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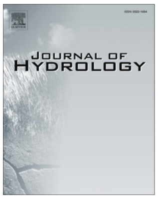

The drought risk atlas: Enhancing decision support for drought risk management in the United States

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SUMMARY

Decision makers have continuously asked for better tools and resources to help them assess their risks related to climate variability and extremes. Drought is one of the risks they face, and the need for better drought risk tools and resources has also been expressed. With drought continuing to be one of the most problematic and costly natural disasters within the United States, and building on the work of the original National Drought Atlas (NDA) (1996), an updated and expanded Drought Risk Atlas (DRA) decision support tool for the United States was developed and is housed at the National Drought Mitigation Center. The DRA (1) provides *weekly* calculations of multiple indices/indicators, with more than a billion records made freely available, including the SPI, SPEI, PDSI, scPDSI, Deciles and U.S. Drought Monitor; (2) houses more than 3000 stations with data through 2012, nearly tripling the station count of the original NDA; (3) utilizes a much longer period of record, nearly double that of the NDA in most cases; (4) when fully completed, will house a cache of more than 500,000 gridded drought index maps; (5) will allow us to analyze and assess trends and various characteristics of drought, including frequency, intensity, duration and magnitude; (6) will become a resource for the National Weather Service (NWS) personnel around the country by transferring the application into the field through integration within the NWS's newly developed Local Climate Analysis Tool (LCAT); and (7) work directly with the National Integrated Drought Information System (NIDIS) program office to include the information contained in the DRA into NIDIS's regional drought early warning system pilot basins and the U.S. Drought Portal for broad dissemination to the user community and general public.

1. Introduction

Decision makers have continuously asked for better tools and resources to help them assess their risks related to climate variability and extremes (Jacobs, 2002). Drought is one of the risks they face, and the need for better drought risk tools and resources has also been expressed (GSA, 2007). Drought is a natural phenomenon that impacts every location and climate regime around the world. Understanding how droughts develop (and have developed), evolve, propagate and affect us is vital to knowing how to better prepare and plan for them and mitigate their impacts. The Multihazard Mitigation Council (2005) estimated that every dollar spent by the Federal Emergency Management Agency on hazard mitigation provides the nation with approximately $4 in future benefits. By its very nature, drought is typically characterized by slow onset and slow recovery. Since drought is usually not associated with widespread structural damage or loss of life in the United States, it typically does not receive the same attention as other disasters. According to the National Climatic Data Center (NCDC) (2014), eighteen droughts between 1980 and 2013 resulted in just over $253 billion in damages. More recently, the ongoing droughts of 2011–2014 in the central/southern Great Plains and California have already surpassed $50 billion (NCDC, 2014) in damages, and this number will continue to grow as more losses are assessed and calculated.

Given the importance of and need for a current online drought atlas resource, the National Drought Mitigation Center (NDMC) began a process to create an enhanced web-based Drought Risk Atlas (DRA), building on the efforts of the first National Drought Atlas (NDA) and recent work at the state level via the *Hydrologic Drought Atlas for Texas* (Rajsekhar et al., 2014). With the DRA's emphasis on providing usable information, this work also compliments other delivery systems such as the U.S. Drought Monitor (USDM) (http://droughtmonitor.unl.edu) (Svoboda et al., 2002), National Integrated Drought Information System (NIDIS) Portal

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(http://drought.gov), NDMC's portal (http://drought.unl.edu), Global Integrated Drought Monitoring and Prediction System (GIDMaPS) (Hao et al., 2014; Momtaz et al., 2014) and the U.S. Surface Water Monitor (Wood and Lettenmaier, 2006).

The NDA was developed in 1994 (Willeke et al.) by the U.S. Army Corps of Engineers (ACE), the National Oceanic and Atmospheric Administration (NOAA) and IBM. The NDA analyzed 1,036 stations from the United States Historical Climatology Network (USHCN) (Karl et al., 1990), which contained data from the Cooperative Observer Program (COOP) of the National Weather Service (NWS). The NDA focused primarily on hydrology and the Palmer Drought Severity Index (PDSI), which was calculated from monthly precipitation and temperature totals.

Developing a strategy to mitigate drought risk and manage water resources for any location is dependent upon understanding the climate regimes and drought climatology for the specific area of interest. The challenge moving forward is to have the best available data and assessment tools for decision makers—especially producers, water resource managers and planning practitioners—to adequately plan and prepare for drought events. With a changing climate, the ability to compare trends over the last several decades to historical values will give decision makers the ability to contrast current drought events with historical drought events, with a goal of making better informed management decisions to account for, and reduce, drought risk in the future.

Climate data and various drought indicators and indices are key components used to monitor drought. From a historical archive perspective, the PDSI suite and Standardized Precipitation Index (SPI) drought indices have been computed each month on a climate division (multi-county) scale for the entire United States by the NCDC with data that extends back to 1895. For a generalized perspective on drought, this approach is adequate. Problems associated with using information on a coarse climate division scale can be eliminated with other techniques that allow for county and sub-county level analyses. With each new drought event, the question comes up as to how the current drought compares to others historically with regard to frequency, severity, duration and spatial extent for a specific location, county or basin. From the NDMC's DRA database, queries can be made to help users find answers to these questions and more for a given location or region. The results and data are then freely available for downloading or viewing through a number of visualization tools made available through the DRA's web interface.

The NDMC approached the idea of an enhanced drought risk atlas by expanding upon the work in the NDA by including more stations, using stations with a longer period of record than what was available to the NDA in the early 1990s (along with an additional two decades worth of data), using a weekly time step instead of a monthly period, and calculating more drought indices and providing access to the tools and outputs in a user-friendly interface by implementing GIS techniques and delivering data and information digitally via the web. The DRA consists of more than one billion index records and will house more than 500,000 grids once fully complete, and all of this data will be cached and made readily available, with the data running through 2012. We assigned each station a unique start date based upon the characteristics of that station.

2. Objectives

The NDMC's DRA was built with the intention of providing a wide range of decision makers and users with locally and historically tailored drought information via a web-based tool and database in order to visualize and assess their risk to drought. At this time, few tools are available for decision makers and scientists to use in evaluating drought characteristics, or climatology, on a localized scale for the United States. The DRA fills a gap by providing a much-needed mechanism for research, decision making and planning perspectives on both past and future drought episodes by providing historical climate data and drought indices at a more localized level (using a station-based approach) and on a more frequent time step (weekly instead of monthly for several indices). One of the primary goals of this tool is to increase users' capacity to understand their drought history and to identify past and present trends along with past, present and future vulnerabilities to drought in order to make more informed decisions aimed at reducing risk to future droughts.

The DRA is focused on increasing the capacity of users and decision makers (including policy makers and planners, as well as producers and water and natural resource managers) to analyze their potential risk to drought in any particular location for any time of the year. The regionalization techniques developed for the first drought atlas allowed for the estimation of drought frequencies from several locations instead of just one, by calculating frequencies using L-moments statistical techniques. The NDMC has developed methods to do all of this work in an ArcGIS environment, allowing for the rapid assessment of results and graphical output via a web interface available at http://droughtatlas.unl.edu. The data, maps, graphs and other derivative output products are freely available to be shared with the scientific research community and in support of the NIDIS and NWS-Climate Services Division (CSD) efforts, along with the general public.

Tailoring the DRA to the needs of planners, producers, university extension agents, natural resource decision makers and NOAA–NWS field personnel through a series of workshops and webinars during development allowed for the integration of their feedback throughout the process. These efforts led to the improvement of analyzing drought as an extreme event by providing data and visualization tools to help them better understand the frequency, historical context, magnitude, spatial extent and trends of drought at the local (station), basin, tribal, regional or state level. The DRA is already populated for the entire continental United States and can serve as an immediate application tool within any of the NIDIS regional drought early warning system (RDEWS) pilot regions. The tool's built-in spatial flexibility will provide producers, natural/water resource managers and planners with a valuable resource to help them better inform their constituents on how to cope with climate variability and change at all scales and under various levels of risk or uncertainty.

3. Data and methods

3.1. Station screening

More than 12,000 stations were initially screened and run through a quality control process by the NDMC and High Plains Regional Climate Center (HPRCC) using the Applied Climate Information System (ACIS) database. Of these initial stations, 3059 stations (nearly triple the number analyzed in the first drought atlas) collecting precipitation from NOAA's–NWS COOP network housed within ACIS were identified by the NDMC as meeting our specific selection criteria, making them the best long-term climatic stations found within the USHCN. All of the stations in the selected subset have at least 40 years of daily data (with an average period of record of nearly 70 years) with no more than two consecutive months of missing data occurring at any point in the period of record. Of these 3059 stations, 2569 have both temperature and precipitation data, which are needed for calculating several of our chosen indices such as the PDSI suite and the Standardized Precipitation Evaporation Index (SPEI).

After final extraction of the COOP station data from ACIS (accomplished with our partners at the HPRCC), the following criteria were established for a station's inclusion in the drought risk atlas: (1) the station had to currently be open and taking regular observations; (2) the station had to have a minimum of 40 years of data available, going backward from 2012; and (3) the station could not have more than 2 consecutive months of missing data at any time within the period of record.

Based upon the above criteria, a unique period of record (POR) was established for each station. Using the 12,000+ stations found within the COOP database, two screenings of the data were done. The first screening looked for stations that had at least 30 years of data in their record and had 80% or more of the daily data available. A report for each station was made showing the months that had missing data for each year. By looking at the most current data and going back in time, we determined for each station how far back the data met our criteria. Gaps in the records were investigated to determine if the data existed somewhere else and was not present in the digital data archive within ACIS. The National Climatic Data Center (NCDC) provided access to scanned copies of the COOP forms in their archive via the Web Search Store Retrieve Display (WSSRD) system, which has transitioned over to the Environmental Document Access and Display System (EDADS). By comparing the data that was available on paper with the gaps in ACIS, we identified 288 stations for which the data gaps could be rectified and entered into the digital ACIS archive. HPRCC staff keyed in the data for the gaps we identified using Datzilla, and these stations were then incorporated into our DRA database and eventually into the NCDC archives as well. Although a 30-year historical record is a good recommended starting point, periods of 40–60 years of monthly data would be better (Guttman, 1994) in order to give a reasonable sample size used in the approximation of the computed means, so we arbitrarily adjusted the initial station query to include only those stations having 40 or more years of data.

Next, a secondary screening (gap) analysis was conducted on each station to identify where the gaps in the POR fell within each station that passed the initial screening as a way of helping us determine the unique starting date for the POR associated with that station. All stations have an ending period through December 2012. Many stations have records that go back to the late 1800s, but the earlier data is often incomplete and contains many gaps. By taking these years of missing data out of the record and establishing a unique starting point that differs from the date the station first began taking observations, a unique and complete POR was established. By providing each station with a unique starting date, the longest periods of record were made available by allowing the record to stop when the established criteria were no longer met, but an adequate climatic time period was established. To aggregate the daily data into a weekly time step, weeks had to be established to provide a summation of precipitation for each week. We determined that Week 1 starts on March 1 and includes seven days. The last week of the year ends in February and, depending on the year, may include additional days in the summation to account for leap years.

After this daily summation exercise, we presented the information to the American Association of State Climatologists (AASC) at their annual meeting and through interactions with the AASC list server. We asked for their assistance in determining whether our chosen stations were of high quality and also if they knew of additional stations missing from our screenings that would potentially meet our criteria. Twenty-two state climatologists and one regional climate center offered feedback, including notification that there were other candidate stations we should consider. It was determined that another screening of the full COOP dataset was needed. Using the established criteria, we looked at the data going backward and stopped our search the first time a two-month gap was found. Using the 80% of available data criteria threshold excluded a number of stations where the data period had large gaps early in the record, but were otherwise fairly complete. The 80% criteria also excluded stations that are primarily "event reporters" in that they only record precipitation when it takes place and do not record zeros very often. By screening the data a second time and comparing the stations to those we already had, we were able to add 915 stations into our catalog, bringing the total number of stations in the DRA up to a total of 3059, which is where it currently stands as of this writing (see Table 1). Fig. 1 shows the

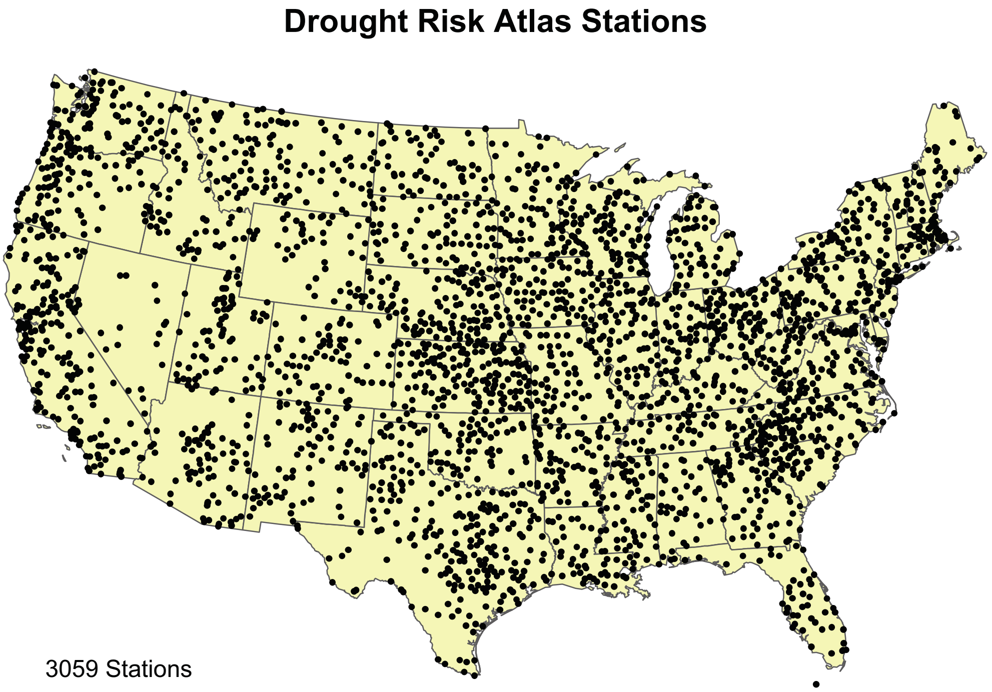


Fig. 1. All COOP precipitation collection stations meeting the DRA selection criteria and having a minimum of 40 years of record.

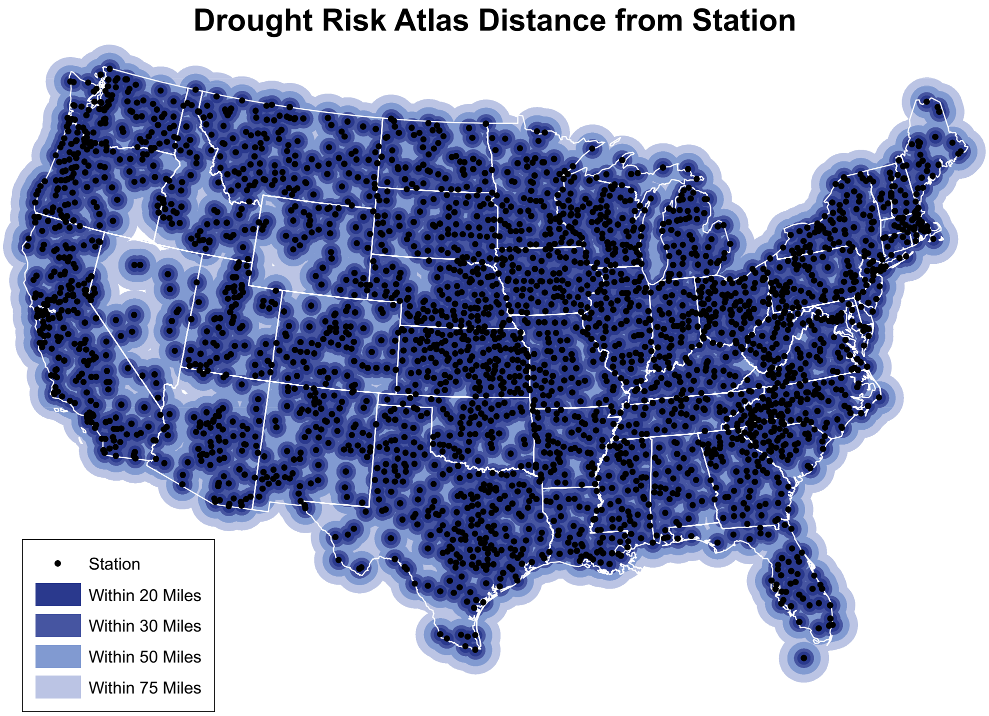


Fig. 2. GIS analysis shows the density of the DRA network of precipitation stations. Note that one should be able to find a similarly behaving station within at least 75 miles from any given point of interest for all but parts of the West. Density and distribution is quite good east of the Rocky Mountains where most stations are within 20–30 miles of another station.

spatial distribution of those COOP stations recording precipitation and having the minimum amount of 40 years across the lower 48 states. The most notable gaps in station density (Fig. 2) were, as expected, found in the West across parts of the Great Basin, Four Corners region and within Wyoming. East of the Rocky Mountains, station density and distribution is quite good with most stations falling within 20–30 miles of one another. For the country as a whole, virtually all stations were no farther than 75 miles apart, expect for parts of the West as noted above.

3.2. Cluster analysis

For the DRA, a regional frequency analysis technique was applied for the 3059 stations based upon an L-moments approach (Hosking and Wallis, 1997) in which a cluster analysis was performed to develop unique climate regions in which stations within the same cluster showed similar climatic and statistical behaviors with regards to precipitation. The concept, given the lack of ideal station density and spatial distribution around the country, is aimed at providing a homogeneous region of similar climatic stations whereby users can choose from multiple stations having similar drought behaviors to use in the decision-making process instead of a single point. This is important given the fact that in many cases users will have to choose a station that is not their hometown, or preferred, station. Using the cluster analysis, return frequencies were generated for the cluster and for each station within the unique climate region using the L-moments techniques.

The cluster analysis process consisted of grouping stations together based upon each station's latitude, longitude, elevation and precipitation characteristics. A GIS widget was developed by the NDMC that aided in the process of determining where to place stations that could fit in more than one cluster. For each cluster, precipitation characteristics were developed for each season (winter, spring, summer and autumn), giving us the ability and flexibility to cluster the stations based upon data from any of the seasons. We decided the summer season, because of the widespread convective nature and consequent variability of precipitation, would be our best choice to determine our clusters. Utilizing the final cluster analysis based upon the station attributes and the summer precipitation characteristics for each station, 139 unique clusters (Fig. 3) were developed. Each cluster was tested for homogeneity and discordancy, with less than 3% of the points being discordant for any particular season and only nine of the clusters determined to be inhomogeneous for the summer months. From these established clusters, individual drought/climate regimes were established in which frequency and return periods could be calculated.

The average cluster size contained 22 stations and the range of cluster populations varied between 5 and 49 stations. Fig. 4 represents a fairly typical cluster in terms of size, number of stations and distribution. The stations falling within each cluster share common drought and statistical behavior. After the 139 clusters were decided upon, discordancy testing was done on each of the 139 clusters and for each season. Only 37 points (1.21%) within our clusters were considered discordant for the summer precipitation season. Our reasoning for this is explained below in the homogeneity testing discussion. Following the Hosking and Wallis L-moments methodology (1997), discordancy was tested using the clusters developed for the summer season, but with the

Table 1
Final number of stations meeting at least the minimum DRA selection criteria.

Number of stations	Years of data	Percent of stations (%)
3059	40	100.00
2462	50	81.04
1733	60	57.04
1170	70	38.51
827	80	27.22
537	90	17.68
349	100	11.50

precipitation characteristics of the other seasons used instead. For autumn, there were 80 discordant points (2.62%); for spring, 84 discordant points (2.75%); and for winter, 75 discordant points (2.45%). These results were considered acceptable as we discovered that several points were discordant regardless of the cluster they were put into, so they were subjectively assigned into a cluster that

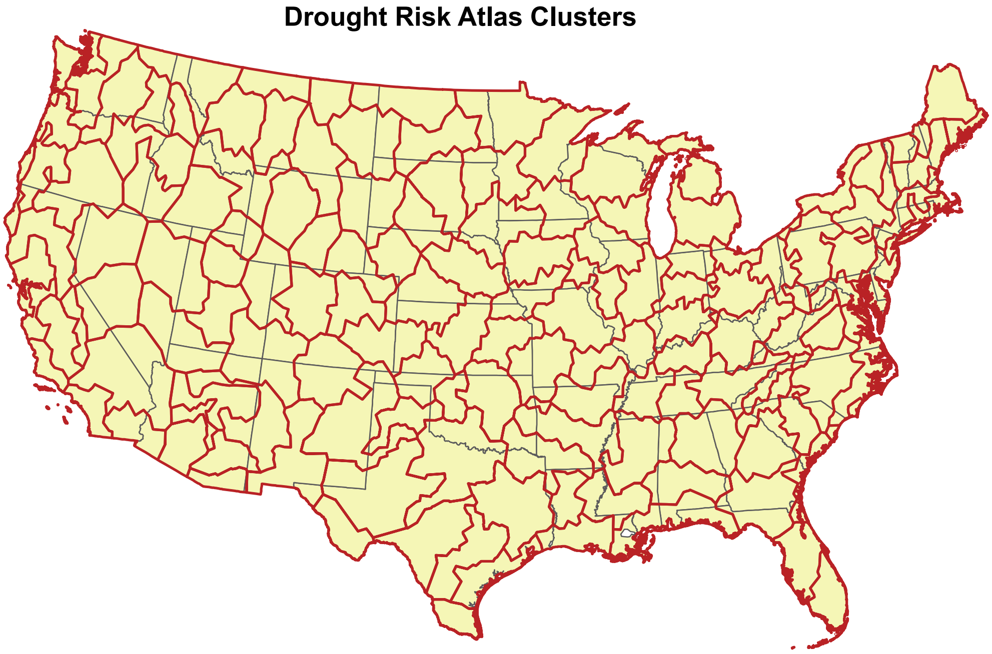


Fig. 3. Total number of clusters in the DRA as determined from L-moments and homogeneity testing.

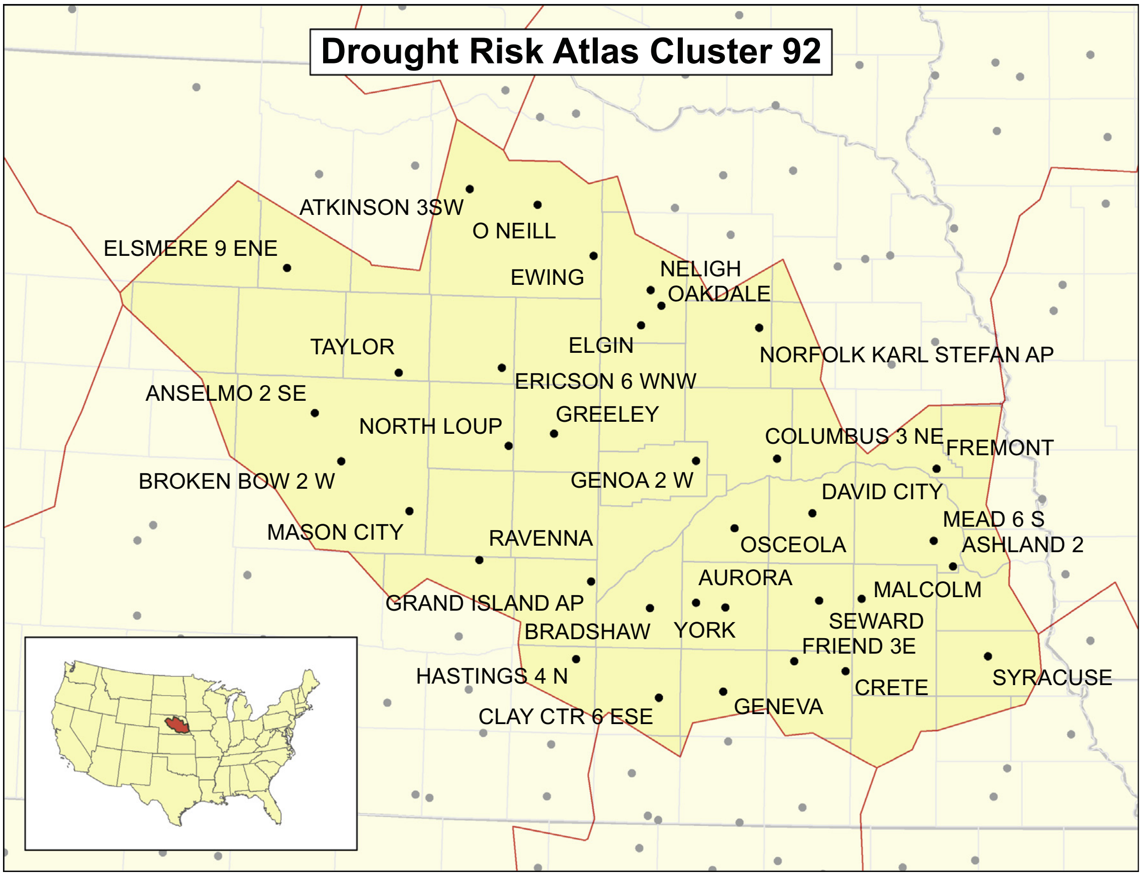


Fig. 4. Example of a DRA cluster and station distribution. Stations in clusters exhibit similar statistical and precipitation behavior allowing a user multiple options for assessing drought history in their point of interest.

made the most sense geographically. We could have also chosen to dismiss these discordant stations from the DRA, but given the fact that the stations were of such high quality, we decided against that course of action.

3.3. Homogeneity tests

Homogeneity tests (H1) (Hosking and Wallis, 1997) were conducted upon each cluster using the clusters derived from the summer precipitation characteristics. A Monte Carlo simulation was used, with 2000 simulations being conducted for each season. For the summer season, 9 of the 139 clusters failed the homogeneity test (6.45%). Of the clusters that failed, many were located in the western United States where the summer season is dry and not the most ideal period of the year to look for similarity in station records, as a precipitation event is an anomaly. For autumn, 35 clusters did not pass the homogeneity test (25.2%), spring had 20 failures (14.4%) and winter produced 16 failures (11.5%). It also makes sense climatologically that the transitional seasons of spring and autumn would have the most variability for most of the country and have the most in-homogeneities compared to the summer season. Only 3 of the 139 clusters failed the homogeneity tests for all four seasons. This was not surprising as some clusters were developed in terrains and landscapes that have tremendous variability, and regardless of how the stations were clustered they would not become homogeneous. In addition, these three particular clusters contained fewer reporting stations and covered large arid areas in the Desert Southwest, which also contains contrasting elevations over short distances. During development of the cluster regions, the clusters were made available for review and critiquing by the state climatologists and Regional Climate Centers. Feedback from these groups resulted in adjustments to the clusters, with some clusters being divided into two or more clusters.

The L-moments were calculated for each season and for various probabilities. The quantiles calculated were 0.01, 0.02, 0.05, 0.10, 0.20, 0.50, 0.80, 0.90, 0.95, 0.98, and 0.99. In calculating the L-moments for each cluster, several distributions were available to use, including: Exponential, Gamma, Generalized extreme-value, Generalized logistic, Generalized normal, Generalized Pareto, Bumbel, Kappa, Normal, Pearson Type-III and Wakeby.

From our analysis, we found the Pearson Type III to perform and best fit our overall needs given the fact that no one distribution will typically fit all sites. The other distributions were tested and our results were not changed, or improved, in any significant manner such that it warranted changing from the use of the Pearson Type III.

3.4. Data and indices

Millions of daily temperature and precipitation values were collected (see Table 2) and aggregated in order to be able to calculate each of the indices across various time steps.

For the estimation and data filling component, work was conducted at the HPRCC to generate the serially complete datasets for both precipitation and temperature for those stations having missing daily data. The HPRCC has developed and refined several methodologies (You et al., 2008) over the years aimed at providing data estimates as part of their data quality control and assurance programs. Using a nearest-neighbor approach along with inverse distance weighting and spatial regression testing techniques, the HPRCC generated temperature and precipitation estimates for the missing DRA data, thereby giving us a serially complete daily dataset to complement the raw daily set. Given the quality screening and resultant completeness of those stations meeting the screening criteria, the amount of daily data that ended up being estimated from a total of nearly 82 million records was minimal at just 1.02%. In the interface, the user has the option to analyze, display and/or download the data using either the raw or serially complete dataset.

For each station meeting the screening criteria, drought indices were computed using a weekly or monthly time period and utilizing both the raw and serially complete (estimated) datasets. From these daily raw and serially complete datasets, the following indices, indicators and climatic information were calculated and are made available through the DRA web interface: the Standardized Precipitation Index (SPI), Standardized Precipitation Evapotranspiration Index (SPEI), Palmer Drought Severity Index (PDSI), Self-Calibrated Palmer Drought Severity Index (scPDSI), Deciles, analog climate and indices data and historical rankings, frequency and return periods by location, and the U.S. Drought Monitor (USDM).

Using the selected stations, batch programming was done in order to calculate the SPI, SPEI, and Deciles for the 1–12-, 15-, 18-, 24-, 36-, 48-, 60-, 72-, 84- and 96-month periods using a weekly and/or monthly moving window time step. Gridded maps (0.25°) for each week from 1887 to 2012 are still being generated for the indices where there are enough data to support them.

As shown in Table 3, in order to compile the indices for the atlas, millions of records were calculated for each index resulting in more than one billion records generated and archived in our

Table 2
The total number of climate records used in computing the indices.

Data types	Total records	Start date
Raw data (daily data)	81,861,427	10/2/1849
Serially complete (daily data)	80,464,757	1/1/1908
Aggregated data (weekly, monthly, etc.)	40,574,010	n/a

Table 3
The total number of records generated by each drought index.

Index	Total records
SPI (weekly)	554,211,720
SPEI (monthly with weekly coming)	46,156,540
PDSI (monthly)	2,125,528
Self-calibrated PDSI (monthly)	2,125,520
Deciles (weekly)	538,915,840

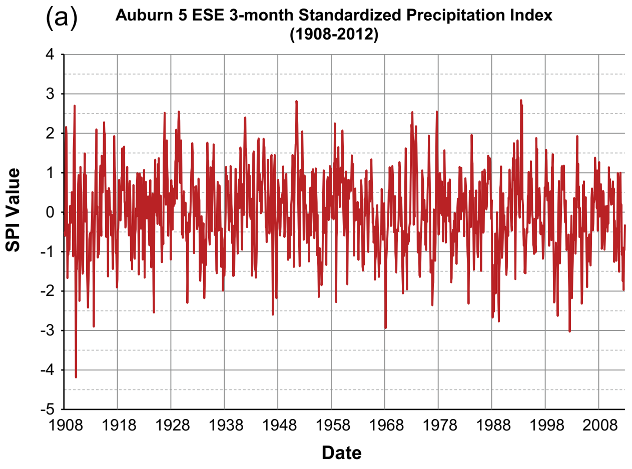


Fig. 5. (a). Example of a short-term, seasonal 3-month SPI time series for Auburn 5 ESE, Nebraska. (b). Example of an annual 12-month SPI time series for Auburn 5 ESE, Nebraska. (c). Example of a long-term 24-month SPI time series for Auburn 5 ESE, Nebraska.

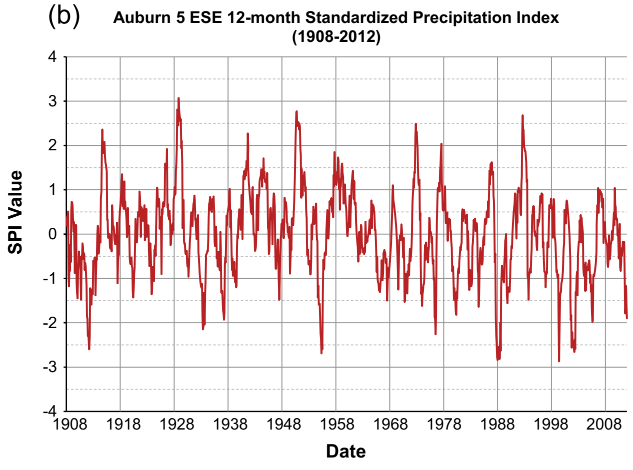


Fig. 5 (*continued*)

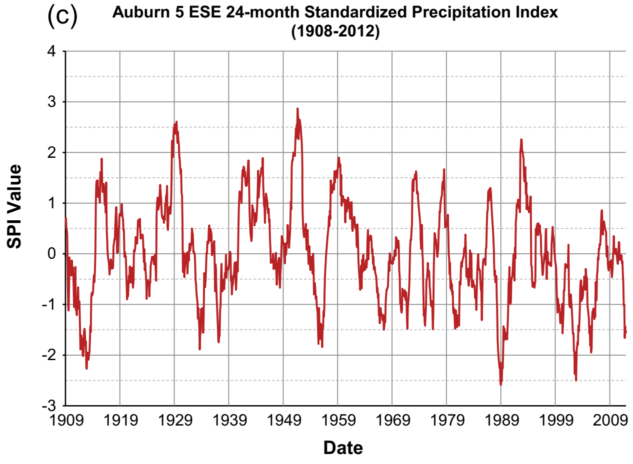


Fig. 5 (*continued*)

database. Efforts will be made to periodically update the database over time in order to keep the statistics and information current and relevant.

The SPI (McKee et al., 1993) is available for all 3059 stations in the DRA and was calculated using both weekly and monthly aggregates of precipitation data using either raw or serially complete data, although fewer stations (2569) are available for any serially complete analyses.

Calculation of the SPEI (Vicente-Serrano et al., 2010), PDSI (Palmer, 1965) and scPDSI (Wells et al., 2004) requires precipitation and temperature inputs along with serially complete data, thus it is available for computing on just those 2569 stations containing both precipitation and temperature data within the DRA. The SPEI is currently calculated using monthly aggregates of data although work is underway to allow for weekly moving window calculations within the SPEI, as is currently the case with the SPI. For this project we used the original version of the SPEI as coded by Vicente-Serrano, which uses a Thornthwaite calculation for the PET values.

The Deciles (Gibbs and Maher, 1967) rankings were also calculated for all 3059 stations in the DRA. Like the SPI and SPEI, Deciles are relatively straightforward to compute and interpret, with a value that falls within the lowest 10% of the record said to be in the first Decile, and so on. For the purposes of determining when a region is in drought, the first or second Decile is typically used as the breaking point. Any values that fall within the first decile are considered to be in drought. Like the SPI, Deciles can be calculated using multiple time-steps. This is done by determining the length of the time-step and summing the precipitation values over the entire time-step. A given value for one time-step is then compared to the historical record of values for that same time-step. These rankings were completed using both weekly and monthly aggregates of data, and the 1st through 10th Deciles periods were computed.

Although the USDM (Svoboda et al., 2002) was not calculated specifically for the DRA, it is included in our database and made available through the tool so that the DRA indice archives can be compared to the state-of-the-art system used to monitor drought

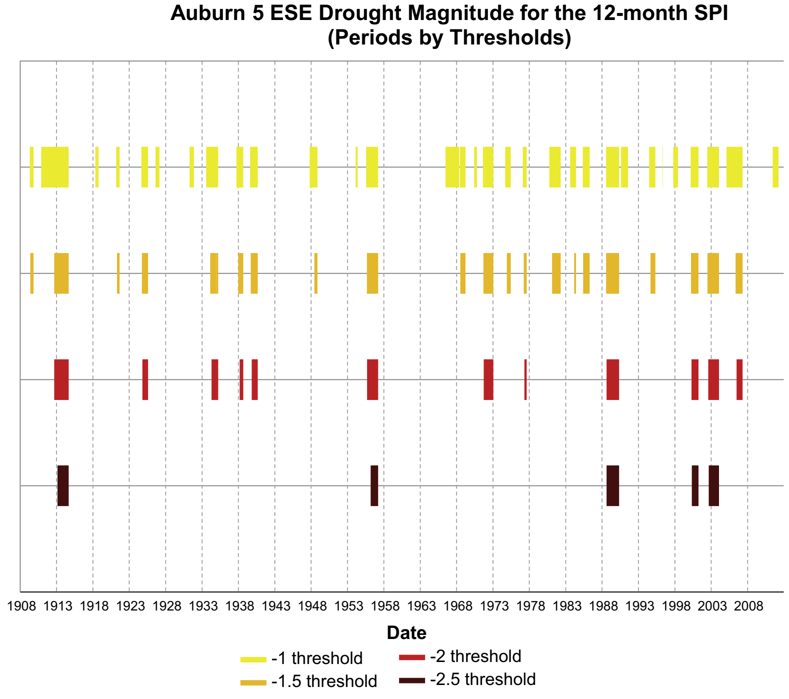


Fig. 6. Drought periods (duration) and magnitude by various 12-month SPI thresholds for Auburn 5 ESE, NE.

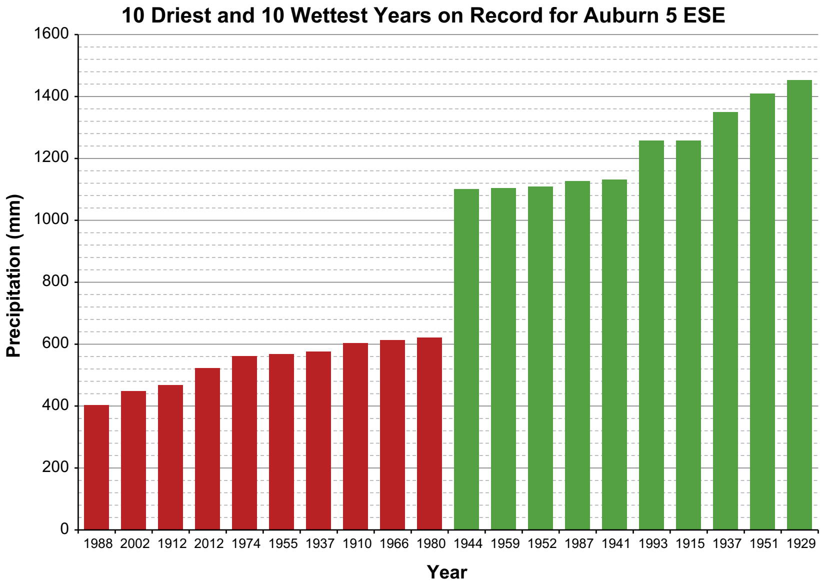


Fig. 7. Sample DRA query for the driest and wettest years on record for Auburn 5 ESE, NE.

today. The key limitation with the USDM is that the archive only goes back to January 2000.

4. Results and derivative products

A combination of tabular and visualization tools can be used to assess a location's drought history through a web-based interface at http://droughtatlas.unl.edu. The DRA tool was designed to deliver data and products in a way that allows both novice and expert users to benefit from the information housed within. Using database management techniques, the output includes: user defined and interactive time series, heat maps, index comparison charts, analog rankings, drought periods, raw and serially complete tabular data, drought frequency, intensity and magnitude, and more than 500,000 gridded index maps.

The DRA decision support tool allows for data sorting (and extraction) and the viewing of multiple indices over a user-defined period of time. The time series are interactive and the user can highlight and choose, within the time series chart, subset periods of interest by clicking and dragging on the *x*-axis of the time series graphic. This flexibility is critical in that users and decision makers can assess and compare various drought indices to see both their previous and potential behavior as a trigger for impacts and/or decision making, which can then ultimately be tied to a drought mitigation plan or framework within the context of a Drought Early Warning System (DEWS).

The DRA's Map Viewer displays gridded drought indices and other basic information such as the locations of the stations used in the Atlas. The climate layers mainly consist of the different drought indices and also the basic atlas stations and clusters. Each of the drought indices layers provides the option to select a specific time period and time step. Multiple geospatial base layers can be displayed on the map. These include counties, climate divisions, NWS county warning areas, RMA regions, river basins, congressional districts, tribal lands and federal lands. These layers will be

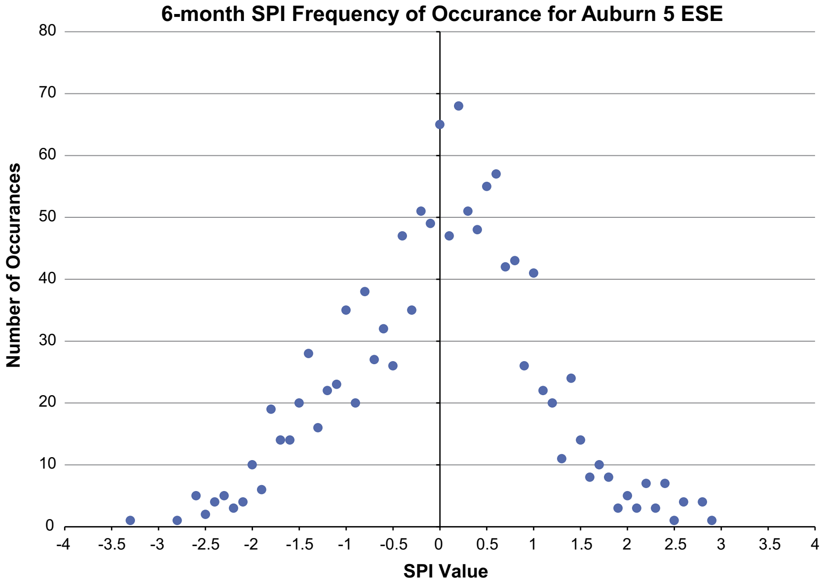


Fig. 8. Sample frequency plot of all 6-month SPI threshold values for Auburn 5 ESE, NE.

displayed underneath the climate data. The data viewing tool has three main functions: The ability to select a station, the ability to view datasets, and the ability to download datasets. There are three ways to select a station: by state, by keyword or ID, and by radius. Data queried and chosen for downloading are made available in either CSV or TXT file format. Geospatial information and

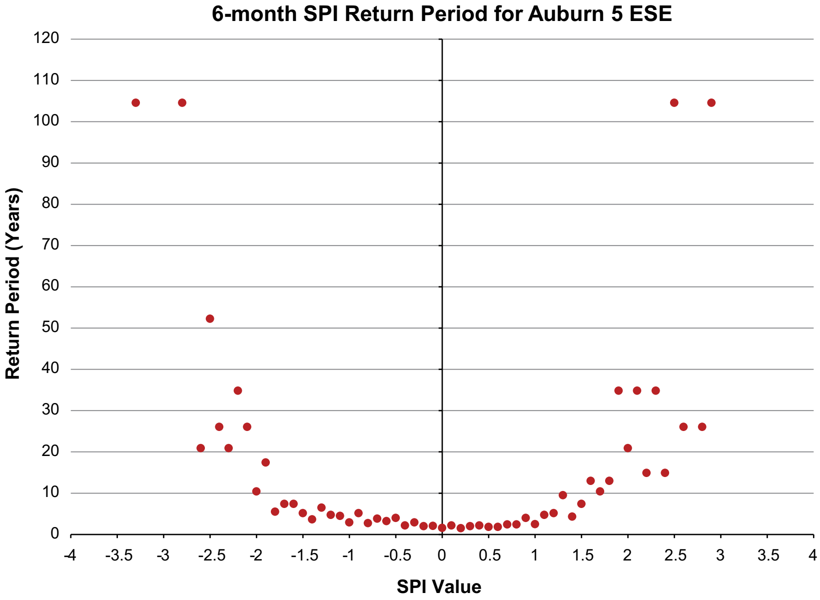


Fig. 9. Return periods (in years) for various 6-month SPI values for Auburn 5 ESE, NE.

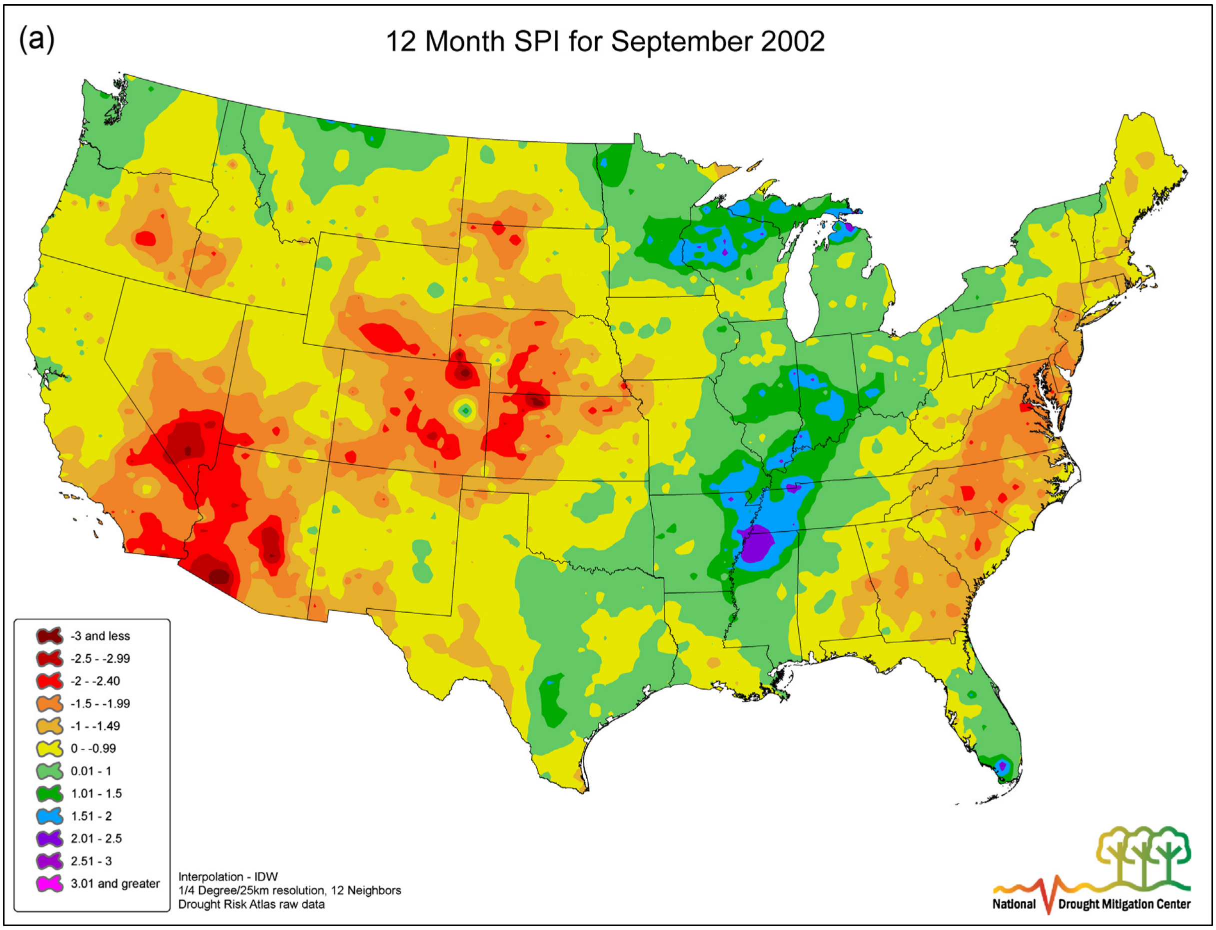


Fig. 10. (a). Gridded 12-month SPI map for September 2002. The red (warm) colors represent dryness and the green and blues (cool) represent wet areas. (b). Gridded 6-month SPI map for September 2011. The red (warm) colors represent dryness and the greens and blues (cool) represent wet areas.

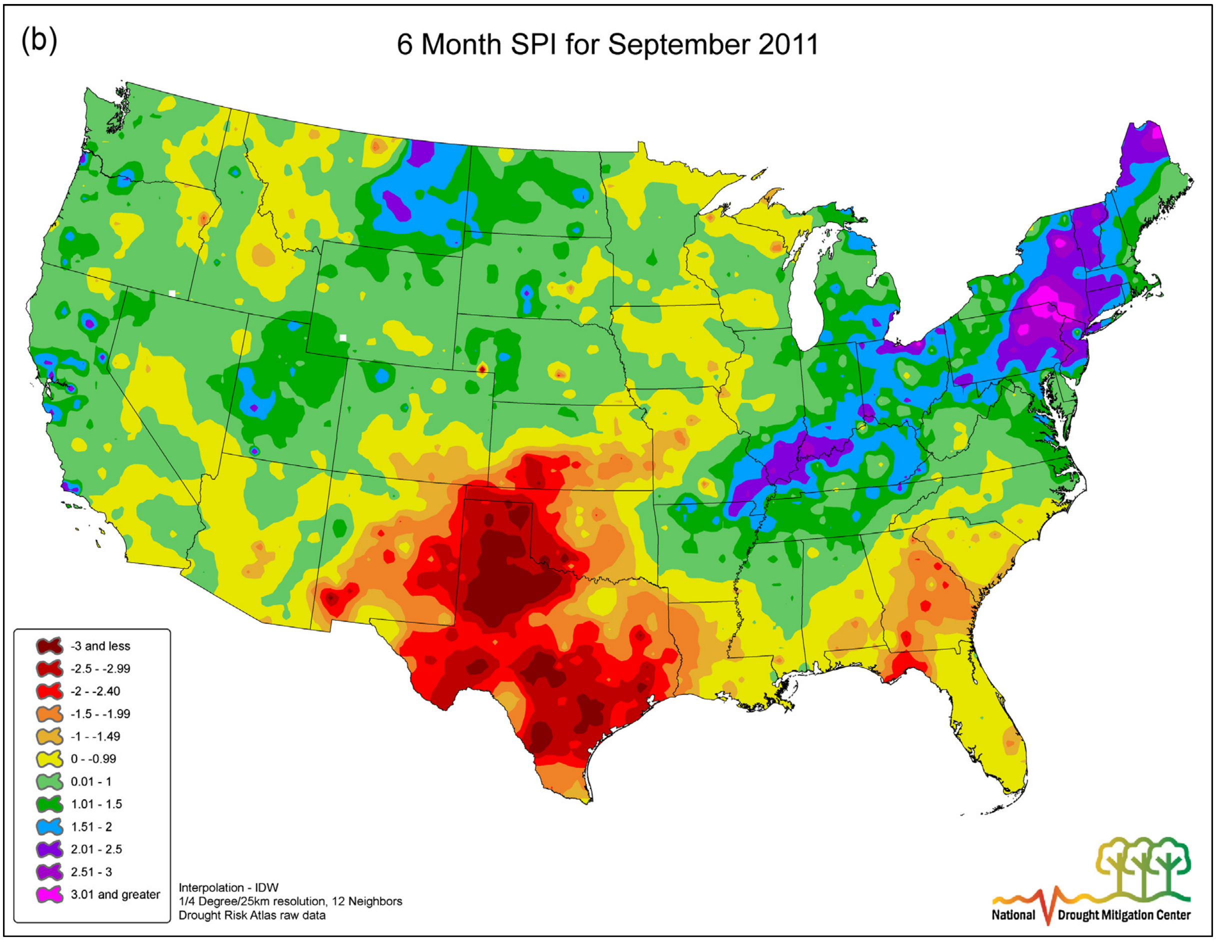


Fig. 10 (*continued*)

products generated and provided by the DRA will be made discoverable and available in Open Geospatial Consortium (OGC)-compliant web services formats.

Users frequently want to know how the severity of a current drought/time period compares to other historical droughts or if the current period is the driest (or wettest) on record. By providing the analog data, using a weekly and/or monthly time step, comparisons can be made and users can answer such questions using the tool. The ability to rank order the various climatic indicators and drought indices allows decision makers to have a better idea of how their climate, or drought, profile (i.e. climatology) has changed over time. Fig. 5 illustrates the flexibility that the SPI offers through time series analyses at various time scales. The 3-month SPI allows for tracking drought (or wet) periods at the seasonal level (Fig. 5a), which is more indicative of a growing season, or agricultural, drought. Hydrological droughts typically evolve more slowly and lag behind agricultural drought before presenting impacts to water resources making annual (Fig. 5b) 12-month SPI or multi-year (Fig. 5c) 24-month SPI more applicable.

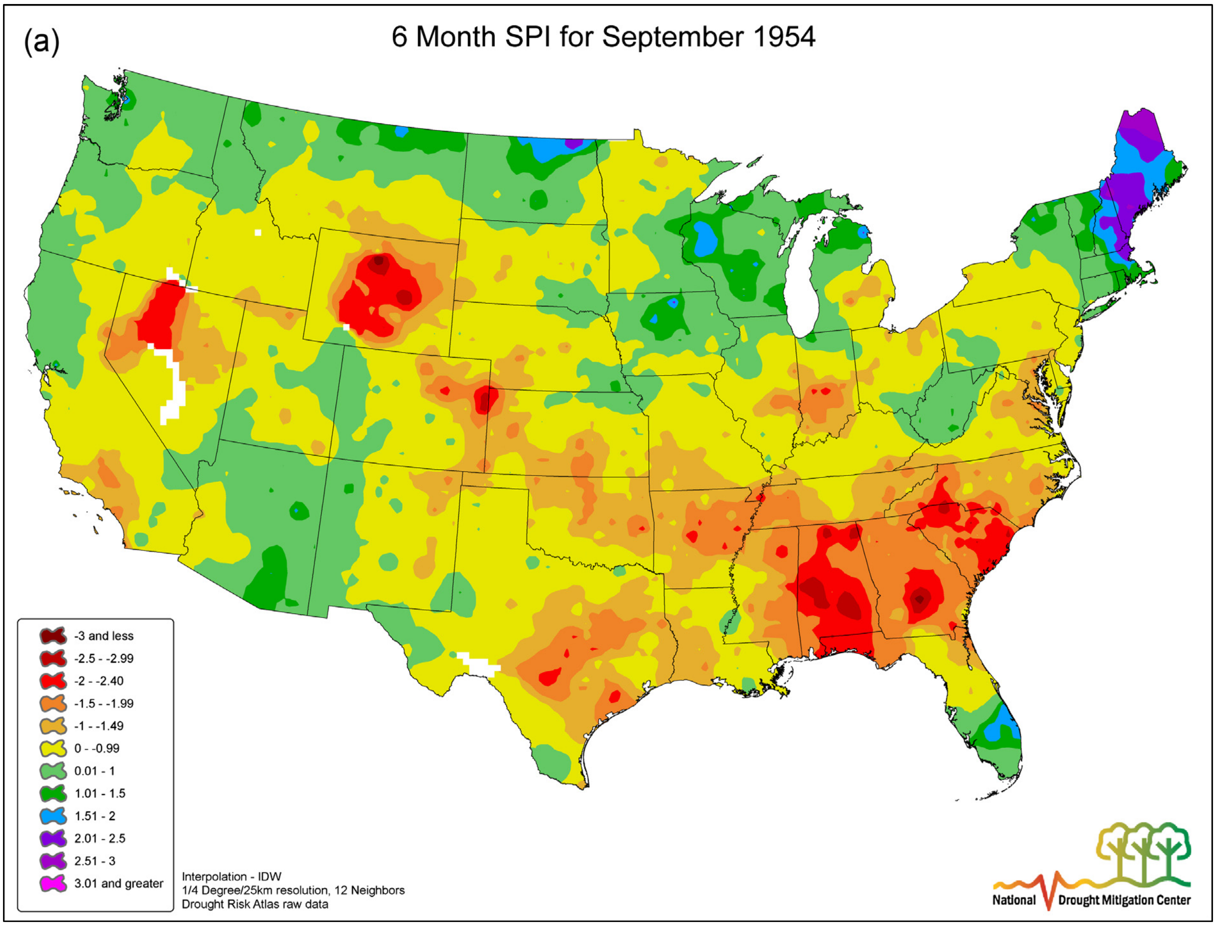
Other visualization tools within the DRA offer up ways of illustrating drought magnitude by various thresholds (Fig. 6). Severity and duration are both key to better understanding and comparing droughts and drought impacts over a station's period of record. A long lasting, lower intensity drought may end up causing more impacts than a very intense, very short-lived drought depending on timing and other factors that vary by region and season. A quick look at drought periods results in tables showing, depending on the user query, either the driest or wettest periods (Fig. 7) as determined by each index in the DRA database. This allows for a quick look at which years stand out from the rest. Drought frequency is yet another parameter of great interest by users and the DRA delivers this in a couple of ways. The user can see the number of occurrences for each index threshold (either positive/wet or negative/dry) value to see the distribution and how the tails (extremes) behave on both ends of the spectrum, both wet and dry (Fig. 8). In addition, return periods (based on years) show the user (Fig. 9) how often you can expect to see a particular drought index value occur based on the station history of that particular location. For example, the user can see how often a SPI (or any other index within the DRA) value of -2 (or any other threshold) occurs, expressed as once in every *n*-amount of years.

More than 500,000 gridded raster maps are being generated using ArcGIS for all indices and for all weeks/months within the DRA's database period of record where enough data and derived indice values are available and can support it. A user map interface has been created for this application as well. Currently, not very many historical maps are available for any drought index using a station-based approach, especially at the weekly time scale. The DRA will provide, for each index (and all time frames computed for each index), a gridded map for each time step using the available stations for each particular week/month for all years back to the late 1800s where there is enough data to support it. With the current number of stations available, the optimal grid will have a radius of 25 km from the data point. The older maps do not have as many points available for the gridded surface as compared to more recent maps where more stations are readily available, which can result in some white (no data) areas on the respective grid. With each station having at least 40 years of data, every map from 1970 to present will include all data points for each week of each year. In addition to standard mapping tools, the mapping interface will allow users to overlay various geographic and political boundaries and have an interactive platform for customizing the map. These visual depictions can be used to determine the spatial extent of drought events and how they impacted a region. While transferring these data to users, specific geographic overlays will be made available, such as the NWS county warning areas for each Weather Forecast Office (WFO); 2-, 4-, 6-, and 8-digit HUCS; climate divisions; congressional districts; and tribal and federal lands. Fig. 10a and b are examples of the .25° gridded maps that will be generated for all weeks, or months depending on the index, back to the early 1900s. Various time steps can be utilized and both drought and wet patterns can be easily seen when mapped in this format. This also allows for a variety of ways to quickly visualize and package data to a particular time or area of interest. Fig. 10a represents more of an annual snapshot showing the hydrological drought in the West during 2002 whereas the 6-month SPI for September 2011 shows more of a growing season drought that afflicted the southern Great Plains and parts of the Four Corner region, eastern New Mexico and southeastern Colorado. A user can use the map feature to identify hot spots, which can then be followed up by zooming into regional or state templates (still to come within the DRA) for a closer look and then down to the cluster, or station, level for even more tailored and specific drought information queries and data retrieval. Fig. 11a shows that drought is not just a western phenomenon and that the tool can also be used in identifying and assessing extreme wetness as is clearly depicted in Fig. 11b given the heavy rains (and resultant high/positive SPI values) that led to a lot of flooding on the Missouri River during summer 1993.

5. Discussion

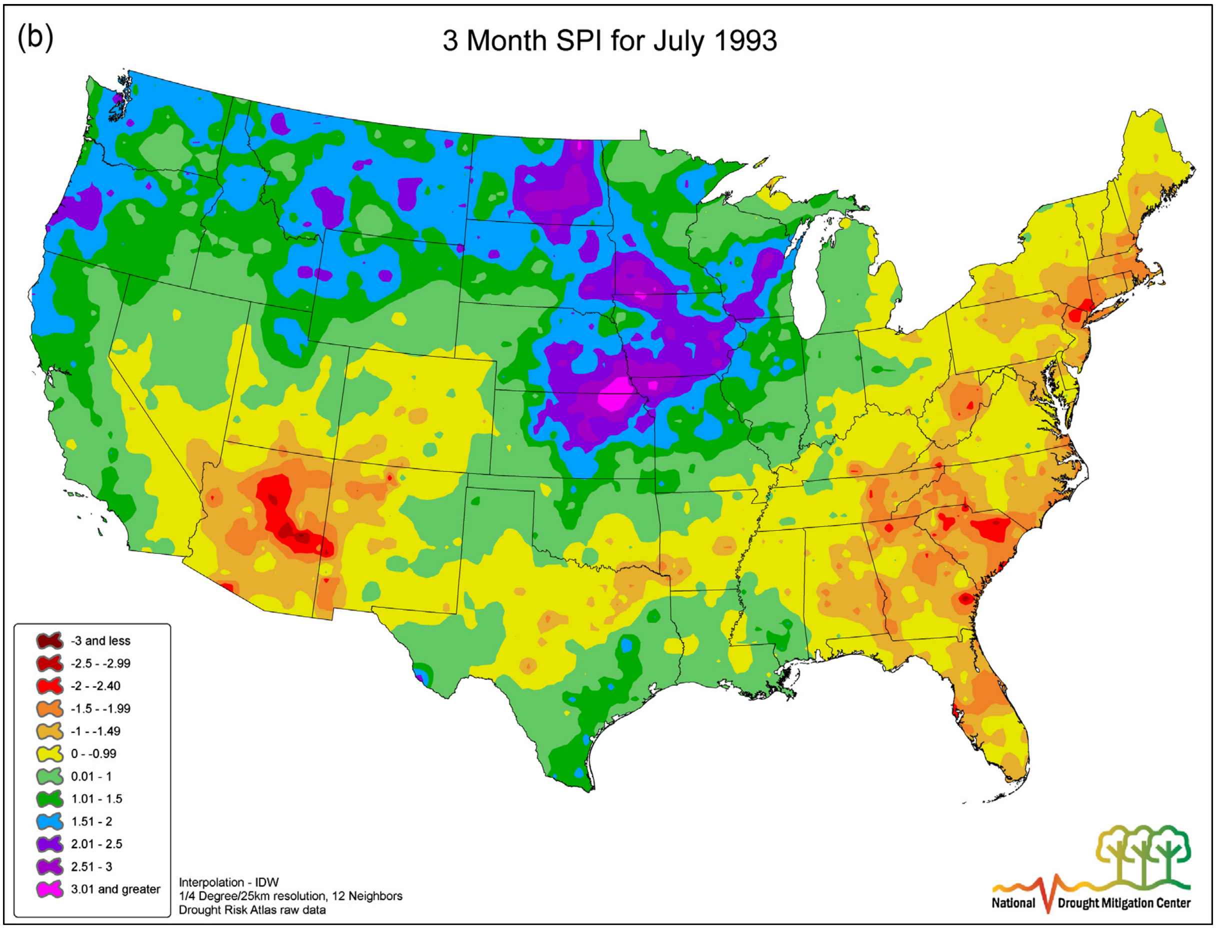
As we continue to face an unknown and changing climate, drought will continue to be a prominent natural disaster within any resultant climate regime. The more that is known of past drought events and their impacts, the better prepared we can be as a society to face and plan for drought in future (Woodhouse and Overpeck, 2000). It has been shown that not all drought indicators work well for all locations, and providing a drought risk atlas for decision makers will allow for better and more informed choices by producers, decision makers and the drought planning and services community at the local level. This is especially true for water resource managers, who will need to adapt to supplying water to users in a climatic environment that has changed over the last several decades. As the climate regimes are changing across the United States, the DRA will give water resource managers the ability to "drill down" to their basin, watershed or local area of interest to find detailed information on the climate and historical drought trends for that area.

The ability for users to query and tailor the DRA to their needs should allow for an increased capacity in analyzing drought by providing data and visualization tools to help them better understand



Interpolation - IDW
1/4 Degree/25km resolution, 12 Neighbors
Drought Risk Atlas raw data

Fig. 11. (a). Gridded 6-month SPI map for September 1954. The red (warm) colors represent dryness and the greens and blues (cool) represent wet areas. (b). Gridded 3-month SPI map for July 1993. The red (warm) colors represent dryness and the greens and blues (cool) represent wet areas.



3 Month SPI for July 1993

Interpolation - IDW
1/4 Degree/25km resolution, 12 Neighbors
Drought Risk Atlas raw data

Fig. 11 (*continued*)

the frequency, historical context, magnitude and trends of drought at the local, basin, tribal, regional or state levels. The tool's built-in spatial flexibility provides natural and water resource planners with a valuable resource for better informing their constituents about how to better cope with climate variability and change at all scales and under various levels of risk or uncertainty.

In addition, data and information from the DRA will be made available within the NWS's developing Local Climate Analysis Tool (LCAT). We also intend to work closely with NOAA's CSD to provide tailored training and education on drought (and various drought indices) by specifically making them aware of the potential uses and applications of the DRA tool and its extensive database and derivative products. The DRA tool has already been integrated into the NIDIS Portal at drought.gov.

Continued outreach and collection of feedback will be done by the NDMC team through the provision of webinars and/or hands-on training on how to use and get the most out of the DRA tool. With each webinar, for example, the technology is available to archive these sessions while developing a "Frequently Asked Questions" informational page that would be contained in the drought risk atlas web delivery system. Feedback from webinars, surveys, workshops and professional meetings will allow for enhancement of the DRA. Ideally, the users will continually help us identify and determine what can be added to make the tool better.

6. Summary and future work

Dissemination of the DRA tool will be broad, given the NDMC's linkages with our NOAA and USDA partners (including the new Regional Climate Hubs) and the vast number of other partners such as the Regional Climate Centers, state climate offices and university research community (including extension, which the NDMC is engaged with locally, regionally, nationally and even internationally). Our strategy includes free distribution via the NDMC web site (drought.unl.edu) and the NIDIS Portal mentioned above, which allows for direct access by all existing NIDIS RDEWS pilot region communities and any future pilot regions/basins that may come on-line in the future. The NIDIS Engaging Preparedness Community will also be tapped into, as this is a large body of practitioners dealing with drought planning and preparedness around the country. The U.S. Drought Monitor network of authors and experts is yet another collection of drought experts (now numbering more than 350 people) that serves as a direct conduit to users around the country, along with our networks involving the American Planning Association (APA) and the state drought contact network maintained at the NDMC.

The DRA tool has the potential to serve as a vehicle for assessing risk to extreme drought events, which should help planners to determine their vulnerability and deal with drought proactively. One such potential application is through the integration of DRA deliverables into a framework like the Drought Ready Community (DRC) program (DRC, 2011), which is aimed at helping users develop and understand their drought climatology, risk and potential trends when undertaking a drought planning exercise. In addition, recent work between the NDMC and the APA led to the development of a Planning Advisory Service (PAS) on drought planning (APA, 2013). The PAS is geared toward exposing planning practitioners to decision support tools and best practices in the drought planning arena that they can utilize in their planning work. Finally, the NDMC continually educates users through workshops, webinars and other interactions about the merits and potential information available with tools like the DRA. Providing and maintaining a tool such as the DRA will allow us to offer a stable and timely climate service that is well equipped to address mitigation and adaptation measures for producers, decision makers and planners alike.

It is a given that the COOP data records constantly change, and therefore the criteria need to be investigated again over the entire period of record for all 12,000+ stations. Working with our partners in the HPRCC and utilizing their ACIS database, we will look for the stations in the COOP network that have a long enough period of record (meeting stringent quality-control data requirements) to use in the DRA. With continual updates to the COOP data as well as corrections, quality control and data recovery projects, the database changes often enough that routine investigation is necessary to determine if more long-term COOP stations are reaching the criteria for inclusion in the DRA.

There is also a need to assess the current criteria and station locations to determine if more long-term stations could be utilized if the current criteria were modified with less restrictive screening steps. The reason for modifying the current criteria is to try to fill in spatial gaps across the United States while maintaining an adequate climate record for long-term analyses. If it is determined that areas not represented by an adequate number of stations could be better represented, the strict criteria could be amended for those regions to find the best climatic stations available in the COOP network. Additionally, with each year that passes, some stations may stop recording and others may reach our minimum requirement of 40 years, so there is a continual need to update the database and statistics along with the various derivative index products, including the grids.

Two other significant DRA enhancements are already under way as work has begun on identifying and bringing screened stations for Alaska and Hawaii into the DRA, along with all of the derivative products. Work also continues on lengthening the hydrology locations period of record in order to bring the hydrology data back into the final DRA. Streamflow locations void of human management are harder to come by, and budget cuts and stations being taken off-line are also concerns. All of these factors hurt the history and availability of high quality, long-term gauge stations that meet the DRA's screening criteria.

With the database in place, we are just beginning to research and assess changes and/or trends in drought frequency (and return periods) along with the intensity and various characteristics of drought behavior across the United States. The DRA allows for an in-depth analysis of the entire period of record, by decade(s), or by other user-defined periods, allowing for the detection of potential trends in both frequency and intensity of drought along with comparisons between current and past droughts for every COOP station and cluster contained within the DRA.

The NDMC DRA project team also realizes that not every drought index is ideal for every location or season. By providing several different indices at multiple time steps, the DRA gives users a vast menu of options to study and investigate drought for their region aimed at helping them find which indicators and time steps are most suitable for their location. Using these techniques, the ability for decision makers to concentrate on time periods that are specifically relevant to them and their application is possible.

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