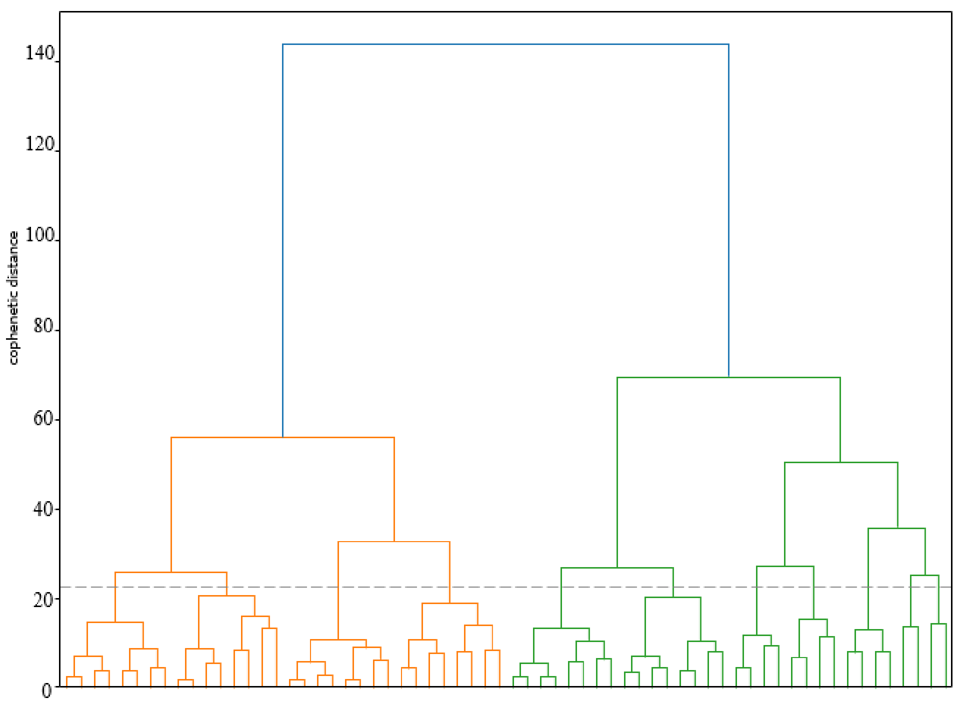

Figure 3: Dendrogram of linkage matrix produced by Ward's hierarchical clustering method, representing the dissimilarity between the combined temperature-precipitation anomaly time series at each grid point. The blue lines at the top show that there are two clusters that are very dissimilar, and then decreasing dissimilarity descending down the dendrogram.

Amidon (2020), the hierarchical clustering routine in the scipy package (Virtanen et al. 2020) was used to calculate a linkage matrix, using Ward's method, which minimizes the variance within each cluster (the same method used by Wolter and Allured (2007)). This linkage matrix can be visualized using a dendrogram, which illustrates how similar or dissimilar the combined time series are at each grid point (Figure 3). From this matrix, clusters can be calculated, with a cluster label assigned to each of the 16660 grid points, and then mapped back to physical space with the associated 170×98 latitude/longitude grid.

3. Results

The primary subjective decision required in this method is where to apply the "cutoff" between clusters, or in other words, how many clusters should there be? Figure 3 shows that there are two clearly defined clusters (the blue lines near the top), and then decreasing dissimilarity descending the tree. The grid points associated with each of these clusters were identified and visualized on maps, and this information along with the authors' understanding of the climate and geography of Colorado were used to select an appropriate cutoff.

The two most clearly defined clusters correspond approximately to the areas west and east of the Continental Divide (Figure 4a). These parts of the state do indeed correspond to very different climate variability, and *a priori* were the general divisions the authors would have identified if defining only two divisions. This result lent confidence that the method was producing reasonable results. Maps for increasing numbers of divisions were then inspected (Figure 4). Using the current number of official climate divisions in Colorado (five), the results of this method bear some similarity to those divisions, with the divisions encompassing northeast and southeast Colorado corresponding roughly to the Platte and Arkansas River drainages (Figure 4b), and another division in south-central Colorado that includes the Rio Grande River drainage. An advantage of this method, however, is that western Colorado is divided into northern and southern portions, unlike the existing division that includes all of western Colorado, even though there are substantial differences in climate variability from north to south. Increasing to eight divisions further splits both western and eastern Colorado (Figure 4c).

After inspecting the results of different numbers of clusters, the authors determined that the map with 11 clusters (Figure 5) struck a balance between too few and too many divisions, and identified key regions of the state that are often considered in contexts such as weather forecasts. They correspond reasonably well, though with some differences in the details, with the divisions of Wolter and Allured (2007) and Lukas et al. (2014) based on station data. These 11 climate divisions were assigned descriptive names (Figure 5), and will be used as the "final" set of alternate climate divisions for the analysis to follow.

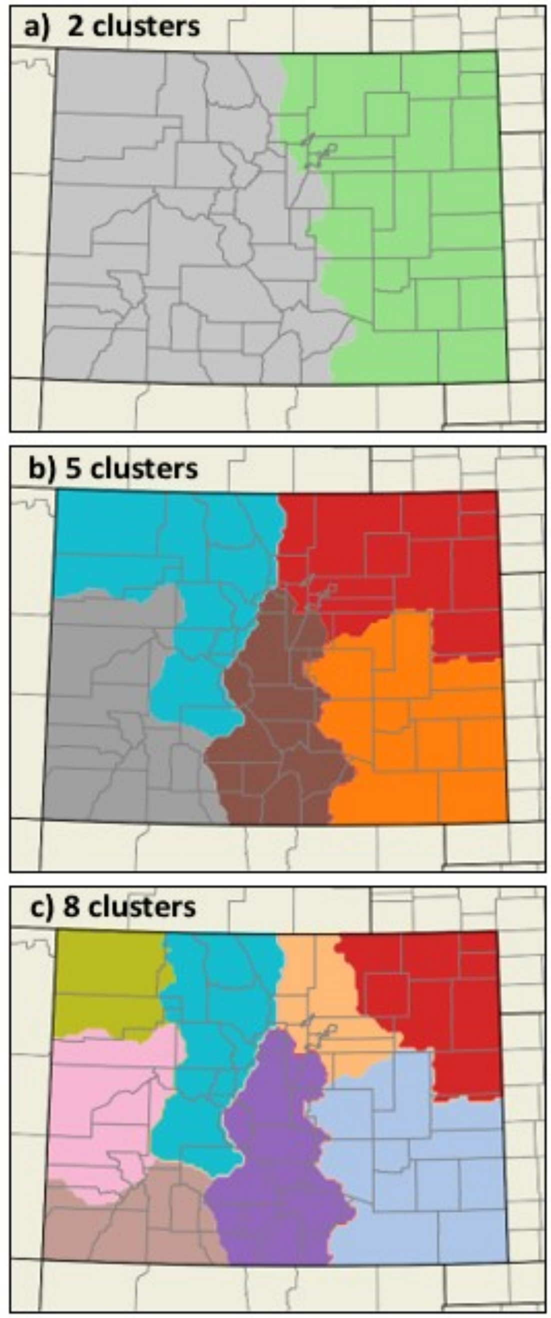

FIGURE 4: Maps illustrating the results when choosing to divide the state of Colorado into (a) 2, (b) 5, and (c) 8 clusters.

4. Applications

A key motivation for developing this set of alternate cli-

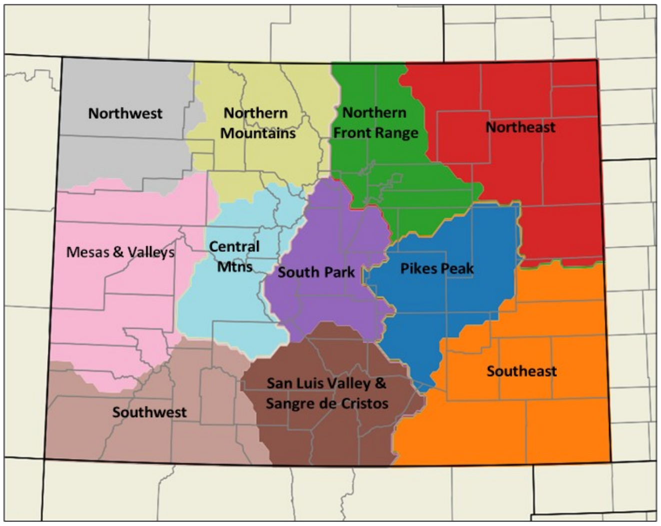

FIGURE 5: Final set of eleven alternate climate divisions, with names assigned by the authors based on how they are often referred to in relation to climatology or local convention.

mate divisions is an update to the state- level climate change assessment report of Lukas et al. (2014). In that report, the Wolter and Allured (2007) alternate divisions were used to provide a more granular depiction of climate variability and change in Colorado, and the authors wanted to provide similar perspective in the updated report. However, the Wolter and Allured (2007) divisions were based on station data, and not all of the stations used in that analysis have maintained a continuous record. We also did not have access to the divisions assigned to each of the stations used in that analysis. Furthermore, since the publication of that report, new gridded datasets such as nClimGrid became available, and are well suited for use in the updated report.

The alternate climate divisions have been used to characterize changes in temperature and precipitation in different parts of Colorado (e.g., Figures 6 and 7). For example, time series of temperature and precipitation anomalies over the nClimGrid record (1895-2022) were analyzed (Figure 6b), and the Theil-Sen trend estimator was applied to identify trends over each month and season, and also annually. The calculated trends were converted to changes over the period of record, and visualized as heat maps (Figure 6a). Trends and changes were calculated for both the full record, and for the period from 1980-2021, when the signal of anthropogenic warming has become most apparent. Among the alternate climate divisions, the greatest warming over the full record has been observed in March, and in the divisions in northern and western Colorado (+5-7˚F in these divisions in March). In contrast, the South Park division in central Colorado has experienced comparatively less warming.

These changes are also easily visualized on maps of the alternate climate divisions (Figure 7). Over the full period of record, the Northwest and Mesas & Valleys divisions have experienced the most warming (over 4˚F), whereas in the

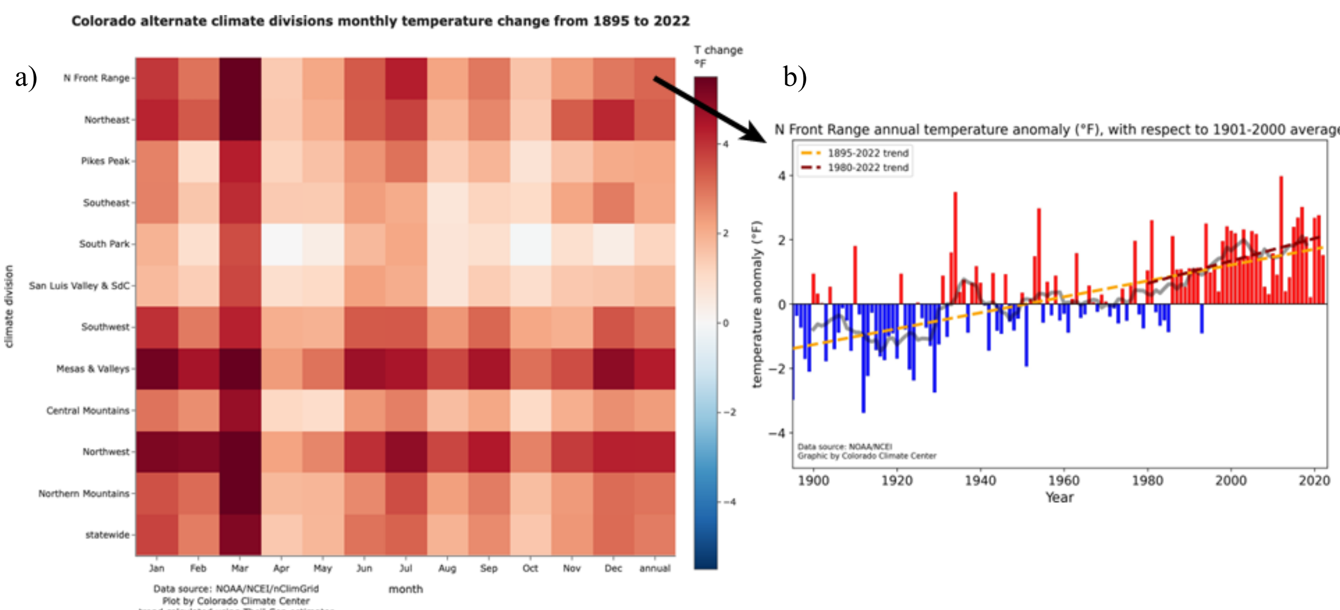

FIGURE 6: (a) Heatmap showing temperature change (in ˚F) from 1895 to 2022 for each month and alternate climate division. Changes were calculated as the endpoints of a Theil-Sen trend line. (b) Example time series of temperature anomalies with respect to the 1901-2000 average for the Northern Front Range division. The 10-year rolling mean is shown in a dark gray line, and the Theil-Sen trend lines are shown in orange for the 1895-2022 period and in brown for the 1980-2022 period.

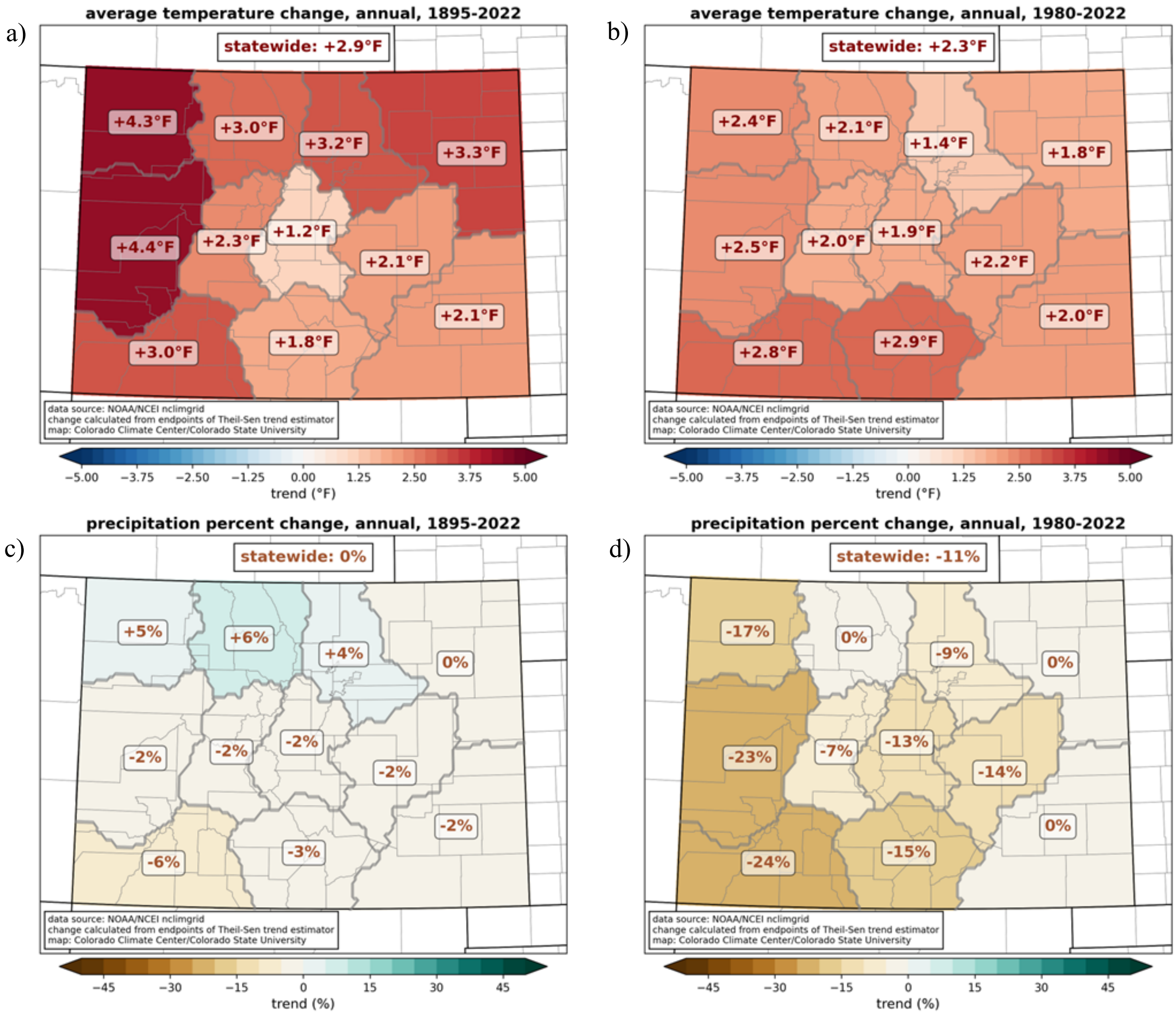

FIGURE 7: (a) Temperature change (˚F) from 1895-2022 for the alternate climate divisions in Colorado, calculated as the endpoints of the Theil-Sen trend estimator. (b) As in (a), except for the period 1980-2022. (c) Percent change in precipitation from 1895-2022 for the alternate climate divisions in Colorado, calculated as the endpoints of the Theil-Sen trend estimator. (d) As in (c), except for the period 1980-2022.

period since 1980, warming has been greatest in the Southwest and San Luis Valley & Sangre de Cristos divisions (nearly 3˚F), with relatively less warming in the Northern Front Range. Trends in precipitation over the full record are minimal, with no overall statewide trend. However, in the period since 1980, which has been characterized by several periods of intense drought, precipitation decreased by over 20% in the Southwest and Mesas & Valleys divisions. In contrast, there has been no trend in precipitation over this period in the Northeast, Southeast, and Northern Mountains divisions. (A full set of these maps, including monthly and seasonal trends, is available at https://climate.colostate.edu/cc_in_CO/div_trends.html). Displaying the trends using these alternate climate divisions reveals changes that may be harder to identify when using the larger official climate divisions, while still providing regional summaries that may be more robust and easier to understand than county-by-county analyses. (Colorado has 64 counties, more than any other western state.)

The alternate climate divisions can also be useful for climate monitoring, and for characterizing recent conditions over areas that are more representative than the official climate divisions. An example is shown in Figure 8, for the spring season of 2018. Drought intensified over much of southern Colorado during this period, whereas precipitation was closer to average across the northern part of the state.

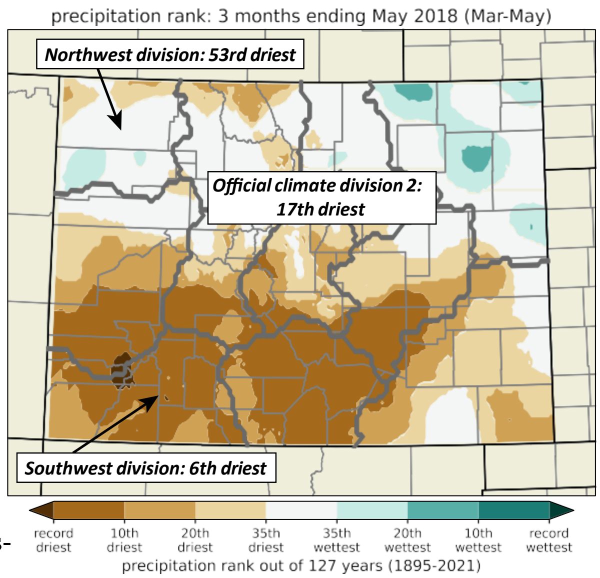

FIGURE 8: Precipitation rank for March-April-May 2018, compared to all other March-April-May periods during 1895-2021 in nClimGrid. The alternate climate divisions are also shown.

Using the official climate division that covers all of western Colorado, this ranked as the 17th-driest spring on record. However, that ranking does not capture the spatial variability that was actually observed. Using the alternate climate divisions instead reveals that for southwestern Colorado, it was the 6th-driest spring on record, whereas for northwestern Colorado it was only the 53rd-driest. The alternate divisions make these spatial distinctions much clearer, and emphasize where the most extreme conditions are occurring, while still being straightforward to communicate.

5. Sensitivity Tests

To test the sensitivity of the calculated clusters to the choices of the data included in the analysis, the cluster analysis was conducted for other possible choices. Specifically, the sensitivity to the record length was tested by including data from the entire nClimGrid record (1895-2021), and from only 1980-2021, for comparison to the data from 1950-2021 that was used in the final version of the analysis. Further, the use of monthly anomalies was compared to rolling three-month periods as were used by Wolter and Allured (2007).

In western Colorado, the clusters are generally insensitive to the record length and the use of monthly vs. 3-monthly data (Figure 9). The divisions identified when using the full record (Figure 9a) and just 1980-2021 (Figure 9b) are almost identical to those in the "final" alternate divisions in western Colorado (Figure 5). When using rolling 3-month periods, the "Northern Mountains" division expands southward, leaving only a very small division to its south (shown in pink in Figure 9c). This small division, which roughly corresponds to the Gunnison River valley, did not seem like a distinct enough region climatologically, and this partially motivated the authors' choice to use the results from monthly data rather than 3-monthly averages.

East of the continental divide, there was somewhat more variation in the details of the divisions identified in the cluster analysis. For example, each of the sensitivity analyses placed a division between the San Luis Valley and the Southeast division, whereas the final set of divisions has the San Luis Valley & Sangre de Cristos division bordering the Southeast division, with another division to its north (Pikes Peak) (cf. Figure 9 and 5). Each of the sensitivity tests also depicted the northward extent of the division encompassing the San Luis Valley in southern Colorado differently. Overall, the sensitivity analyses point to a few different conclusions. Most importantly, they show that the general layout of alternate climate divisions in Colorado is not overly sensitive to the details of the data chosen for analysis. This gives confidence that the final set of divisions is robust and not simply an artifact of arbitrary decisions. On the other hand, they also show that choices related to the dataset do result in differences in the details of the final map, and that there is likely no "perfect" version of this analysis. The highly variable climate of Colorado is not easily put into categories such as these, and other researchers or users might prefer one of the other maps shown in Figure 9 to the final version chosen by the authors. This is one motivation for providing the code used to conduct the cluster analysis, which uses open-source tools, along with the manuscript.

6. Conclusion

Building upon the previous work of Wolter and Allured (2007), this manuscript describes the development of alternate climate divisions for the state of Colorado, which has complex climates that are not well-represented by the current official climate divisions. Applying hierarchical cluster analysis to gridded climate data, along with knowledge of Colorado's climate variability, 11 alternate climate divisions were established that better reflect the geographic and climatological diversity of the state. The alternate divisions have been used to illustrate trends in temperature and precipitation around Colorado, which are being used in a state -level climate change assessment report1. The alternate divisions are also useful for climate monitoring, as they provide information that is more granular than the existing climate divisions, but more representative than county-level data.

The analysis conducted for this manuscript could be readi-

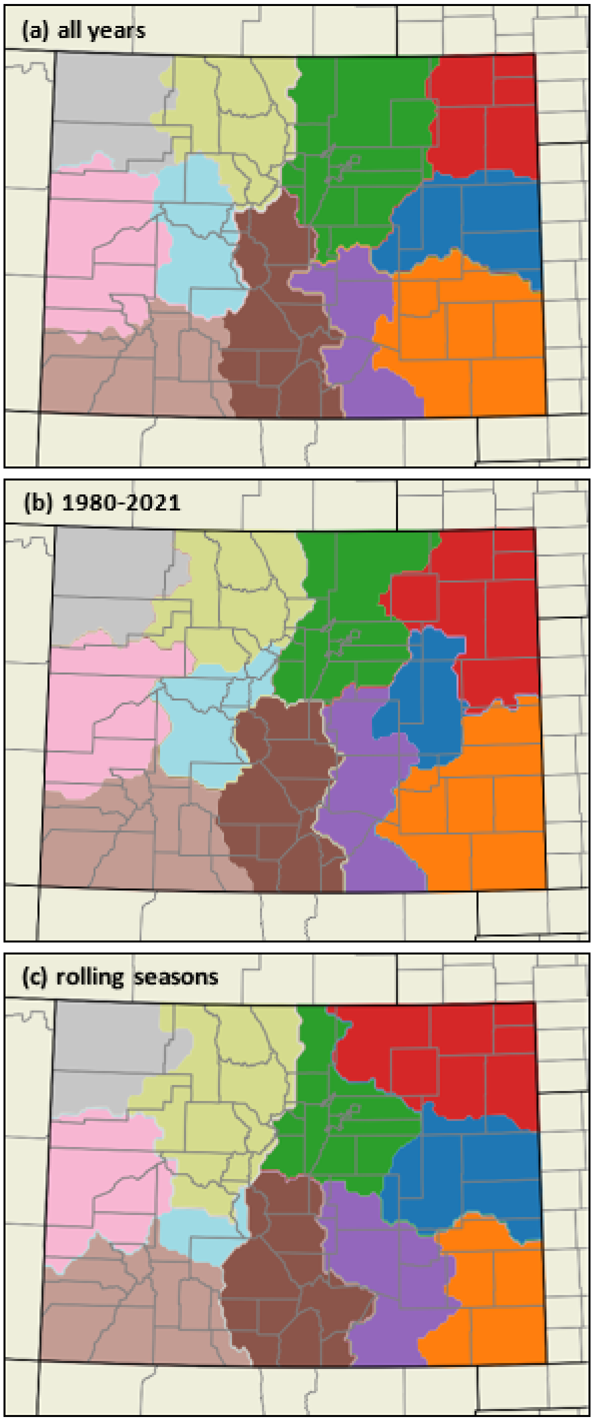

FIGURE 9: Results of cluster analysis when identifying 11 clusters, calculated from using (a) data from all years in the nClimGrid record; (b) data from 1980-2021; and (c) rolling three-month averages for data from 1950-2021.

ly applied to other parts of the CONUS, or to other gridded climate datasets, using the provided code. These methods may allow other state climate offices to assess the representativeness of existing climate divisions, and potentially develop purpose-built alternatives if they are needed for particular applications.

Acknowledgments

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Data Availability Statement

nClimGrid data were obtained from NCEI at: https://www.ncei.noaa.gov/thredds/catalog/data-in-development/nclimgrid/catalog.html

Because nClimGrid data sometimes changes retrospectively (owing to late-arriving observations, etc.), the version of the data used for the cluster analysis is available in the Dryad repository at: https://doi.org/10.5061/dryad.z612jm6h6

A Jupyter notebook with the code used to conduct the cluster analysis, along with a netCDF file of the final set of alternate climate divisions, are available at: https://github.com/russ-schumacher/CO_altclimdivs

References

Amidon, A., 2020: How to apply hierarchical clustering to time series. Available online at: https://towardsdatascience.com/how-to-apply-hierarchical-clustering-to-time-series-a5fe2a7d8447

Guttman, N. B., and R. G. Quayle, 1996: A historical perspective of U.S. climate divisions. *Bulletin of the American Meteorological Society*, **77 (2)**, 293–304, https://doi.org/10.1175/1520-0477(1996)077<0293:AHPOUC>2.0.CO;2

Lukas, J. J., J. J. Barsugli, N. J. Doesken, I. Rangwala, and K. Wolter, 2014: Climate Change in Colorado: A Synthesis to Support Water Resources Management and Adaptation. Tech. rep., Western Water Assessment, University of Colorado Boulder, 114 pp.

Marston, M. L., and A. W. Ellis, 2021: Delineating precipitation regions of the Contiguous United States from cluster analyzed gridded data. *Annals of the American Association of Geographers*, **111 (6)**, 1721–1739, https://doi.org/10.1080/24694452.2020.1828803.

NOAA, 2023: Climate at a Glance Divisional Mapping. Available online at: https://www.ncei.noaa gov/access/monitoring/climate-at-a-glance/divisional/mapping, accessed 13 February 2023.

Virtanen, P., and Coauthors, 2020: SciPy 1.0: Fundamental algorithms for scientific computing in python. *Nature Methods*, **17**, 261–272, https://doi.org/10.1038/s41592-019-0686-2.

Vose, R., and Coauthors, 2014a: NOAA Monthly U.S. Climate Divisional Database (NClimDiv). National Climatic Data Center, https://doi.org/10.7289/V5M32STR.

Vose, R., and Coauthors, 2014b: NOAA Monthly U.S. Climate Gridded Dataset (NClimGrid), Version 1. NOAA National Centers for Environmental Information, accessed 8 April 2022, https://doi.org/10.7289/V5SX6B56.

Wolter, K., and D. Allured, 2007: New climate divisions for monitoring and predicting climate in the U.S. *Intermountain West Climate Summary*, **3**, 2–6, available online at: https://wwa.colorado.edu/sites/default/files/2021-09/IWCS_2007_Jun_feature.pdf.