Multiyear Droughts and Pluvials over the Upper Colorado River Basin and Associated Circulations

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Abstract
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Keywords
Atmospheric circulation, Statistical techniques, Time series, Anomalies, Trends, Societal impacts

Disciplines
Atmospheric Sciences | Climate | Hydrology

Comments

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ABSTRACT

This study analyzes spatial and temporal characteristics of multiyear droughts and pluvials over the southwestern United States with a focus on the upper Colorado River basin. The study uses two multiscalar moisture indices: standardized precipitation evapotranspiration index (SPEI) and standardized precipitation index (SPI) on a 36-month scale (SPEI$_{36}$ and SPI$_{36}$, respectively). The indices are calculated from monthly average precipitation and maximum and minimum temperatures from the Parameter-Elevation Regressions on Independent Slopes Model dataset for the period 1950–2012. The study examines the relationship between individual climate variables as well as large-scale atmospheric circulation features found in reanalysis output during drought and pluvial periods. The results indicate that SPEI$_{36}$ and SPI$_{36}$ show similar temporal and spatial patterns, but that the inclusion of temperatures in SPEI$_{36}$ leads to more extreme magnitudes in SPEI$_{36}$ than in SPI$_{36}$. Analysis of large-scale atmospheric fields indicates an interplay between different fields that yields extremes over the study region. Widespread drought (pluvial) events are associated with enhanced positive (negative) 500-hPa geopotential height anomaly linked to subsidence (ascent) and negative (positive) moisture convergence and precipitable water anomalies. Considering the broader context of the conditions responsible for the occurrence of prolonged hydrologic anomalies provides water resource managers and other decision-makers with valuable understanding of these events. This perspective also offers evaluation opportunities for climate models.

1. Introduction

The southwestern United States, including the upper Colorado River basin (UCRB), is highly vulnerable to regional climatic extremes, such as droughts and pluvials, because of the region’s geographic location and climatological characteristics (Laird et al. 1996; Hidalgo 2004). Multiyear droughts and pluvials have severe consequences for the agricultural sector and water...
resources management, such as for Denver Water, a major water utility in the region. Multiyear to multidecadal extremes in precipitation occurred as droughts during the 1930s and 1950s (Woodhouse and Overpeck 1998). The 1930s drought was characterized by numerous dust storms (Hughes 1976), such that the choking billows of dust during these periods inspired the term “Dust Bowl” by Edward Stanley (Mencken 1979). The drought that lasted from 1934 to 1937 occurred as a result of a climatic anomaly (Cook et al. 2014) exacerbated by unwise land-use practices (Landsberg 1982). The region had barely recovered from the devastating impacts of the 1930s drought when another persistent drought occurred in the 1950s. Drought episodes during the 1930s and 1950s marked the worst droughts experienced in the twentieth century over the region as well as for large areas in the United States (Andreadis et al. 2005). To this day, the 1953–57 drought remains the reference drought for Denver Water to illustrate water management challenges.

More recently, severe multiyear regional droughts in the 2000s led to substantial impacts. A recent study over the UCRB by Woodhouse et al. (2016) observed that a warming trend has resulted in increased snowfall and earlier snowmelt leading to increased runoff. At the same time, the evaporation also increased, causing a significant reduction in streamflow actually reaching the major reservoirs, especially during drought. The ongoing multiyear drought over the UCRB has been linked to warming (Nowak et al. 2012; Woodhouse et al. 2016) and has had substantial impact on the socioeconomic activities of the region as well as downstream. For example, the decline of water levels in Lake Powell and Lake Mead resulting from this drought combined with warming temperatures gives a situation where agriculture and hydropower production will likely suffer. A continued trend would yield the potential for more costly extreme conditions, which calls for better understanding of the drought characteristics and associated dynamics in the UCRB. The work presented in this study is part of an effort by the research community and the Denver Water management to characterize long-term droughts and pluvials over the basin and to assess the quality of climate models in reproducing real-world conditions. The work will inform scientific communities, water managers, and policymakers, and through that information help make better decisions on planning, distribution, and managing the best use of water resources.

There is no universal definition of drought, in large part because of different contexts and applications. However, in practice, drought is generally accepted as a natural hazard that originates from a precipitation deficit over an extended period of time (Wilhite and Buchanan 2005) coupled with changes in other atmospheric variables including solar radiation, wind speed, evaporation, and temperature (Sheffield et al. 2012). Drought is a multiscalar phenomenon (Vicente-Serrano et al. 2010a) with complex characteristics that can exert a great impact on the environmental and socioeconomic condition of a nation (Palmer 1965; Wilhite 1993, 2000; Bryant 2005).

The impacts of drought on water resources management and on the economy in the UCRB as well as the broader Southwest have prompted numerous studies (e.g., McCabe et al. 2004; Seager et al. 2005, 2008; Christensen and Lettenmaier 2007; McCabe and Wolock 2007; Meko et al. 2007; Schubert et al. 2009; Dawadi and Ahmad 2012; Nowak et al. 2012; Vano et al. 2014; Woodhouse et al. 2016). There is consensus that ongoing drought episodes in UCRB are related to both natural climate variability and, increasingly, to climate change associated with global warming. For example, Woodhouse et al. (2016) indicated that droughts over the basin have been amplified by warmer temperature relative to precipitation deficits. Under the current warming conditions, Barnett and Pierce (2008) showed that there is a 50% chance that storage in Lake Powell will be depleted by 2021. This projection is consistent with studies listed above that examined the impact of climate change on the basin. In addition, previous studies highlighted the link between UCRB hydroclimatic behavior during regional droughts and atmospheric–oceanic circulation patterns. These patterns are related to sea surface temperature (SST) anomalies over major ocean basins (e.g., tropical and North Pacific and North Atlantic) that are associated with major climatic modes. The effects of El Niño–Southern Oscillation (ENSO) and Pacific decadal oscillation (PDO) on UCRB’s hydroclimatic variations was the focus of study by Hidalgo and Dracup (2003). They observed that during winter the basin was characterized by wetter-than-normal conditions during El Niño events (associated with tropical Pacific SST warming) and drier-than-normal conditions during La Niña events, consistent with previous studies. Hidalgo and Dracup (2003) further showed that hydroclimate shifts were even more significant when El Niño (La Niña) coincided with the positive (negative) phase of the PDO. Hoerling et al. (2009) also found that the southwestern United States’ vulnerability to drought during 1946–56 was a result of the region’s sensitivity to SST anomalies in the tropical Pacific. In contrast, studies such as Kerr (2005) and Sutton and Hodson (2005) suggested that the Dust Bowl of the 1930s and the 1950s drought were associated with the warm phase of the Atlantic multidecadal oscillation. The results of these studies indicated the
existence of several large-scale atmospheric patterns interacting with modulate droughts at different time scales.

Kingston et al. (2015) suggested that part of the uncertainty in the relationships between atmospheric circulation and drought comes from the method of drought identification. There are different ways to characterize drought, such as agricultural, hydrological, and meteorological droughts. Agricultural drought is defined in terms of soil moisture deficit, hydrological drought in terms of anomalously low streamflow, and meteorological drought in terms of precipitation deficit. Both soil moisture and precipitation deficits are prerequisites to hydrologic drought. These definitions are based on different objectives, and hence, several indices have been developed for representing different types and intensities of droughts or pluvials, and often with different time scales in mind. Among them are the Palmer drought severity index (PDSI; Palmer 1965; Karl 1983), the standardized precipitation index (SPI; McKee et al. 1993; Guttman 1998), and the standardized precipitation evapotranspiration index (SPEI; Vicente-Serrano et al. 2010a). These indices are commonly used to provide useful information on drought detection and for monitoring evolving drought conditions to the public, water resources managers, and policy-makers as part of an effective early warning system (Wilhite 2002). They inform planning processes in water resources management for water allocations to minimize the impact of persistent drought (Yurekli and Anli 2008).

Although these indices offer robust information on drought events, there are inherent limitations associated with them. For example, although PDSI is advantageous for characterizing soil conditions, it has limitations for use in climate studies (e.g., Karl 1986; McKee et al. 1995; Guttman 1998; Hu and Willson 2000). Because of its inherently fixed time scale (between 9 and 12 months), the PDSI lacks the ability to distinguish different drought types given the multiscalar character that is important for assessing drought (McKee et al. 1993; Guttman 1999; Vicente-Serrano et al. 2010a,b). The SPI is a multiscalar index and can be applied across different geographical regions, at different time scales, but it is based only on precipitation. It fails to account for the influence of changes in evaporation and transpiration on the climatic water balance. In addition, studies have indicated that SPI at shorter time scales can be misleading in regions with normally low seasonal precipitation totals (Hayes et al. 1999). Vicente-Serrano et al. (2010a) have proposed the SPEI as another important tool for drought evaluation. It is a modification of the SPI that incorporates potential evapotranspiration in its algorithm, thus allowing an evaluation of a complete climatic water balance. As a result, SPEI combines the advantages of being multiscalar (like the SPI) and being able to account for the role of temperature (like the PDSI; Chen et al. 2013). Finally, studies such as Woodhouse et al. (2016) and work they cite show that trends in snowfall accumulation and earlier snowmelt in the UCRB are influencing drought in the region. The indices above do not explicitly include effects of snow, which could influence characteristics of multiyear drought (Van Loon et al. 2014). However, Van Loon et al. (2014) also show that their results that included snow were consistent with earlier studies such as Vidal et al. (2010) that used other drought indicators that did not include snow.

This study uses 36-month SPEI and SPI to analyze drought and pluvial episodes over UCRB, the region that supplies water for Denver Water. Keeping in mind the example of the 1950s drought, Denver Water managers are especially interested in 36-month and longer droughts for planning water management, both for maintaining supply and for adequate operating revenue. Our analysis is part of an effort to understand the basis for past droughts and pluvials, and how they might change in the future, with an eye toward translating the knowledge to inform the water utility’s needs. Aims of this study include: 1) diagnosing characteristics of multiyear droughts and pluvials (e.g., onset, duration, cessation, intensity, and frequency), 2) revealing the contrasts between drought and pluvial characteristics, and 3) extracting atmospheric large-scale features associated with the initiation and maintenance of extended drought and pluvial periods.

2. Study location, data, and methods
a. The study area

The UCRB is located within 35°–44°N, 105°–113°W, and drains an area of about 284,380 km² across five states: Wyoming, Colorado, New Mexico, northern Arizona, and Utah (Fig. 1). The basin has diverse topographic features with the Rocky Mountains on the eastern half and Wasatch Mountains on the western half. The relief ranges from 3,636 m (highest peak of the Wasatch; Mount Nebo) to 4,400 m (highest peak of the Rocky Mountains; Mount Elbert) above sea level. The topographic setting leads to complex regional microclimates across the basin, with a general transition of more maritime climates in the west to more pronounced continental conditions in the interior (Hirschboeck 1991; Pitlick 1994).

The climate of the UCRB is semiarid, with highly varied climate regimes that occur in the cold (October–March) and warm seasons (April–September). During
the study period, the annual average temperature ranged from 5.1 to 7.9°C, and the mean annual precipitation ranged from 510 to 1060 mm. A large portion of the UCRB’s accessible water comes from snowmelt during spring and heavy rainfall during summer (Christensen et al. 2004; Christensen and Lettenmaier 2007). The precipitation events come mainly from frontal storms from the Pacific Ocean and convective storms whose moisture comes from the Gulf of Mexico or the Gulf of California (Barry 1992).

The overall Colorado basin, whose water is often referred to as the life blood of the southwestern United States, supplies water for domestic use by approximately 26 million people, including residents of several major cities, such as Denver, and for various forms of recreation, irrigation, and hydropower production (Hidalgo 2004).

b. Data

The analysis in this study uses monthly maximum and minimum temperatures, potential evapotranspiration, precipitation, streamflow, and reanalysis datasets.

The monthly precipitation and maximum and minimum temperatures over UCRB are from the archives of the Parameter-Elevation Regressions on Independent Slopes Model (PRISM; http://www.prism.oregonstate.edu; Daly et al. 1994, 2008) datasets. PRISM uses a statistical interpolation method involving point measurements and digital elevation data. Further information on the dataset is available at the Oregon State University Climate Service website. The gridded datasets are available on a 4 km × 4 km grid from 1895 to 2012. Specifically, this study uses data for the 1948–2012 period to overlap with atmospheric reanalyses. The usefulness of this dataset in climate and many other applications is evident by its wide use (e.g., McCabe and Wolock 2007; Nowak et al. 2012; Woodhouse et al. 2016).

We use monthly streamflow data aggregated over three gauging stations as representative streamflow data for the UCRB. The stations are Blue River below Dillon, Fraser River near Winter Park, and Williams Fork near Leal (see Fig. 1). The streamflow data were sourced from a combination of the State of Colorado’s Division of Water Resources website (http://www.dwr.state.co.us/SurfaceWater/Default.aspx), the U.S. Geological Survey National Water Information System website (http://waterdata.usgs.gov/nwis), and the Raw Water Operations database of Denver Water records. The data are available from October 1915 to December 2014. For consistency with the length of the period of the other datasets used in this study, we use the streamflow data starting in January 1948 and ending in December 2012.

The large-scale atmospheric conditions associated with droughts and pluvials during the study period are examined by analyzing reanalysis fields from two reanalysis datasets; the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalyses dataset (Kalnay et al. 1996) and the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim) dataset (Dee et al. 2011). The NCEP–NCAR reanalyses use a comprehensive analysis/forecast system with 3D variational analysis to perform data assimilation from 1948 to the present. The output is available every 6 h on a 2.5° × 2.5° grid and at 17 pressure levels from 1000 to 10 hPa. Although the NCEP–NCAR reanalyses resolution is coarser than ERA-Interim’s, we chose this dataset because it has a relatively long temporal record. Also, the dataset has been widely used in several studies and found to produce reasonable results. We use it to examine composites during droughts and pluvials in the UCRB of precipitable water, geopotential height, omega vertical velocity, and zonal u and meridional v components of wind anomalies. The ERA-Interim dataset is available at both coarser and finer resolutions at 37 pressure levels from 1000 to 1 hPa, for the period 1979–2012. The gridded data products available online include, among others, 6-hourly and monthly upper-air fields covering the troposphere and stratosphere. We use the monthly time scale at 0.125° × 0.125° resolution. In particular, we use ERA-Interim data to analyze and examine the
vertical integral of zonal and meridional moisture flux and the flux divergence.

c. Methods of analysis

The SPI developed by McKee et al. (1993) to estimate and monitor drought has received widespread application, and it is commonly recommended by the research community and the World Meteorological Organization (WMO 2006) as a key tool to quantify drought at different locations and time scales. It is calculated by fitting a parametric statistical distribution to precipitation data that have been accumulated over a period of time, from which nonexceedance probabilities are transformed to the standard normal distribution (Stagge et al. 2014). Detailed descriptions can be found in McKee et al. (1993) and Guttmann (1998). The second drought index used in this study, SPEI, was developed by Vicente-Serrano et al. (2010a) to characterize droughts at different time scales. The SPEI is obtained by fitting a log–logistic Pearson III distribution to the climatic water balance. Details are provided in Vicente-Serrano et al. (2010a), Beguería et al. (2014), and Yu et al. (2014). Unlike the SPI, the SPEI incorporates temperature effects and thus potential evapotranspiration (PET) in its algorithm, which allows for an evaluation of a more complete climatic water balance. Details are provided in Vicente-Serrano et al. (2010a), Beguería et al. (2014), and Yu et al. (2014). Unlike the SPI, the SPEI incorporates temperature effects and thus potential evapotranspiration (PET) in its algorithm, which allows for an evaluation of a more complete climatic water balance. Details are provided in Vicente-Serrano et al. (2010a), Beguería et al. (2014), and Yu et al. (2014).

There are several methods for estimating PET (Vörösmarty et al. 1998). However, there are three commonly used approximations: Thornthwaite (Th; Thornthwaite 1948), Hargreaves (Hg; Hargreaves and Samani 1985), and Penman–Monteith (PM; Monteith 1965). While Th requires only mean temperature and latitude of the location, the PM formulation requires temperature, solar radiation, relative humidity, and wind speed. However, the third equation, Hg, requires only maximum and minimum temperatures. Although PM is recommended for the estimation of PET and it has been widely used, its extensive data requirement for variables that are not routinely measured by many meteorological stations (Beguería et al. 2014) has limited its application. The Th method, on the other hand, has been found by previous studies to overestimate PET with increasing temperature (Beguería et al. 2014; van der Schrier et al. 2011). Also, Th does not give reliable results in semiarid regions, as it underestimates PET (Jensen et al. 1990). This study uses Hg to compute PET in the climatic water balance. We use Hg because PRISM does not have all variables required to estimate PET by PM, but it does have those needed by Hg. In addition, PET values estimated from the Hg and PM equations at monthly and annual time scales are very similar (Beguería et al. 2014; Droogers and Allen 2002).

Because the three methods use different input variables to compute PET, there may be differences in the SPEI results obtained from these methods. We present the evolution of the 36-month SPEI obtained from the three methods in the appendix. The SPEI series from the three methods are identical, although there are slight differences in magnitude. The drought events during the 1950s, 1960, and the more recent drought episodes during the 2000s are well captured by the three PET methods, except for Th method, which underestimated the 1950s drought episodes.

Recently, Beguería et al. (2014) updated the SPEI algorithm to allow the user to select between different approaches to calculate the PET, with some consequences for climate studies. This study uses the revised SPEI algorithm to compute SPEI and SPI at 36-month time scale (hereafter SPEI36 and SPI36) based on PRISM monthly precipitation and maximum and minimum temperatures at each grid point over the UCRB using the SPEI function developed and made available through an R package by Beguería and Vicente-Serrano (2013). The classification of the intensity of dryness (negative values) and wetness (positive values) used in this study for the drought and pluvial episodes is given in Table 1, consistent with literature (Hayes et al. 1999; Lloyd-Hughes and Saunders 2002). We focus on 36-month periods ending in December, identified by the year of their ending month. We develop the time series at each grid point using an overlapping 36-month running mean window. For example, data designated as December 1950 come from the mean from January 1948 to December 1950, December 1951 data come from the mean from January 1949 to December 1951, etc. For the temperature and precipitation series, these are running averages; for the drought indices, these are moving windows of more complex cumulative quantities as derived in the index calculations.

Recall that SPEI and SPI are standardized anomalies, as implied by their names. For ease of comparison of the hydroclimatic variables with these indicators, we also determine the anomaly of all the data used in this study. The anomalies were computed by subtracting the long-term mean from the monthly value at each grid point. Standard deviations at each grid point were also calculated. We use 1981–2010 as the baseline period for consistency with the baseline used in the SPEI algorithm. Then we obtain the normalized anomalies of the variables by dividing the anomalies by the standard deviations. This method has been used in several research studies involving extremes and synoptic-scale events (e.g., Grumm and Hart 2001; Hart and Grumm 2001; Junker et al. 2008). The trends in the hydroclimatic variables are calculated and the statistical significance of
and pluvials events over UCRB. Large-scale atmospheric features influencing droughts and pluvial events over UCRB. This enables us to compare and contrast the region experienced widespread drought and pluvial events derived from SPEI because the two analyses for composites developed using the indices, SPEI and SPI, have nearly identical extreme index values. We present the results in order to remove potential effects of trends that might yield false indication of significant behavior. We develop composite maps of atmospheric variables corresponding to the average conditions of all the widespread drought or pluvial events for each of the two indices. Prior to compositing, we detrend the time series of the large-scale fields by removing the linear fit to the time series at each grid point. This is done in order to remove potential effects of trends that might yield false indication of significant behavior. We present analyses only for composites derived using the widespread events derived from SPEI because the two indices, SPEI and SPI, have nearly identical extreme event years. In addition to the composites, we also present analyses for two selected periods when the study region experienced widespread drought and pluvial conditions. This enables us to compare and contrast the large-scale atmospheric features influencing droughts and pluvials events over UCRB.

3. Results and discussion

a. Mean climatology

To understand the nature of extreme conditions over UCRB, we first examine the climatology of the region by analyzing the 36-month moving average of the surface variables used in this study to compute the drought indices. In particular, we analyze and examine the spatial distributions and time series of maximum temperature $T_{x}$, minimum temperature $T_{n}$, potential evapotranspiration $P_{e}$, and precipitation $P$ during the period of study using the PRISM 4-km data.

The spatial pattern of mean $T_{x}$ is shown in Fig. 2a, with a distinct spatial variability. The eastern sector and parts of the northern axis, the mountainous regions with height at 2750 m and above, are characterized by lower temperatures, while higher values with slight-to-moderate temperature gradients dominate the northern and the southern parts of the basin. The areal mean maximum temperature over the basin is about 14.7°C, with a mean standard deviation of about 3.9°C. The temperature range is 20.7°C, with maximum value of 23.0°C and minimum value of 2.3°C. Unlike the maximum temperature, a clear north–south temperature gradient is shown by the spatial distributions of minimum temperature (Fig. 2b). Temperatures over the eastern sector of the basin are generally cooler. The core of the minimum temperature over the basin is located at the southwestern regions extending in a narrow strip over the central part. Areal mean temperature is $-0.6°C$, with a standard error of 3.7°C. The temperature range is 19.2°C, with maximum value of 9.0°C and minimum value of $-10.2°C$.

Figure 2c shows the spatial pattern of mean $P_{e}$ over the UCRB during the period of study. This pattern shows a close resemblance to that of mean $T_{x}$ (Fig. 2a), with higher evapotranspiration characterizing the lower parts of the basin while the high-elevation regions are characterized by lower evapotranspiration. As expected, the observed pattern of the long-term average $P_{e}$ (Fig. 2c) is very similar to that of the 36-month moving average mean temperature $T_{x}$, as the potential evapotranspiration in this study is calculated using temperature. Areal mean potential evapotranspiration over UCRB is 90.4 mm, with a standard deviation of 15.1 mm and a median value of about 89.3 mm. The climatological minimum and maximum values of $P_{e}$ are 45.3 and 120.7 mm, respectively. The similarities between the spatial distributions of maximum temperature and potential evapotranspiration over the basin suggest their important roles in extreme conditions over the basin.

Figure 2d shows the mean $P$ over UCRB. Unlike the other three hydroclimatic fields, large parts (well over 90% of the area) of the basin have precipitation below the average value (815.4 mm). However, several portions of the high-elevation regions have precipitation above the spatially averaged mean value (815.4 mm). Pockets of maximum values of about 4457.7 mm can be seen over the mountainous regions. The precipitation over the low-lying areas can be as low as 293.6 mm with a standard deviation of about 495.4 mm.

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**Table 1. Classification scale for drought/pluvial indicator values.**

<table>
<thead>
<tr>
<th>Category</th>
<th>Index range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extreme dry</td>
<td>$-2.0 &lt; \text{Index} \leq -1.0$</td>
</tr>
<tr>
<td>Severe dry</td>
<td>$-1.5 &lt; \text{Index} \leq -1.0$</td>
</tr>
<tr>
<td>Moderate dry</td>
<td>$-1.0 &lt; \text{Index} \leq -0.5$</td>
</tr>
<tr>
<td>Normal</td>
<td>$0.0 &lt; \text{Index} \leq 1.0$</td>
</tr>
<tr>
<td>Moderate wet</td>
<td>$1.0 &lt; \text{Index} &lt; 1.5$</td>
</tr>
<tr>
<td>Severe wet</td>
<td>$1.5 &lt; \text{Index} &lt; 2.0$</td>
</tr>
<tr>
<td>Extreme wet</td>
<td>$2.0 &lt; \text{Index}$</td>
</tr>
</tbody>
</table>

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lower values of precipitation over large fractions of the
basin suggest, in general, that the basin has drier con-
ditions at lower elevations.

b. Spatial and temporal distributions of hydroclimate
variables and drought indices

1) TEMPORAL CHARACTERISTICS OF CLIMATE
VARIABLES AND DROUGHT INDICES

In consideration of the climate variability over the
UCRB, we examine the temporal evolution of the nor-
malized anomalies of maximum temperature, potential
evapotranspiration, precipitation, and the drought in-
dices at a 36-month time scale, averaged over the study
domain (Fig. 3) and a subregion (Fig. 4). The subregion
contains the locations of the streamflow observations
used here (outlined black box in Fig. 1). The streamflow
observations are concentrated in the extreme north-
eastern portion of the UCRB, the region that supplies
water for Denver. Thus, we also examine the time series
of the surface hydroclimates and drought indices along
with the streamflow SF36 data spatially averaged over
this subregion. The result of the streamflow analysis
over this region will be used as a proxy for the charac-
teristics of streamflow for the entire basin region.

Figure 3 shows the temporal evolution of normalized
TX36, PET36, P36, SPEI36, and SPI36 anomalies spatially
averaged over our study domain. The normalized TX36
anomalies show clusters of hot and cool periods
(Fig. 3a). Hot years are found during 1954–64 (with a
break in 1957), 1977–78, 1981–82, 1988–90, 1996–97, and 2000–08, while there have been cool years during 1950–53, 1965–76, 1979–80, 1983–87, 1991–95, and 2009–11. Of the clusters, the most obvious are the positive anomalies spanning 1954–64 and 2000–08 and negative anomalies spanning 1965–76, 1983–87, and 1991–95. The TX36 shows a statistically significant cooling trend (−0.40 decade\(^{-1}\), \(p = 0.0084\)) from 1950 to 1980 and a nonsignificant warming trend (0.41 decade\(^{-1}\), \(p = 0.1660\)) from 1981 to 2012, which is consistent with Gleason et al. (2008). In general, the linear trend in normalized TX36 anomalies during the period 1950–2012 shows non-significant warming at a rate of 0.05 decade\(^{-1}\) (\(p = 0.6311\)).

Figure 3b shows the temporal evolution of PET36. This pattern is similar to that of TX36 (Fig. 3a), although with slight differences in timing and duration. For example, in contrast to \(T_{36}\), PET36 shows a cluster of positive anomalies during 1950–53. The longer duration of positive PET36 anomaly during the periods 1950–64 and 2000–08 indicate the higher evaporative demand by the atmosphere over UCRB during those periods. The temporal pattern of PET36 shows a decreasing trend (−0.33 decade\(^{-1}\), \(p = 0.1577\)) in the field during the first half of the period and an increasing trend (0.24 decade\(^{-1}\), \(p = 0.4606\)) during the later period. Overall, normalized PET36 anomaly is characterized by a nonsignificant decreasing trend (−0.07 decade\(^{-1}\), \(p = 0.4667\)). The time series of normalized \(P_{36}\) anomalies is shown in Fig. 3c. In general, clusters of dry years span the periods 1950–64, 1972–79, 1989–92, 2000–05, and 2008–12, while the other periods are characterized by positive anomalies, with the longest duration in 1980–88. The trend in \(P_{36}\) shows a nonsignificant increase (0.08 decade\(^{-1}\), \(p = 0.3409\)) during 1950–80 and a statistically significant decrease (−0.45 decade\(^{-1}\), \(p = 0.0362\)) during 1981–2012.

As shown in the time series of SPEI36 (Fig. 3d) the dry episodes (negative anomalies) span 1950–58, 1960–64, 1974–79, 1989–91, 2000–09, and 2007–09, while wet episodes (positive anomalies) occur during 1965–71 with breaks in 1968, 1982–88, 1992–95, and 1997–99. Figure 3e shows that the time series of SPI36 (Fig. 3e) exhibit a temporal pattern consistent with \(P_{36}\). The similarity is due to the sole contribution of precipitation in the SPI calculation. Although the temporal patterns of SPEI36 and SPI36 are similar, indicating the influence of precipitation in both indices, the opposite-phase relationship of SPEI36, in particular, with TX36 and PET36 suggests that warming coupled with higher evaporative demand may also be playing a significant role in variations of extreme SPEI36 events over UCRB.

Examination of trend analysis during the two periods considered above indicates that trends in these drought indicators show increases during the first half of the period from 1950 to 1980, with changes of 0.09 and 0.17 decade\(^{-1}\) for SPI36 and SPEI36, respectively. The upward trend is a result of the reduction in drought intensity toward the end of the period. However, during 1981–2012, trends in SPI36 and SPEI36 are −0.41 (significant; \(p = 0.0320\)) and −0.35 decade\(^{-1}\), respectively. The downward trend in the drought indicators may be due to the weakening in intensity of the wet conditions and subsequent intensification during the dry conditions, especially during the 2000s. The drying during the recent decades is consistent with the results by other researchers, who studied PDSI (e.g., Cook et al. 2004; Dai et al. 2004). The results suggest, in agreement with
other studies, that the increase in $P_{36}$ over UCRB between the first half and second half of the period is the main cause for the upward (moistening) trends observed in the drought indicators. Also, the warming trend during the second half of the period and simultaneous significant decrease in precipitation is responsible for the later drying trends.

The time series of normalized anomaly of SF$_{36}$, hydroclimatic variables, and the drought indices for the subregion is shown in Fig. 4. It can be seen that there is a close resemblance between the hydroclimatic variables and drought indices in Fig. 4 with those in Fig. 3 for the UCRB. The few differences that occur are related to the onset and cessation of events. Also, the magnitudes appear higher in Fig. 4 than in Fig. 3. The disparities may be due to the difference in spatial coverage, coupled with elevation effect.

The streamflow data shown in Fig. 4d indicate that the periods of anomalous positive and negative SF$_{36}$ are in good agreement with the wet and dry years presented by both SPEI$_{36}$ (Fig. 4e) and SPI$_{36}$ (Fig. 4f). More specifically, the correlation of SF$_{36}$ and SPEI$_{36}$ is 0.78, whereas the correlation of SF$_{36}$ and SPI$_{36}$ is 0.79; both indices appear to be indicators of streamflow into Denver Water’s reservoirs. The trends in SF$_{36}$ during both the first half and second half of the period show weaker nonsignificant decreases $[-0.13 ~ (p = 0.6833)$ and $-0.07 ~ (p = 0.8793)$ decade$^{-1}$, respectively]. Overall, the pattern displayed by the normalized SF$_{36}$ anomalies indicates an increasing trend with magnitude of about 0.07 decade$^{-1}$.

Figure 5 shows the percentage area of the UCRB in moderate and severe-to-extreme droughts (Fig. 5, left) and pluvials (Fig. 5, right). The panels each consist of the temporal evolution of the SPEI (solid) and SPI (dashed) at 36 months. In general, although the two indices have similar patterns, there are slight differences in percent area and period. For example, the SPEI result indicates that 58% of the UCRB experienced moderate drought in 2004, while in 2002 about 54% of the region had moderate drought according to the SPI (Fig. 5a). For severe-to-extreme drought (Fig. 5b), there are about 83% (76%) and about 62% (37%) of the region in this classification of drought in 2003 (2002) as indicated by SPEI$_{36}$ and SPI$_{36}$, respectively. Furthermore, the period with the highest percentage area in moderate-to-extreme drought over UCRB is 1956 with about 66% as indicated by SPI$_{36}$. Droughts during these periods have a significant impact on water resources over the western region of the United States.

As in the temporal patterns depicted in Figs. 5a and 5b for the moderate and severe droughts over UCRB, there is a similarity in the time series of each category of pluvial events according to SPEI$_{36}$ and SPI$_{36}$ (Figs. 5c,d). We see that 1983, 1984, and 1985 had the largest percentage of area in moderate and severe-to-extreme wet conditions, respectively. In 1983 and 1984, about 61% and 80% of UCRB was affected by moderate wet conditions as indicated by SPEI$_{36}$ and SPI$_{36}$, while SPEI$_{36}$ (SPI$_{36}$) indicated that about 46% (33%) of the area experienced severe-to-extreme wet conditions in 1984 (1985).

Overall, the percentage of area in drought in the 2000s stands out as a prominent feature of the temporal pattern over the region, with a peak in 2003. The other prominent features of the time series of percentage area
in drought over UCRB are the mid-1950s, 1960s, 1970s, and 1988–90. The 1980s and late 1990s are characterized by pluvial conditions. These results are in agreement with other studies over the western United States (e.g., Andreadis et al. 2005).

2) SPATIAL PATTERNS OF SPEI36 AND SPI36

In Colorado, the recent drought conditions, which started in late 1999 and initially peaked in the summer of 2002, had a great impact on the Colorado River basin. The basin experienced the worst 11-yr drought in the last century (Bureau of Reclamation 2012) and the reservoir storage declined. Snowpack was much below average, and in 2002 it was extremely low throughout the state. The natural annual flow volume at Lees Ferry stood at 6.03 million acre feet (MAF) below average annual flow of approximately 14.8 MAF (https://www.doi.gov/water/owdi.cr.drought/en/). To better understand the climate variability over this region for planning purposes requires the application of appropriate tools. In an effort to show the similarities and/or differences in the patterns depicted by the two indices, we examine the spatial patterns of the indices in that extreme drought year of 2002 and compare conditions with the years 1956 and 1984 when the drought indicators exhibit the largest percentage of area in either drought or pluvial conditions over UCRB.

We show the spatial patterns of SPEI36 and SPI36 during the periods ending in 1956, 1984, and 2002 in Fig. 6. Although the spatial patterns of the two indices bear a clear resemblance to each other, there are slight differences in magnitude. This suggests that different large-scale atmospheric features may be responsible for extreme events over the UCRB. In 1956, the magnitude of drought in SPI36 (Fig. 6d) is slightly higher than in SPEI36 (Fig. 6a). The drought intensity appears to be higher over the southern parts of the region and over the subregion. Previous studies have shown that the 1950s drought over the United States was related to a deficit in precipitation rather than a warming temperature (Dai et al. 2004). Unlike the spatial patterns in 1956, the regions in severe droughts in 2002 are spatially larger in SPEI36 (Fig. 6c) than in SPI36 (Fig. 6f) (see also Fig. 5), indicating that drought intensity in SPEI36 is larger than in SPI36. The 2002 drought was accompanied by warming during the second half of the study period (Fig. 3). This is consistent with Dai et al. (2004), which indicated that increases in percentage areas after the mid-1980s were primarily caused by surface warming.

The spatial structure of the pluvial event in 1984 is shown in Figs. 6b and 6c. This study finds that while SPEI classifies large areas as having severe pluvial conditions, SPI displays more areas in normal-to-moderate pluvial conditions. Figure 4 shows that anomalies in temperature and potential evapotranspiration were below normal, indicating that evaporative demand over the river basin was lower. Concurrently, there was a positive precipitation anomaly that then could yield higher streamflow (Fig. 4d). Finally, the SPI in Fig. 6 shows more spatial heterogeneity than the
SPEI. This difference may be a consequence of the inherently larger spatial scale of temperature anomalies that are part of an SPEI computation.

The temporal and spatial analysis of drought and pluvial conditions indicated, for example, that droughts during the 1950s were a response to precipitation deficits, while droughts during the 2000s show an increasing influence of temperature in addition to rainfall deficits, although the patterns portrayed by SPEI_{36} and SPI_{36} are spatially similar. This result, however, underscores the potential advantage of SPEI as an appropriate tool for drought monitoring, especially under climate change because it takes the effect from rising temperatures into account.

c. **Atmospheric large-scale features associated with drought and pluvial events**

Previous studies indicated that extreme events over the southwestern United States are likely related to changes in atmospheric circulation. A few examples were highlighted in section 1. In this section, we analyze the spatial arrangement of composites of large-scale atmospheric features, including the precipitable water, zonal and meridional moisture transport, geopotential height, and omega vertical velocity, to examine their physical structure during widespread droughts and pluvials as indicated by SPEI_{36} over UCRB, using the NCEP–NCAR reanalyses dataset. The robustness of these large-scale fields was examined using the finer-spatial-scale ERA-Interim dataset, in particular, for the divergence of vertically integrated moisture flux. To put the large-scale patterns influencing extreme events over UCRB into perspective, we repeat the above analyses for two periods, 1984 and 2002. The selection of these two years is motivated by the time series of the drought indices shown in Figs. 3 and 5. The results presented in this section refer to composite fields that have been detrended to remove the influence of linear trends. For ease of readability and interpretation, the outline of the study region is shown in green.
Figures 7–9 show the anomaly maps of precipitable water content $W$ in the atmospheric column superposed on 925-hPa wind (Fig. 7), 500-hPa geopotential height $Z_{500}$ and 500-hPa wind (Fig. 8), and vertical cross sections outlining the vertical velocity field $\omega$ with meridional wind (Fig. 9). Figures 7a and 7b, 8a and 8b, and 9a and 9b are the composites of widespread droughts and pluvials, while the spatial patterns of the 2002 drought and 1984 pluvial are shown in Figs. 7c and 7d, 8c and 8d, and 9c and 9d.

The result shows that drought events (Fig. 7a) are associated with anomalous negative $W$ in the atmospheric column over the Pacific Ocean with an extension over the basin. The low-level circulation shows a band of weaker anticyclonic circulation between 30$^\circ$ and 40$^\circ$N. The reduced strength of the westerlies thus acts to promote dryness over the region. The reduced $W$ content in the atmospheric column over the UCRB is associated with enhanced $Z_{500}$ (Fig. 8a). Overall, the contiguous U.S. region is dominated by a ridge with positive $Z_{500}$ anomalies. The maximum height anomaly is located over the western United States, encompassing the UCRB. Thus, the dry conditions coupled with warmer-than-normal climate over the region are directly associated with this positive height anomaly, consistent with previous studies (Schubert et al. 2004). The anomalies of enhanced easterly wind vectors over the region are linked with negative $W$ anomaly, and this suggests the presence of midtropospheric subsidence air over the region, which acts to promote the dryness. This feature is supported by the latitude–height analysis of $\omega$ displayed in Fig. 9a. The figure showed the pattern of $\omega$ and wind spatially averaged over the longitudinal extent of UCRB (Fig. 1). It is seen that, while the northern part of the basin is characterized by shallow ascent below the 500-hPa level, the entire basin is dominated by anomalous positive omega vertical velocity (descent) with the core axis extending over wider atmospheric levels.

The widespread pluvial events (Figs. 7b, 8b, 9b) over the UCRB exhibit large-scale atmospheric circulation patterns that are different from, but not mirror images of, the anomalous behavior of the widespread drought events. Figure 7b displays the spatial distribution of $W$ anomaly during widespread pluvial events. This figure
features a northeast–southwest-oriented positive W anomaly that extends eastward from the eastern tropical Pacific Ocean over the basin, with two maxima: one over the oceanic area and the other over the inland area. This core over the Pacific Ocean acts as the source of moisture transport from the Gulf of California to inland regions, while the inland core acts as the sink. The strong southwesterly wind anomaly with circulations over the basin indicates the transport of moisture over the basin. In contrast to Fig. 8a, the \( Z_{500} \) during widespread pluvial events (Fig. 8b) shows a height anomaly pattern that is oriented from northwest to southeast. The core of the anomalous height is seen over the basin. The positive W and negative \( Z_{500} \) anomalies are associated with deeper and enhanced cyclonic anomaly at the 500-hPa level. The enhanced low-level and midtropospheric winds indicate the presence of stronger ascent through the depth of the atmosphere over the region. In fact, Fig. 9b lends support to these analyses, where enhanced ascending motion is the dominant feature over the basin.

The composites of normalized large-scale atmospheric anomaly fields during widespread drought and pluvial events derived from SPEI36 over UCRB show patterns that are spatially dissimilar. These results indicate, to a first approximation, that drought and pluvial events are not simply mirror images of each other and that they are modulated by different large-scale features. This is further confirmed by the spatial distributions during two specific periods with opposing events (Figs. 7c,d; 8c,d) over the region. Differences occur in spatial distributions of W and wind vectors between Fig. 7c (a component of Fig. 7a) and Fig. 7a. Analysis of individual drought events (figures not shown) that made up Fig. 7a indicates that drought episodes over UCRB are associated with large-scale features of different magnitudes and patterns in W and 925-hPa wind vectors. By and large, there tends to be an easterly wind component during drought (e.g., Fig. 10). Further study on pattern classification of features linked with drought episodes over the region will contribute to knowledge on drought events over the region.

The results presented above indicate differences in moisture availability during widespread drought and pluvial events over UCRB. So, in order to further differentiate between drought and pluvial characteristics, and also to put into perspective the large-scale anomaly

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**Fig. 8.** Composite mean standardized anomaly of \( Z_{500} \) superimposed with 500-hPa wind vector during widespread (a) drought and (b) pluvial events and mean standardized anomaly of \( Z_{500} \) superimposed with 500-hPa wind vector for (c) 2002 drought and (d) 1984 pluvial from SPEI at the 36-month time scale over the UCRB. The shading interval is 0.3σ.
associated with extremes over the UCRB, we analyze the moisture transport and its convergence over the region. Since the divergence of the vertically integrated moisture flux is readily available from the ERA-Interim dataset, we multiply this field by $2$ to obtain moisture convergence. The NCEP–NCAR reanalyses are too coarse to resolve well this field for the UCRB. Figure 10 shows the anomalies of vertically integrated moisture convergence and the moisture flux vector during extreme events over UCRB. Consistent with the anomalous positive $Z_{500}$ (Fig. 8a) and omega vertical velocity (Fig. 9a), the enhanced easterly moisture flux during drought conditions is linked with anomalous negative moisture convergence (Fig. 10a), with maximum anomalies over the eastern half of the basin. There appears to be an interplay between these large-scale fields, as the enhanced sinking motions in anomalous positive $Z_{500}$ results in enhanced moisture divergence. In addition, the enhanced easterlies here seem to suppress the moisture-bearing westerlies over the ocean and thus act to promote a drought-conducive environment over the river basin. In contrast, for pluvial events, Fig. 10b displays different patterns compared to the drought events. For the pluvial events, the enhanced westerly moisture

Fig. 9. Vertical structure of composite mean standardized anomaly of $\omega$ and wind vector $(v, -\omega)$ averaged between the longitudinal length of UCRB during widespread (a) drought and (b) pluvial events and mean standardized anomaly of $\omega$ and wind vector $(v, -\omega)$ for (c) 2002 drought and (d) 1984 pluvial from SPEI at the 36-month time scale over the UCRB. The shading interval is 0.2.$x$. 
flux is associated with increased moisture convergence, consistent with the enhanced rising motion (Fig. 9b) associated with anomalous negative $Z_{500}$ (Fig. 8b) over the basin area. The persistent rising motion coupled with abundant precipitable water in the atmospheric column and enhanced westerlies promoting orographic precipitation favors the conversion of atmospheric moisture into clouds and precipitation (Liu et al. 2004). Thus, the interplay between these fields in the atmospheric column over UCRB acts to promote the moisture convergence during widespread pluvial events. Overall, this pattern indicates an enhancement above the long-term mean of moisture transport from the Gulf of California and from the Gulf of Mexico. Similar large-scale environmental features displayed during the 2002 drought and 1984 pluvial in comparison with the composite patterns during all drought and pluvial events, respectively, suggest that extreme events over the UCRB are associated with anomalous negative moisture convergence (droughts) and anomalous positive moisture convergence (pluvials) concomitant with other interrelated anomalies of large-scale atmospheric fields.

FIG. 10. Composite mean anomaly of moisture convergence (MC) superimposed with vertically integrated moisture flux anomaly (arrows) during widespread (a) drought and (b) pluvial events and mean anomaly of MC superimposed with vertically integrated moisture flux for (c) 2002 drought and (d) 1984 pluvial from SPEI at the 36-month time scale over the UCRB. The climate variables are from the ERA-Interim dataset.
All the figures presented in previous sections indicate the links between hydroclimatic variables and drought indicators. Also, the results show the relationships between extremes and large-scale atmospheric features over UCRB. The patterns indicate that there is a difference in the physical mechanisms responsible for widespread droughts and pluvials over UCRB during the period of study.

4. Conclusions

This study focused on diagnosing characteristics of multiyear droughts and pluvials over the upper Colorado River basin (UCRB) using two drought indicators. We examined and compared the temporal and spatial patterns of droughts and pluvials depicted by SPEI and SPI at the 36-month time scale. We chose this longer time scale because Denver Water managers are interested in persistent, multiyear droughts for planning water management. Shorter anomalies can be managed with the existing reservoirs and other infrastructure. The data used for this study included monthly mean maximum temperature, minimum temperature, and precipitation from the PRISM datasets for the period 1948–2012. The streamflow data came from the archive of the U.S. Geological Survey National Water Information System. The two drought/pluvial indices (SPEI_{36} and SPI_{36}) were calculated using monthly mean maximum temperature and precipitation from the PRISM datasets. The study also examined large-scale physical processes associated with widespread droughts and pluvials over UCRB using NCEP–NCAR reanalyses for 1948–2012 and ERA-Interim for 1979–2012.

The results of our analyses can be summarized as follows:

- There has been a marked warming with increased PET and decreased precipitation leading to widespread droughts.
- Clusters of warm anomalies in $T_{36}$ coupled with positive anomalies of PET_{36} and negative anomalies of $P_{36}$ coincide with periods of severe to extreme droughts, while periods of severe to extreme pluvials are associated with cool anomalies in $T_{36}$ in conjunction with negative anomalies of PET_{36} and positive anomalies of $P_{36}$. Clusters of warm and cool anomalies in $T_{36}$ coupled with positive (negative) and negative (positive) anomalies of PET_{36} ($P_{36}$) coincide with periods of severe to extreme droughts and pluvials.
- SPEI_{36} and SPI_{36} exhibit similar temporal evolution, but the SPEI_{36} variations are greater than SPI_{36} variations. Also, the magnitude of the trend in SPEI_{36} is greater than that of SPI_{36} during the two subperiods of 1950–80 and 1981–2012.
- The SPEI_{36} shows a higher percentage of area in drought or pluvial conditions in comparison with SPI_{36}. According to the SPEI_{36}, the largest area affected by moderate, severe, and extreme droughts occurred in 2004, 2003, and 1956. The year 1999 marked the period with the highest percent area of UCRB in moderate wet conditions, while severe and extreme wet conditions occurred especially in 1984.
- Reduced precipitable water anomaly coupled with easterly wind anomalies are associated with widespread droughts, while enhanced positive anomaly of precipitable water and associated strong westerly wind anomalies are linked with widespread pluvials over the UCRB.
- The anomalous high geopotential height field during widespread drought is linked with reduced precipitable water content in the atmospheric column over the UCRB, while the deepened geopotential height anomaly over the region during widespread pluvial conditions is linked with increased precipitable water. The Pacific Ocean, the Gulf of California, and the Gulf of Mexico are important sources of moisture transport into the region. However, the enhanced high geopotential height anomaly is responsible for blocking moisture transport from reaching the interior of the United States through subsidence associated with the circulation; this results in dry conditions over the region.
- Consistent with reduced precipitable water and positive height anomaly, an area of descending motion over the latitudinal extent of the basin is observed during drought conditions. In contrast, pluvial conditions over the basin occur as a result of the interplay between positive precipitable water content, low height anomalies, and sustained rising motions.
- Because of the links between the previously discussed large-scale fields, the moisture convergence is anomalously low during drought episodes and anomalously high during pluvial episodes.

In conclusion, the findings of this study have shown that widespread droughts (pluvials) as represented by SPI_{36} and SPEI_{36} occur in association with anomalous warm and dry (cool and wet) conditions over UCRB. The analysis further shows that droughts and pluvials are not simply mirror images of each other in their characteristics, so that one is not simply the opposite phase of the other. This is particularly true of the large-scale circulation patterns associated with droughts and pluvials. Furthermore, the results of this study underline the impacts of warming on regional water balance and...
climates. Corroborating other studies that have shown that the frequency and severity of drought increases with rising temperature (Dai 2011; Lorenzo-Lacruz et al. 2010; Vicente-Serrano et al. 2010a); results here demonstrate that drought indicators that incorporate the influence of temperature would be more appropriate for monitoring drought and pluvial conditions in this region. In this regard, this study indicates that SPEI as an alternative to SPI better captures and quantifies drought conditions. Thus, SPEI appears to be well suited for Denver Water to estimate streamflow and thus is a better climate indicator for water management than precipitation-based indicators alone.

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APPENDIX

Comparison of SPEI Using Different PET Methods

The SPEI time series in Fig. A1 use the PET methods described in the main body of the paper, applied to the datasets discussed there, except that the SPEI data obtained from the PM approach using the Climatic Research Unit dataset is from the SPEIbase, version 2.4 (v2.4), archive (Beguería et al. 2014). The correlations between the SPEI series from the three methods are high ($r > 0.85$) and statistically significant ($p < 0.0001$) at the 5% significance level (values shown in Figs. A1d–f).

Using the test statistics for the difference of two means (Devore 1995, section 9.1), the result indicates that there are no significant differences between the means of the SPEI series from the three methods. In fact, for the most part, the difference is below 0.5. The Student’s $t$ test for the difference of two means for PM versus Hg is substantially higher ($t = 1.14$) than that of PM versus Th ($t = -0.24$) and Hg versus Th ($t = -1.46$). These results indicate that using PET obtained from the Hg method instead of PM method will not affect the SPEI results.

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