New Climate Divisions for Monitoring and Predicting Climate in the U.S.

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This article describes a long-term effort to create a more rational, statistically based set of national climate divisions that would help improve drought monitoring and climate forecasting in the U.S.

Motivation

Near-real time climate monitoring, long-term climate change assessments, and statistical climate predictions in the U.S. are often based on so-called "Climate Divisions" (Figure 1a; Guttman and Quayle, 1996). These come from century-long efforts to organize climate observations across the country, which were finalized in the 1950's to match up with crop reporting districts, county lines, and/or drainage basins. Perhaps surprisingly given their use, the representation of the underlying climate was not an explicit consideration (Guttman and Quayle, 1996). The vast majority of data used in climate division analyses comes from climate stations that are part of NOAA's voluntary Cooperative Observer Program (COOP). This network of climate stations has been collecting daily high and low temperatures, precipitation, and snowfall since 1890. Climate division time series are computed by simply averaging all available, "representative" COOP station data since 1931 into single monthly values, while older time series (between 1895 and 1931) were derived from state-wide averages.

Climate divisions are used in many climate-related monitoring products, like the U.S. Drought Monitor, regional SPI, and temperature assessments, because they allow for an easy calculation of regional averages, and a comparison of recent climate anomalies against a century-long record. The Climate Prediction Center (CPC) has used so-called "mega-divisions" (based on merging smaller climate divisions) as targets for statistical climate predictions, and for verification purposes.

The 344 U.S. climate divisions allow for up to ten divisions per state; however, they cover the conterminous United States rather unevenly (Figure 1a). Many states do have ten divisions (such as Wyoming and Idaho), but some rather large states do not. Colorado is a large state with complex topography whose regional climates are not accurately represented by only five climate divisions, for example, there is only one division covering the mountainous western third of the state. Decisions about how to organize climate divisions were made on a state-by-state basis rather than from a national perspective (Guttman and Quayle, 1996). For more information about traditional climate divisions, and to view monthly time series for each one, go to: http://www.cdc.noaa.gov/USclimate/USclimdivs.html.

Climatologists have long suspected that the simple averaging of COOP stations into climate divisions is not optimal for depicting regional climate anomalies, especially for precipitation. We verified that suspicion by correlating individual COOP station

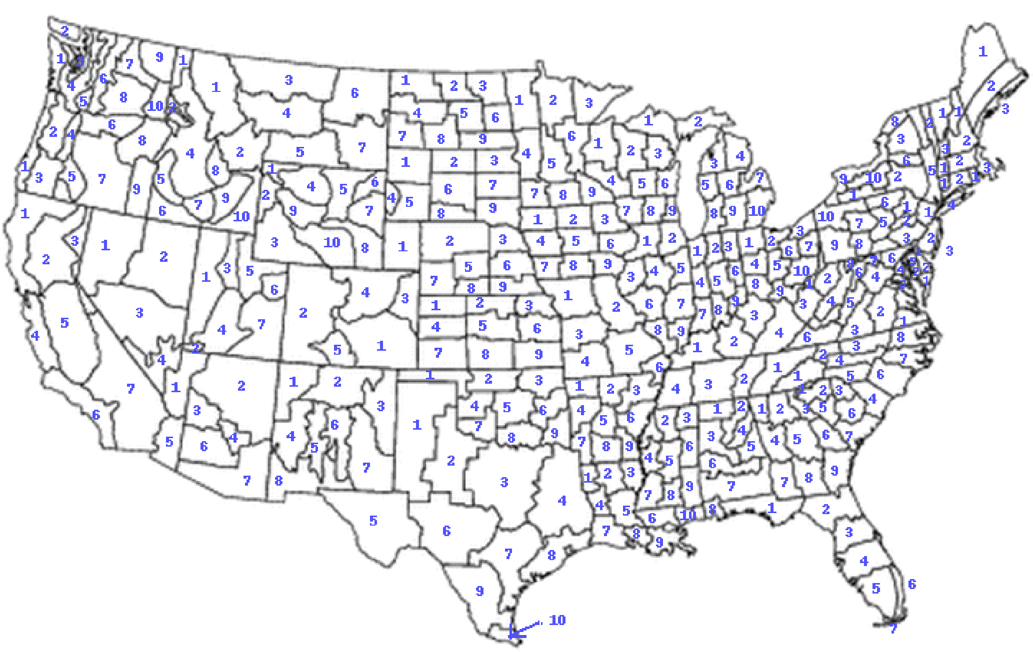

Figure 1a. Climate division map for the lower 48 states in the U.S. (numbered separately for each state).

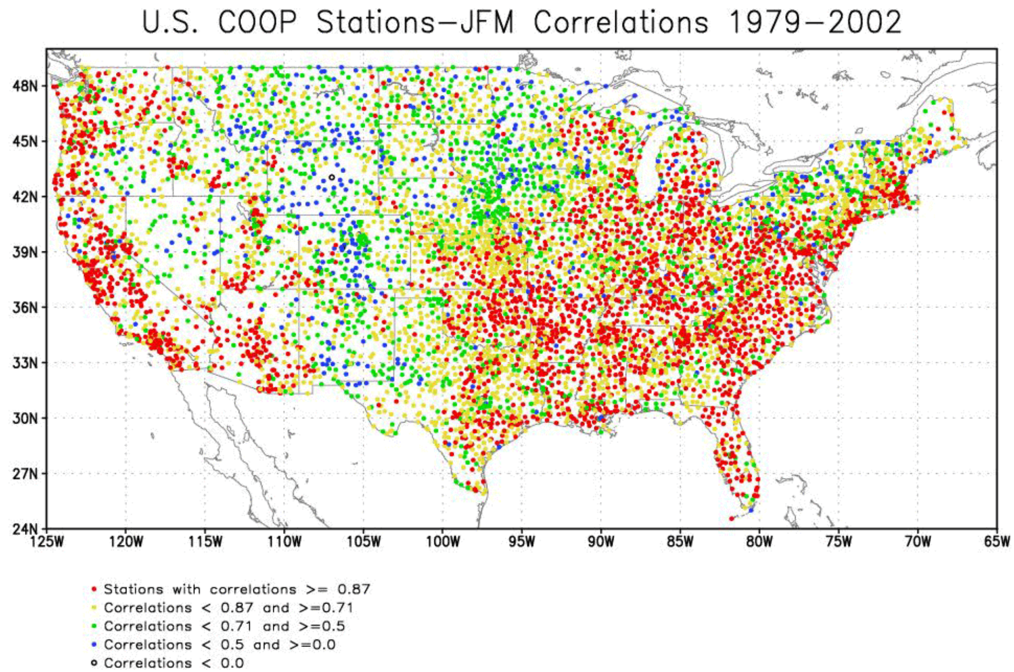

Figure 1b. Seasonal correlations between Climate Division time series and COOP station time series during Jan-Mar 1979-2002 (for precipitation). Green and blue dots show that divisional indices carry less than 50% of the local seasonal precipitation variance in the Great Basin, along the Rocky Mountain Front Range, and even in the Upper Midwest.

time series against divisional averages (Figure 1b). Results show that much of the Interior West is not well represented by divisional averages, particularly those including the higher terrain of Wyoming and Colorado. During the winter snow accumulation season in parts of the Interior West, there are poor correlations between individual stations and the associated climate division (Figure 1b), and the situation is even worse in the summer (not shown).

Low correlations between individual COOP stations and divisional averages translate into poor reliability when large-scale drought assessments or ENSO-related forecasts based on these divisions are scaled down to the station level. This is one reason why drought monitoring and seasonal climate forecasting are difficult in the Interior West. In addition, some of the higher elevation SNOTEL sites may correlate negatively with their climate division time series. This is due to orographic effects of the Rocky Mountains: during the winter season, strong westerly winds yield large snowfall amounts on the windward side of this mountain range, while the valleys to the east may experience chinook-like windstorms and dryness. Because most COOP stations are located in valleys, climate division averages may end up with negative precipitation anomalies, while SNOTEL-based assessments of the snow pack often show a surplus. This type of precipitation pattern is not well captured by traditional climate division data, and the winter of 2005-06 is a recent example.

Analogous maps for seasonal temperature correlations do not show the same disparity between station and climate division data, most likely due to the larger spatial coherence of temperature anomalies. Nevertheless, wintertime regional temperature anomalies are also not well represented by climate divisions in the orographic regions of the Interior West.

In 2003, we embarked on a long-term effort to create a more rational, statistically based set of national climate divisions that would help improve drought monitoring and climate forecasting in the U.S. The rest of this paper documents the employed method for deriving these new experimental climate divisions, the latest version of this product, and follow-up deliverables.

Methodology: Statistical Approach to Experimental Climate Divisions

In order to ascertain which climate stations have the tendency to exhibit the same climate anomalies, we performed analyses on temperature (T), precipitation (P), and combined (T,P) records. We found that the last approach (with combined time series) yielded better defined climate regions, than either precipitation or temperature records alone.

From currently available records for 17,575 COOP stations in the lower 48 states, we selected 4,324 stations with both sufficient precipitation and temperature records to perform statistical analyses for Water Years 1979 through 2006 (October 1978 through September 2006). For much of the U.S., this translates into at least one station per 1000 square miles; but some less populated regions, such as the deserts in the Interior West, have less dense spatial coverage.

There are several thousand more precipitation-only COOP stations of similar quality that have been used for supportive analyses. In addition, there are more than 500 SNOTEL sites in the higher elevations of the Western U.S. that have sufficient precipitation records since WY79 to be analyzed as well. However, their temperature records typically only start in the late 1980s and have been somewhat unreliable.

We used the following statistical approach to develop new experimental climate divisions:

1. For every climate station, we computed average temperatures and precipitation totals for every three-month season from October 1978 through September 2006 (these 'sliding' seasons include all Oct-Dec, Nov-Jan, …, Sep-Nov time periods within the 28-year record). Individual seasonal anomalies were calculated by subtracting the 28-year average for that same season. For missing data, anomaly values were set equal to zero to keep all station anomaly time series to the same length.
2. Multivariate cluster analyses were used to find out which stations tended to experience climate anomalies of the same sign (i.e., above average or below average), based on correlation matrices among all of them. The two cluster analysis techniques applied here were "Average Linkage", and "Ward's" method, which are both well established techniques, and superior to other clustering methods (Wilks, 1995, pp. 419-428).
3. Results from both clustering methods were compared against each other, and used to group stations with similar temperature and precipitation anomalies into "core regions". A large majority of these cores could be identified via simple overlapping station counts, but some less clear-cut groupings were settled by correlating the respective cluster time series against each other. After this initial classification, core time series were computed based on normalized temperature and precipitation time series at the station level. These were used to calculate correlation coefficients between all stations and all cores.
4. The assignment of stations to cores was refined iteratively, until no further changes occurred. In particular, if a station was not classified as belonging to a core, but correlated highly with a near-by core, it was admitted to that core. On the other hand, if a station had been (mis-)classified as being inside a core, but did not correlate highly with the core time series, it was removed from that core. (This was a rare event in the combined temperature-precipitation analysis suite, but more common in precipitation-only analyses). A third scenario involved the transfer of a station from one core to another, if its correlation with the new core was substantially higher than with the old core.

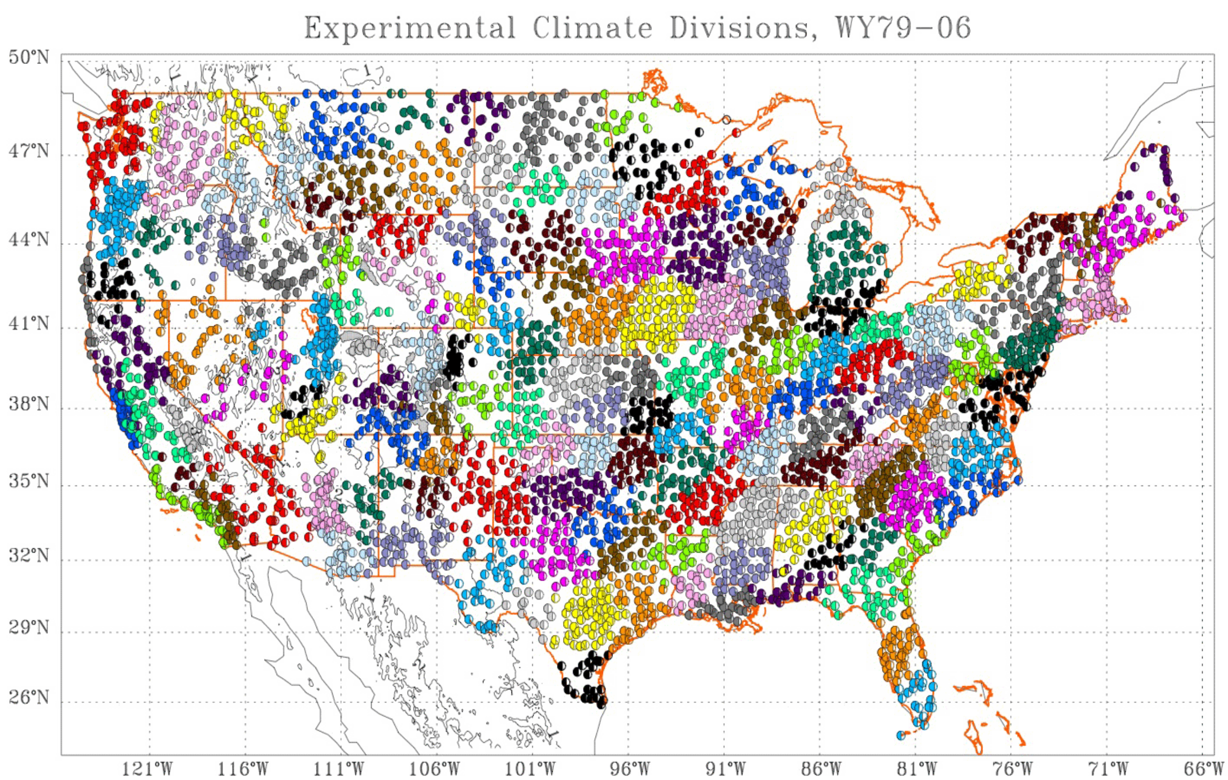

Figure 1c. Near-final map of new climate divisions, based on temperature and precipitation station data. Each dot is a COOP station and a cluster of dots of the same color represents a new climate division.

1. While there was some experimentation with correlation thresholds, the basic procedure always remained the same and yielded similar results. Transfers between core regions required at least a 1% increase in explained variance for that station, and the "drop"-correlation threshold had to be lower than the "add" correlation threshold. The final correlation thresholds were in the 0.55-0.60 range to allow for virtually all stations to be classified. One final check consisted in correlating all new climate division time series against each other to flag regions that were extremely well correlated (r>0.90), thus being prime candidates for mergers, as long as the resulting new division did not exceed certain size limitations.

The current version of the new 139 combined core regions (i.e. new climate divisions) for Water Years 1979 through 2006 (October 1978 - September 2006 data) is shown in Figure 1c. From the pool of 4324 COOP stations with sufficient temperature and precipitation data, the initial core map classified 3112 stations as being within 145 initial "intersection" clusters (Step 3). Using the iterative methodology described above, the remaining stations were gathered into core regions, resulting in a stable classification of all but one station by the 7th iteration in 139 final core regions (Steps 4 and 5; Figure. 1c). While there was no requirement for stations within a core to be spatially adjacent to each other, it is reassuring to see that virtually all of them are indeed 'neighbors,' even in the more challenging terrain of Wyoming, Colorado, and Utah.

While all analyses were performed on the national scale, let us now focus on the Intermountain West region. Figure 1d shows how the COOP stations are grouped into the new climate divisions (by color) in the region. Despite a total count of only 139 new divisions (compared to 344 in the older system), Wyoming has added one new division (now 11 total), Utah has two new divisions (now 9 total), and Colorado has more than doubled its divisions (now 13 instead of 5) (compare Figure 1a against Figure 1d), which is more representative of the diverse climate throughout each state. With the new map, climate divisions are no longer bounded by state lines. For example, note the yellow division that contains parts of southeast Wyoming, northwest Nebraska and one station in northeast Colorado. In addition, there is no upper limit of ten divisions per state.

One of the goals of this project was to integrate SNOTEL sites into the analysis. We found that SNOTEL data correlates well with the new climate divisions (compare Figure 1e against Figure 1d). Most of the SNOTEL sites match up well with the nearest COOP-based climate division, with a few exceptions in northwest Wyoming (Absorka Mountains) and northwest Utah (intersection of Wasatch and Uinta mountain ranges).

Other products and Plans

With the creation of the joint temperature and precipitation maps presented in the last section (Figures 1c, d, and e), this project is almost complete. The main remaining stage is to fine-tune the new division boundaries with precipitation data from SNOTEL and precipitation-only COOP stations. For more information on the new climate divisions, including additional spatial analyses on precipitation data alone, visit: http://www.cdc.noaa.gov/people/klaus.wolter/ClimateDivisions/ . This web page also gives access to long-term time series for each new climate division. We are working on the following additional products (this list is not complete, see the website for more details):

- Additional time series of temperature and precipitation averages in each new climate division, both from 1978-2006, and from 1948-1978, based on new climate divisions for that period. The time series will be available in monthly and seasonal formats, both as straight anomaly time series and as standardized anomaly time series.
- Final new climate division maps, including boundaries, spatial coverages (in percent of area), and new state-wide averages.

References

Guttman, N.B., and R.G. Quayle, 1996: "A historical perspective of U.S. climate divisions." *Bull. Amer. Meteor. Soc.*, **77**, 293-304.

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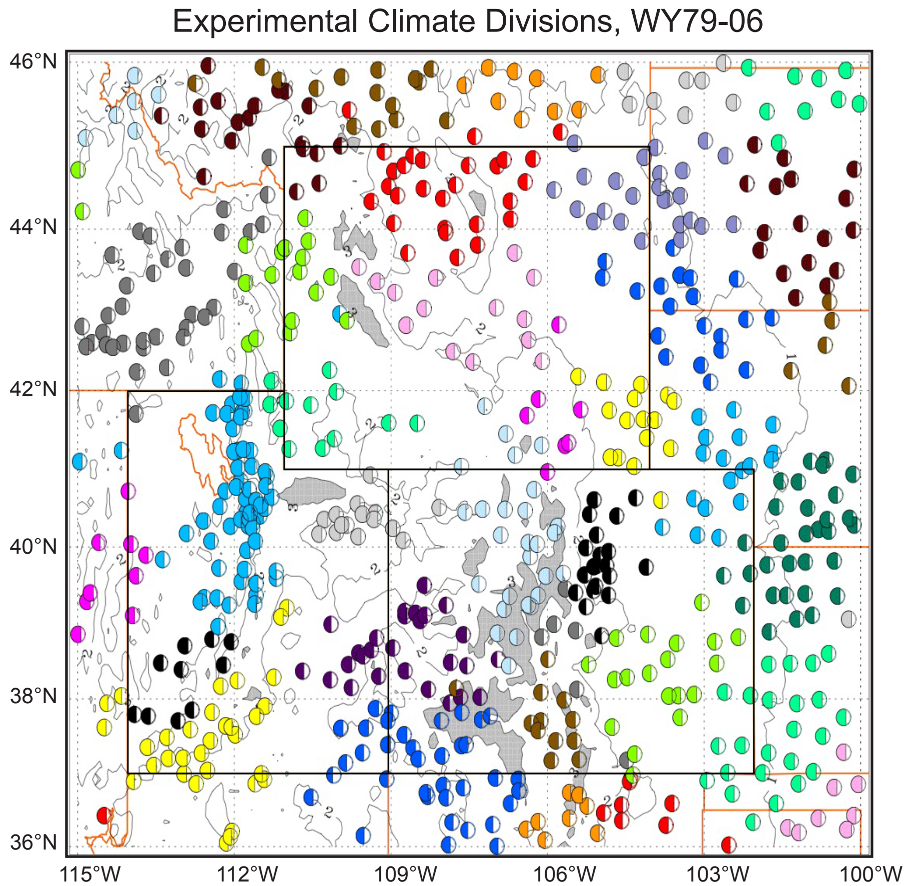

Figure 1d. Near-final map of new climate divisions in the interior western U.S., based on temperature and precipitation station data. Each circle represents a COOP station, featuring the same color within the same climate division. The amount of color in each station symbol represents the amount of local variance that is explained by the new climate division time series.

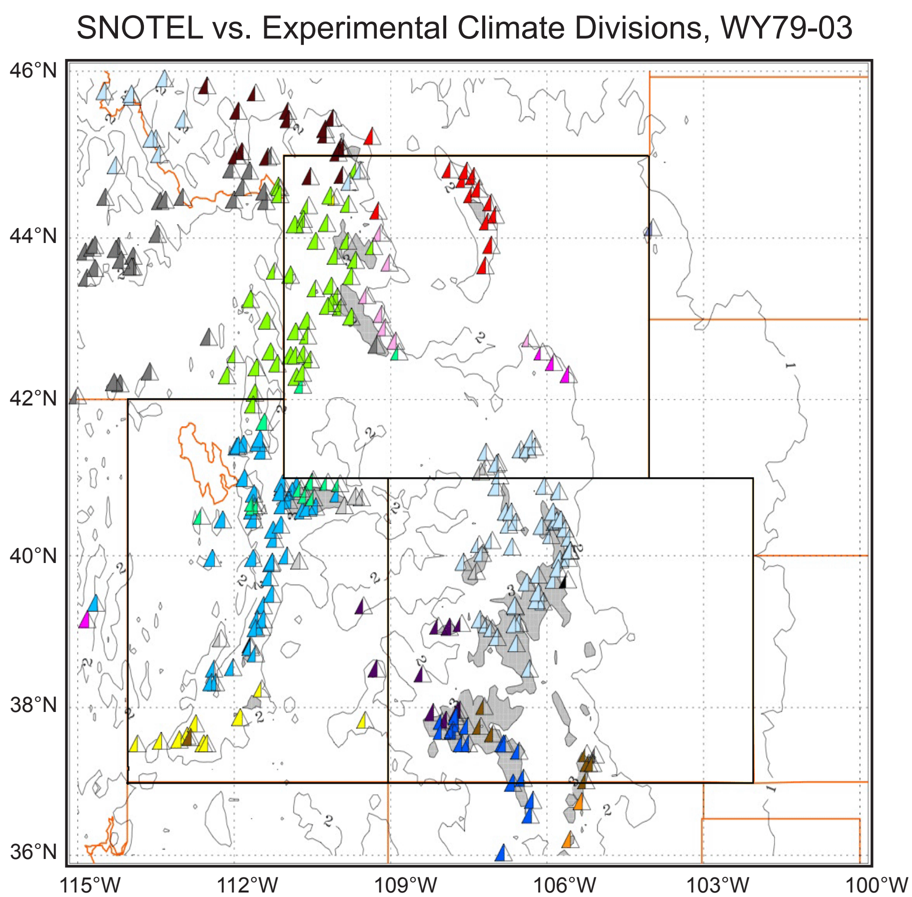

Figure 1e. Color-coded match of SNOTEL precipitation records against new climate divisions. Each triangle represents a SNOTEL station, featuring the same color within the same climate division. The amount of color in each station symbol represents the amount of local variance that is explained by the new climate division time series that correlates highest with the individual SNOTEL precipitation record.

On the Web

- Project web site: http://www.cdc.noaa.gov/people/klaus.wolter/ClimateDivisions/ . We will update the web site as this project progresses. Feedback welcome - contact us at: Klaus.Wolter@noaa.gov or (303) 497-6340.