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Effects of different reference periods on drought index estimations for 1901-2014

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Abstract. This study aims to understand how different reference periods (i.e., calibration periods) of climate data for estimating the drought index influence regional drought assessments. Specifically, we investigate the influence of different reference periods on historical drought characteristics such as trends, frequency, intensity and spatial extents using the standard precipitation evapotranspiration index with a 12-month lag (SPEI-12) estimated from the datasets of the climate research unit (CRU) and the University of Delaware (UDEL). For the 1901–1957 (P1) and 1958–2014 (P2) estimation periods, three different types of reference periods are used: P1 and P2 together, P1 and P2 separately and P1 only. Focusing on East Asia, Europe, North America and West Africa, we find the influence of the reference periods to be significant in East Asia and West Africa, with dominant drying trends from P1 to P2. The reference periods influence the assessment of drought characteristics, particularly for severity and spatial extent, whereas their influence on the frequency is relatively small. Finally, self-calibration, which is the most common practice with an index such as SPEI, tends to underestimate the drought severity and spatial extent relative to the other approaches used in this study. Although the conclusions drawn in this study are limited to two global datasets, they nevertheless highlight the need for the reference period to be clarified in drought assessments to better understand regional drought characteristics and their temporal changes, particularly under climate change scenarios.

1 Introduction

Drought is a complex, slow-onset natural phenomenon affecting more people than any other hazard and seriously influencing water resources, agriculture, society and ecosystems (Hagman, 1984; Wilhite, 2002; Ionita et al., 2015). As drought impacts are largely nonstructural and spread over a relatively large region, the onset and end of a drought as well as its severity are often difficult to determine (Wilhite, 2002). Furthermore, based on recent changes in the 21st century and projected climate warming, such drought phenomena will likely worsen (Sheffield and Wood, 2008; Dai, 2010). Sheffield et al. (2012) state that the severe and prolonged drought events witnessed since the 1970s and their changes are related to higher temperatures and lower precipitation.

Drought can be defined and explained using absolute or relative terminology, allowing these terms or measures to be compared to each other (Dai, 2011; Trenberth et al., 2014). For the absolute term, the amount of precipitation, the amount of soil moisture and other metrics can be used. The relative measures include the

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Palmer drought severity index (PDSI), the standardized precipitation index (SPI), the standardized precipitation and evapotranspiration index (SPEI) and others. Vicente-Serrano et al. (2010) and Vicente-Serrano and Beguería-Portugués (2003) suggested that drought indices were not as useful because they were based on standardized or normalized shortages relative to average conditions in a given station and period. Nevertheless, various drought indices have been widely used in many drought studies.

Dracup et al. (1980) suggested three components of drought: duration, magnitude (average water deficiency) and severity (cumulative water deficiency). Such concepts have been applied to various drought indices to analyze historical characteristics. Wang et al. (2011) defined the intensity-duration-frequency of droughts with the SPI, standardized runoff index (SRI), standardized soil water index (SSWI) derived from observations and future regional climate change projections in central Illinois. To evaluate how well the global climate models simulate observed drying or wetting trends, Nasrollahi et al. (2015) applied the Mann-Kendall trend test to the SPIs derived from global observational climate data, that is, the dataset from the climate research unit (CRU), and 41 predictions with global climate models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5). Similarly, Tan et al. (2015) utilized the climate data from 22 meteorological stations in Ningxia, a well-known food production area in Northwest China, and performed the Mann-Kendall trend tests with SPI and SPEI. They found that increasing drought frequency and intensity depended on the local regions. Furthermore, Touma et al. (2015) used data from 15 GCMs in the CMIP5 and assessed the likelihood of changes in the spatial extent, duration and number of occurrences of four drought indices, including SPI, SPEI, and others.

Estimating the drought index requires a calibration step. Specifically, historical data such as precipitation should be fitted to a specific probability distribution function (PDF) to be used for estimating drought indices. A few previous studies addressed the issue of data periods for the calibration step (e.g., Karl et al., 1996; Dubrovsky et al., 2009). While it is common to use self-calibrated indices (i.e., using the same dataset for calibration and index estimation), some studies suggest calibrating with the reference climate data to allow an inter-comparison of the index among stations or different periods (Dubrovsky et al., 2009). While the reference period (i.e., calibration period) of climate data would be particularly important in climate change studies, we find that only limited studies clarify their approaches to calibration.

For this reason, we aim to understand how a different reference period (i.e., calibration period) of climate data influences the regional drought assessment. Specifically, we investigate the influence of different reference periods on historical drought characteristics such as trends, frequency, intensity and spatial extents with the SPEI estimated with two historical global climate datasets from the CRU and the University of Delaware (UDEL). This study shows that the reference periods influence the assessment of drought characteristics, particularly for severity and spatial extent, while its influence on the frequency is relatively small. These influences are especially significant in regions with dominant drying trends such as East Asia and West Africa. These findings suggest that the reference period should be clarified in drought assessments for a better understanding of regional drought characteristics and their temporal changes.

2 Materials and methods

2.1 Study area and climate data

We investigate the drought characteristics over the Northern Hemisphere with a focus on four different regions, including East Asia (EA), Europe (EU), the United States (US) and West Africa (WA) (Fig. 1). Two widely used global observational datasets from the CRU and UDEL are utilized in this study. From these two datasets, monthly precipitation and temperature data are used with a spatial resolution of 0.5° from 1901 to 2014.

This study uses the latest CRU dataset (CRU TS3.10) as described in Harris et al. (2014). The principal sources of the CRU are the World Meteorological Organization (WMO) in collaboration with the US National Oceanographic and Atmospheric Administration (NOAA). Covering all land area between 60°S and 80°N at a spatial resolution of 0.5°, the dataset includes global monthly climate data on ten variables: precipitation, mean temperature, diurnal temperature range, minimum and maximum temperature, vapor pressure, cloud cover, rain days, frost days and potential evapotranspiration. The dataset is derived from archives of climate station records with extensive manual and semi-automated quality control measures.

The UDEL dataset (V 4.01, Willmott and Matsuura, 2001) is also used in this study. The dataset includes gridded monthly precipitation and temperature data at a spatial resolution of 0.5° across the land over the globe. The dataset was compiled from sources including the Global Historical Climatology Network (GHCN) and the Global Surface Summary of Day (GSOD). To interpolate the station values to the grid, climatologically aided interpolation (CAI) and traditional interpolation were used for precipitation and digital-elevation-model (DEM)-assisted interpolation, traditional interpolation and CAI for temperature. In this work, traditional interpolation is a spherical version of Shepard's algorithm, which employs an enhanced distance-weighting method (Shepard, 1968; Willmott et al., 1985).

2.2 Meteorological drought index

Various drought indices have been used to understand different types of droughts, including meteorological drought, agricultural drought and hydrological drought (Heim, 2002). For meteorological droughts, the indices include the PDSI (Palmer, 1965), the SPI (McKee et al., 1993) and the SPEI (Vicente-Serrano et al., 2010). As different studies used different meteorological drought indices (Seneviratne, 2012; Sheffield et al., 2012; Trenberth et al., 2014; Nasrollahi et al., 2015; Touma et al., 2015), this study focuses on the SPEI. Devised by Vicente-Serrano et al. (2010), the SPEI has the advantage of being able to consider the effects of temperature variability for the drought relative to the SPI (Naumann et al., 2014) because the potential evapotranspiration (PET) can be calculated with air temperature based on Thornthwaite (1948). The SPEI uses the amount of precipitation minus PET and fits the data to the log-logistic probability distribution function. Here, we summarize the steps to estimate SPEI based on monthly precipitation and temperature. The detailed procedure for estimating the SPEI is well presented in Vicente-Serrano et al. (2010).

Step 1: Estimate the water surplus or deficit in month i (D_i) using the difference between precipitation (P_i) and potential evapotranspiration (PET_i):

$$D_i = P_i - PET_i \tag{1}$$

Here, the potential evapotranspiration is estimated based on the method of Thornthwaite (1948), which requires the monthly temperature, latitude, day and month.

Step 2: Estimate the accumulated difference ($X_{i,j}^{k}$) over the time scale k in a given month j and year i. For example, the accumulated difference for a month in a particular year with a 12-month time scale is calculated as follows:

$$X_{i,j}^{k} = \sum_{l=13-k+j}^{12} D_{i-1,l} + \sum_{l=1}^{j} D_{i,j}\,, \qquad if\ j < k \tag{2}$$

$$X_{i,j}^{k} = \sum_{l=j-k+1}^{j} D_{i,l}\,, \qquad if\ j \geq k \tag{3}$$

Step 3: Fit the accumulated difference to a log-logistic distribution as follows:

$$F(X) = \left[1 + \left(\frac{\alpha}{x-\gamma}\right)^{\beta}\right]^{-1} \tag{4}$$

where $F(X)$ is the cumulative probability function of a three-parameter log-logistic distribution with α, β and γ representing the scale, shape and origin parameters, respectively. For the model fitting, the L-moment procedure (Hosking, 1990) is employed as it one of the most robust and easy-to-use approaches.

Step 4: Estimate the SPEI based on the estimated $F(X)$. The SPEI can be derived from the standardized values of $F(X)$ and the classical approximation of Abramowitz and Stegun (1965) following Vicente-Serrano et al. (2010). In this study, we focus on the SEPI with the 12-month lag (SPEI-12). SPEI can be estimated for different lag times such as 1, 3, 6, 9, 12 and 24 months.

2.3 Temporal trends and statistical characteristics

This study investigates various measures of historical droughts, including trend, frequency, severity and spatial extent (Lloyd-Hughes and Saunders, 2002; Wang et al., 2011; Hoerling et al., 2012; Seneviratne, 2012; Trenberth et al., 2014; Touma et al., 2015).

The temporal trend is investigated with a nonparametric and monotonic trend test with the S-statistic (Mann, 1945; and Kendall, 1976) as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{1}$$

where $$sgn(x_j - x_i) = \begin{cases} +1, & (x_j - x_i) > 0 \\ 0, & (x_j - x_i) = 0 \\ -1, & (x_j - x_i) < 0 \end{cases} \tag{2}$$

where sgn is the sign function and n is the sample size. The statistical significance of the trend can be predicted by a Z test as follows:

$$Z = \begin{cases} (S-1)/\sigma_s\,, & if\ S > 0 \\ 0, & if\ S = 0 \\ (S+1)/\sigma_s\,, & if\ S < 0 \end{cases} \tag{3}$$

$$\sigma_s = \sqrt{\left(n(n-1)(2n+5) - \sum_{j=1}^{q} t_j(t_j-1)(2t_j+5)\right)/18} \tag{4}$$

where σ_s is the square root of S in the case that the x values are possible tie situations, q is the number of ties in the dataset and t_j is the number of data in the jth tie group. The trend in the data does not exist for $Z < Z_{\alpha/2}$ at the significance level α.

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For the frequency, severity and spatial extent of drought, different measures have been defined and used in past studies (e.g., Wang et al., 2011; Touma et al., 2015; Um et al., 2016) because it is not straightforward to define these quantities in practice. For example, Touma et al. (2015) defined the duration, occurrence and spatial extent of drought to investigate the drought changes with 15 CMIP5 models throughout the world for the 21st century: the duration of drought is defined as the consecutive period below a certain drought status, the occurrence of droughts is defined as the total number of droughts in the period of interest, and the spatial extent of droughts is defined as the percentage of grid points below the given drought level, in which the corresponding drought index is less than the given drought category for each month.

In this study, we define three measures of droughts with the SPEI-12: (1) the drought frequency as the ratio between the total number of drought events, which is defined as the SPEI-12 ≤ -1, relative to the total effective grid points; (2) the severity as the lowest estimates among the regional monthly average SPEI-12 with moving windows with periods of 1 to 12 months; here, the regional averages are estimated for the four study regions depicted in Fig. 1; and (3) the spatial extent as the number of grids with the annual SPEI-12 ≤ -1.0 relative to the total grids.

2.4 Design of data analysis

To understand the influence of the reference period (i.e., calibration period) on the drought index, three different types of reference periods are used to estimate the SPEI-12 with the CRU and UDEL. To analyze separately the drought characteristics for the estimation periods of 1901–1957 (P1) and 1958–2014 (P2), different sets of reference periods are used (Table 1). Here, we assume that the mean climates of P1 and P2 are different to some extent because of global climate and environmental changes, which will be discussed further in Section 3. For the first type of reference period (Ref1), we calibrate the distribution of a specific PDF (Step 3 in Section 2.2) using the data from 1901 to 2014, which is used for estimating the SPE12 for the P1 and P2 estimation periods. For the second type of reference period (Ref2), calibrations are performed separately for P1 and P2, and thus so-called self-calibrated indices are derived. For the third type (Ref 3), we calibrate the distribution using the data from P1 (i.e., 1910–1957) and then use this distribution for both estimation periods.

3 Results and discussion

3.1 Spatial and temporal patterns of climate variables

Precipitation and air temperature are investigated because they are used to estimate the SPEIs (Figs. 2 and 3 and Table 2). The selected regions show different climate features (Fig. 2), and EA and WA include the regions with a relatively wide range of mean precipitation from almost zero to more than 2000 mm per year. In terms of mean air temperature, it is clear that WA is generally quite warmer than other regions. Furthermore, the mean precipitation and air temperature are quite similar between the CRU and UDEL.

To investigate the temporal changes of precipitation and air temperature, we compared the means and the standard deviations between two periods (i.e., P1 and P2) in Table 2 and performed the Mann-Kendall trend test (Fig. 3). Table 2 presents clearly different temporal patterns for precipitation depending on the regions and all increasing temporal patterns for air temperature. Additionally, the annual precipitation in EA slightly decreased from 637.19 mm to 635.52 mm in the CRU (-0.2%) and from 659.67 mm to 649.21 mm in the UDEL (-1.6%). Moreover, in WA, the annual precipitation decreased substantially from 698.49 mm to 666.59 mm in the CRU (-4.6%) and from 734.84 mm to 676.11 mm in the UDEL (-8.0%). However, the annual precipitation increased in EU (25.17 mm (5.4%) in the CRU and 14.14 (3.5%) mm in the UDEL) and US (37.78 mm (3.7%) in the CRU and 24.92 mm (2.1%) in the UDEL). For annual averaged air temperature, the average growth amounts in the CRU and UDEL between P1 and P2 were slightly different depending on the four regions: 0.48°C in EA, 0.39°C in EU, 0.19°C in US and 0.31°C in WA. However, the averaged change ratios between P1 and P2 were more different depending on the annual averaged temperature. The annual averaged temperature became higher from the EA (6.16°C) to EU (6.99°C) to US (10.59°C) to WA (10.52°C) for P1. Consequently, the increasing ratios of annual averaged temperature were 7.7%, 5.6%, 1.8% and 1.2% in the EA, EU, US and WA, respectively. The Mann-Kendall trend tests for annual precipitation and annual averaged temperature were also performed, as shown in Fig. 3. The data reflect whether these variables showed statistically increasing, decreasing or no trends. For annual precipitation in EA, the areal extent with increasing trend was almost twice than that with a decreasing trend in the CRU, but the areal extent with a decreasing trend in the UDEL was broader than that with increasing area. In EU and US, the areal extent with an increasing trend was clearly greater than that with decreasing area in both the CRU and UDEL. However, in WA, the areal extent with a decreasing trend was larger than that with an increasing trend in both the CRU and UDEL. These patterns were usually more severe in the CRU than those in the UDEL. For annual averaged air temperature, the CRU showed an increasing trend over most of the regions. Similar patterns were found in the UDEL, but the areal extent of the decreasing trend was slightly larger than that in the CRU.

3.2 Temporal patterns of drought index

The drought index (i.e., SPEI-12) is estimated for two periods of P1 and P2 with three different reference periods (Table 1) as described in Section 2.4. Fig. 4 shows the temporal variations of SPEI-12 depending on the reference periods (Ref1, Ref2 and Ref3) and datasets (CRU and UDEL) for the two periods. For US and EU, the SPEI-12 averages are very similar for the two periods: 0.005 (P1) and 0.118 (P2) in the US and -0.011 (P1) to -0.001 (P2) in EU. In EA, the SPEI-12 averages with the three different reference periods slightly decrease from P1 to P2, whereas the deviations of SPEI-12 increase markedly. In WA, the averages and deviations of SPEI-12 significantly decrease and increase, respectively, from P1 to P2. Here, the role of the reference period is not clear with regional averages, and thus we investigate the spatial patterns of SPEI-12 hereafter.

Based on the Mann-Kendall trend test with annual SPEI-12 from 1901 to 2014, we present the increasing (i.e., wetting), decreasing (i.e., drying) or no trend over the regions. First, the spatial distribution of SPEI-12 trends is identical between Ref1 and Ref3 and that in Ref2 is different. Ref1 and Ref2 use different calibration datasets but are similar in using one dataset for the two estimation periods; Ref2 uses a different calibration dataset for different estimation periods (Table 3). Therefore, SPEI-12 with Ref2 shows relatively less area with wetting and drying trends for the first and second periods relative to Ref1 and Ref2.

Regarding the temporal characteristics over different regions, the following are our findings based on Ref1 and Ref3: In WA, the drying trends are clearly dominant. In EU, the drying trends are scattered over the domain. In US, the wetting trends are scattered in the eastern region and the drying trends in the southwestern region. In EA, the drying trends are clearly in the western region.

3.3 Frequency, severity and spatial extent of drought

In this section, we examine how the reference periods play a role in assessing the frequency, severity and spatial extent of drought using SPEI-12. The definitions of frequency, severity and spatial extent of drought used in this study are clarified in Section 2.3, and they may differ in different studies.

As explained above, a drought event is counted when the SPEI-12 is estimated to be under -1.0, and the frequency is the ratio between the total number of drought events and the effective grid points in each region (Fig. 6). We first find that the drought events with longer durations (prolonged right tails in the plot) occur more frequently in P2 than in P1 in all regions. However, we do not find any particular differences among the three different reference periods except in WA. The drought frequencies differ among the three reference periods. The frequencies with Ref2 and Ref3 are higher than those with Ref1 for P1, and slight differences in the frequency among the three reference periods are found around the 12 month duration for P2.

We examine how the severity of drought varies with the moving window sizes for the averaged monthly SPEI-12. Fig. 7 shows the severest SPEI-12 estimates, defined as the lowest value among the regional monthly average of SPEI-12 for the moving windows from 1 month to 12 months. In EU and US, we find no large differences among the SPEI-12s with Ref1, Ref2 and Ref3 for the same period. In these regions, the severest SPEI-12s for P1 are higher than those for 1958–2014, indicating that the drought events tend to become severe from P1 to P2. The precipitation and air temperature changes in Table 2 suggest the important role of air temperature in drought severity. In EA and WA, there exist different patterns in the severest SPEI-12s. The annual precipitation and air temperature exhibit regionally scattered decreases and widespread increases, respectively (Fig. 3). Consequently, the droughts in 1958–2014 are more severe than those in P1. Furthermore, the severities vary significantly with the calibration periods in EA and WA, where the changes in precipitation and air temperature between two periods are marked.

The spatial extents of droughts for the annual SPEI-12 ≤ -1.0 are examined by sorting the results in ascending order (Fig. 8). No specific patterns are evident for EU and US. In EA and WA, the spatial extents are generally broader in P2 than in P1. In particular, the spatial extents in 1958–2014 clearly diverge among the different calibration periods, suggesting the importance of the calibration (i.e., reference periods in assessing the droughts in a region).

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3.4 Case studies with historical drought events

SPEI-12s with different reference periods are evaluated for historical drought events selected in each region to investigate how different reference periods influence the drought assessments of historical events. One drought event is chosen for each region as follows: 1) For East Asia, droughts that occurred in northern China in 2001 are chosen. These events caused economic losses of USD 1.52 billion (Zhang and Zhou, 2015). 2) For EU, we chose a 2003 drought that was caused by the European heat wave and spread over the majority of Europe (Stagge et al., 2013; Spinoni et al., 2015). 3) For US, we chose 2012 as the period of study as drought in that year was the most extensive drought over half of the US since the 1930s and caused economic losses of USD 31.2 billion (Smith and Katz, 2013; National Climate Data Center, 2015). 4) For West Africa, the drought in 1984 is chosen because it is one of severest droughts that has occurred over most Sahel countries (Gommes and Petrassi, 1994; Rojas et al., 2011; Masih et al., 2014).

By estimating SPEI-12 for a chosen year in each region, we compare the magnitudes of SPEIs (Figs. 9, 10, 11 and 12). All SPEI-12s with the different reference periods present the drought status because we chose specific years with drought events. In general, all cases reveal that the SPEI-12 estimates in Ref2 are relatively high (i.e., wet) and those in Ref3 are relatively low (i.e., dry) for EA and WA, where drying temporal trends are clear.

Furthermore, the percentages of drought area are assessed with different drought thresholds (Table 4). In most cases, the spatial extents of drought, the percentage of area with the SPEI less than certain thresholds, such as -1, -2 or -3, are the greatest in Ref3 among the three cases with different reference periods. These results with the spatial extent are consistent with the results with the SPEI-12 estimates above. In addition, for the severe droughts with the drought events, defined with low thresholds such as SPEI-12 less than -2 or -3, greater percentages of drought areas in Ref3 than in Ref1 and Ref2 are consistently obtained without exception in all regions of EA, EU, US and WA.

4 Conclusions

This study seeks to understand how a different reference period (i.e., calibration period) of climate data for estimating the drought index would influence the regional drought assessment. Specifically, we investigate the influence of different reference periods on historical drought characteristics such as trends, frequency, intensity and spatial extents using SPEI-12 from the CRU and UDEL datasets. For the 1901–1957 (P1) and 1958–2014 (P2) estimation periods, three different types of reference periods are used. For the first case, the data from 1901 to 2014 (P1+P2) are used for both estimation periods; for the second case, the data from P1 and P2 are used separately for the estimation periods of P1 and P2, respectively (self-calibrated); and for the final case, the data from P1 (1910–1957) are used for both estimation periods.

Focusing on the EA, EU, NA and WA regions, we find the influence of the reference periods is significant in the regions with dominant drying trends from P1 to P2, such as EA and WA. Furthermore, we find that the reference periods influence the assessment of drought characteristics, particularly for severity and spatial extent; however, their influence on the frequency is relatively small. Finally, self-calibration, the most common practice with an index such as SPEI, tends to underestimate the drought severity and spatial extent relative to the other approaches examined in this study.

This study highlights the need for the reference period to be clarified in drought assessments for a better understanding of regional drought characteristics and their temporal changes, particularly under climate change scenarios. Although this study uses historical data, a similar study with climate change scenarios would undoubtedly strengthen our findings. We note that this study focuses on the temporal aspects of calibration data (i.e., calibration period). As briefly mentioned in the Introduction, using data from a particular station or grid, the averaged data for calibration would permit a meaningful comparison of the drought index among different locations. In conjunction with temporal considerations, such spatial issues could readily be addressed in future studies.

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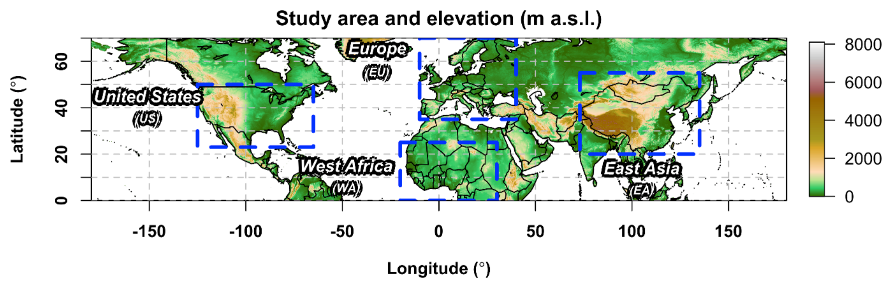

Figure 1. Study area and elevation investigated in this work.

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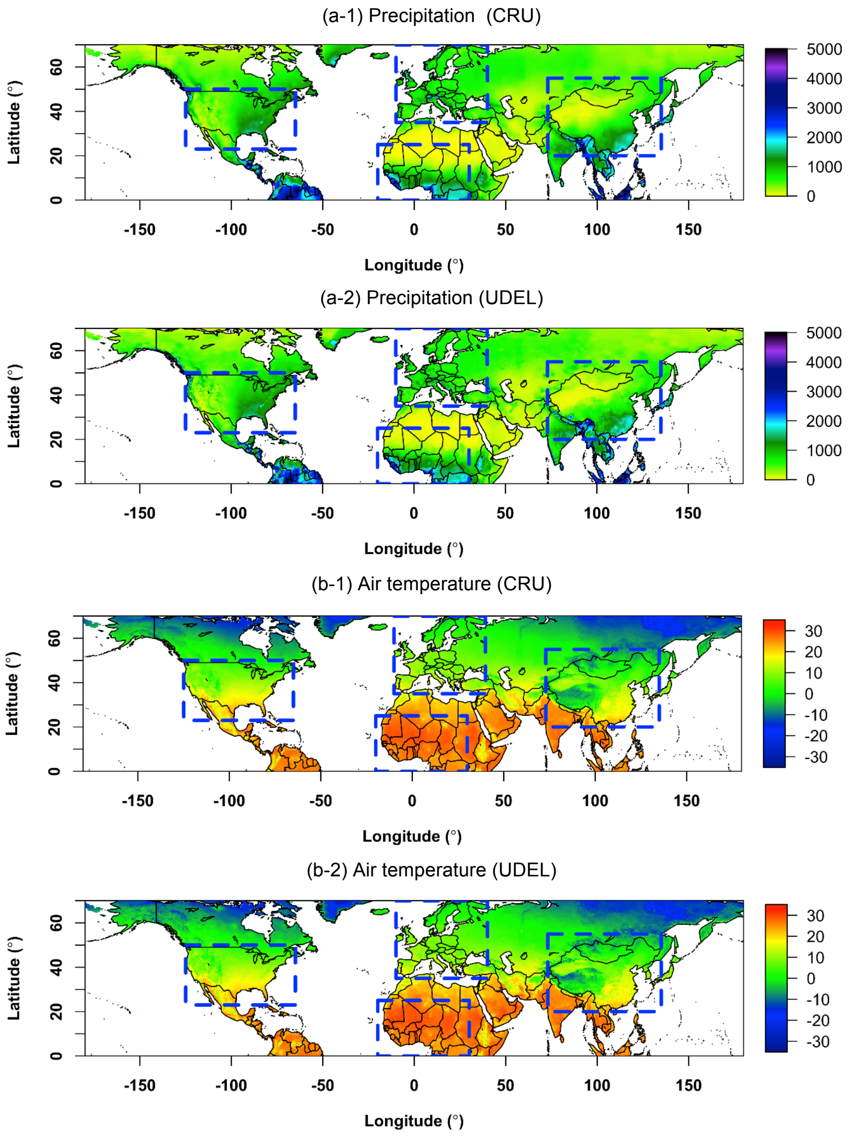

Figure 2. Annual averaged (a) precipitation (mm) and (b) air temperature (°C) for the CRU and UDEL datasets for 1901–2014.

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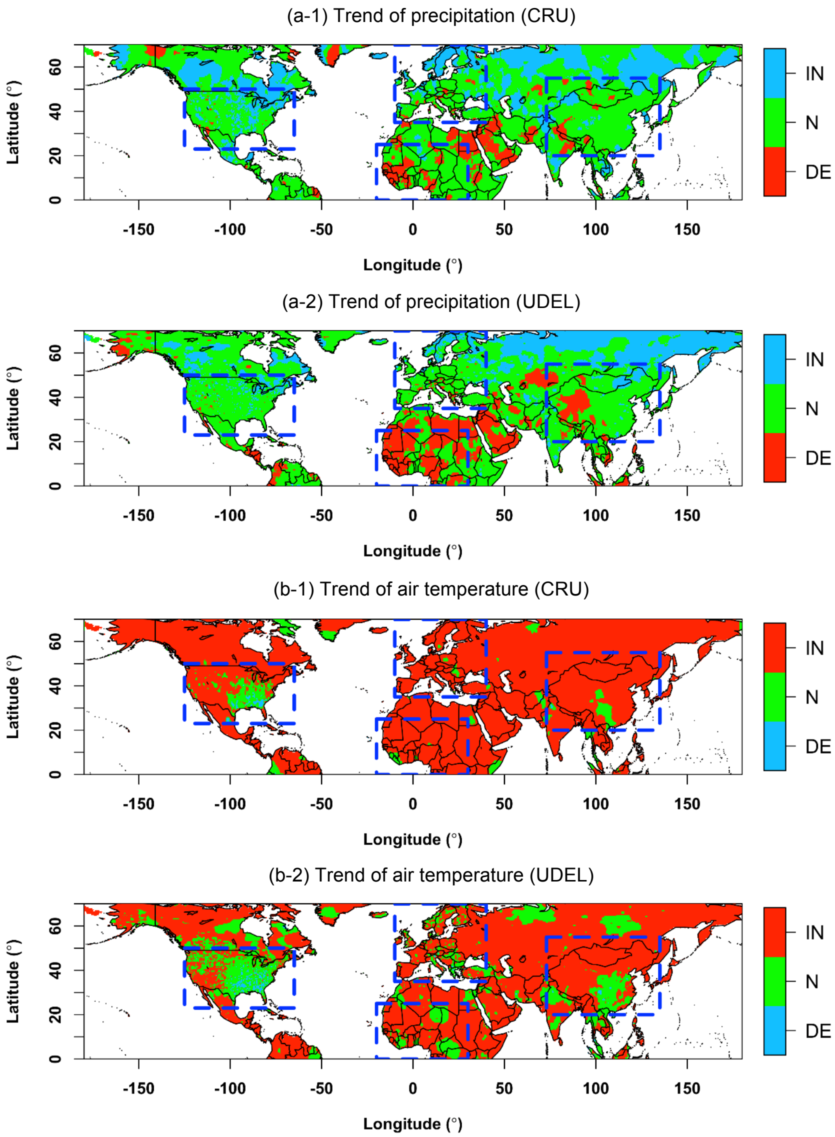

Figure 3. Trends of (a) annual precipitation and (b) annual averaged temperature for the CRU and UDEL datasets. IN, N and DE indicate increasing, no trend and decreasing, respectively.

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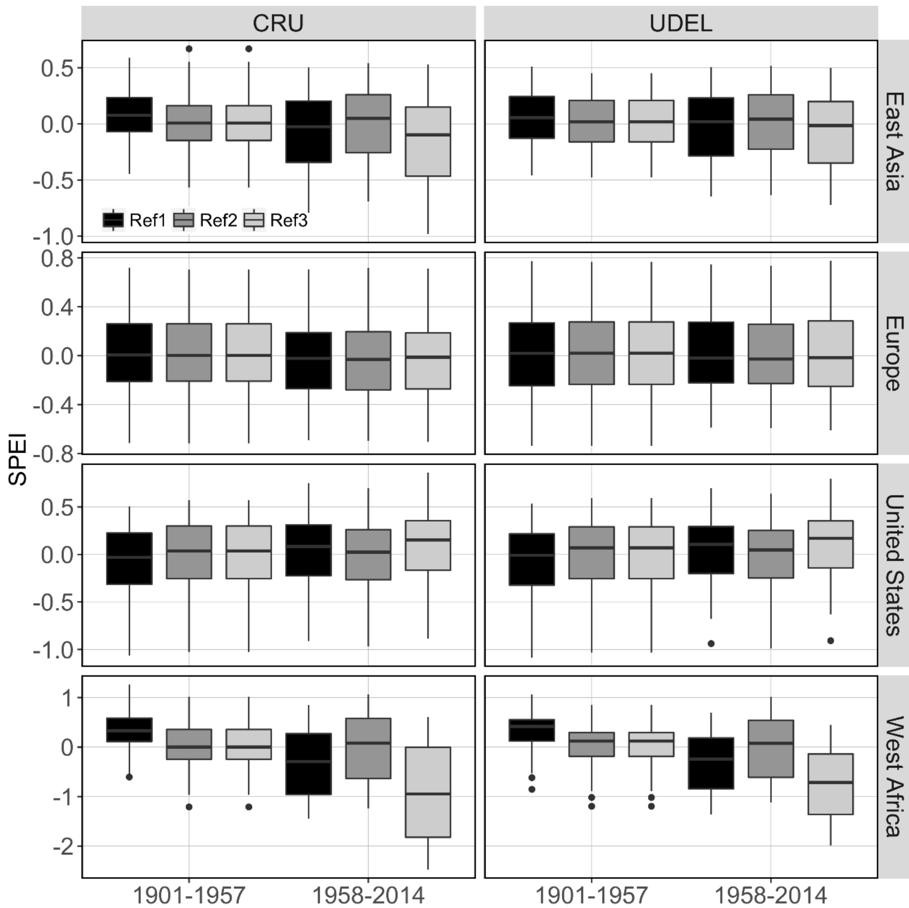

Figure 4. Temporal variations of SPEI with 12-month lag for three different reference periods (Ref1, Ref2 and Ref3) for the CRU and UDEL datasets and the periods 1901–1957 and 1958–2014.

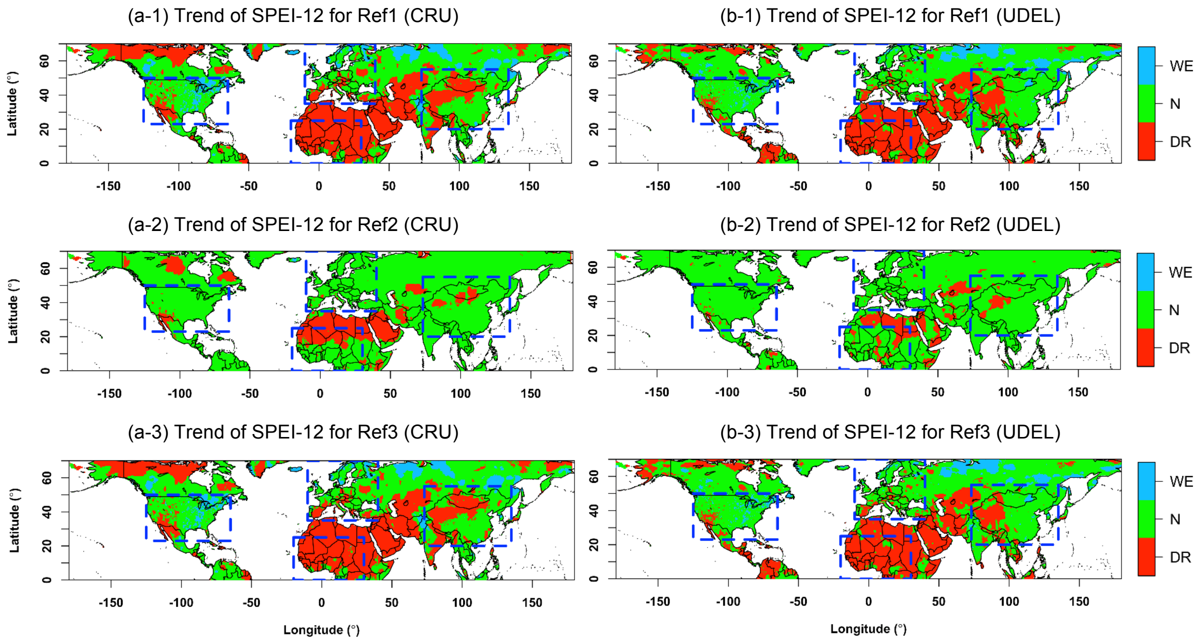

Figure 5. Trend of SPEI with 12-month lags (SPEI-12) for three different reference periods (Ref1, Ref2 and Ref3) for the (a) CRU and (b) UDEL datasets. WE, N and DR denote wetting, no trend and drying, respectively.

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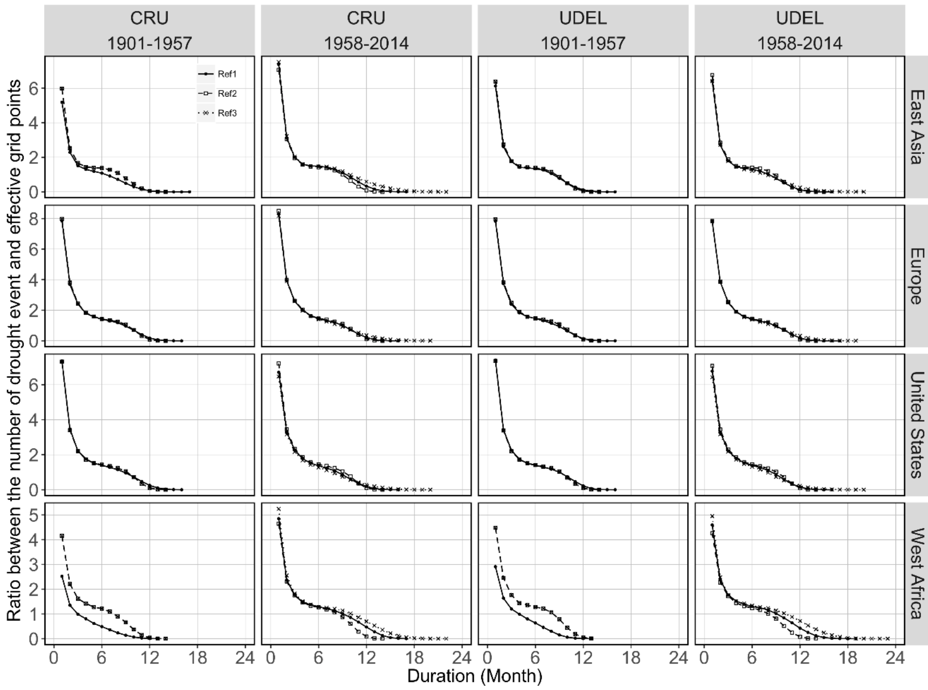

Figure 6. Ratio of the number of drought events and effective data grid points for the CRU and UDEL datasets and the periods 1901–1957 and 1958–2014.

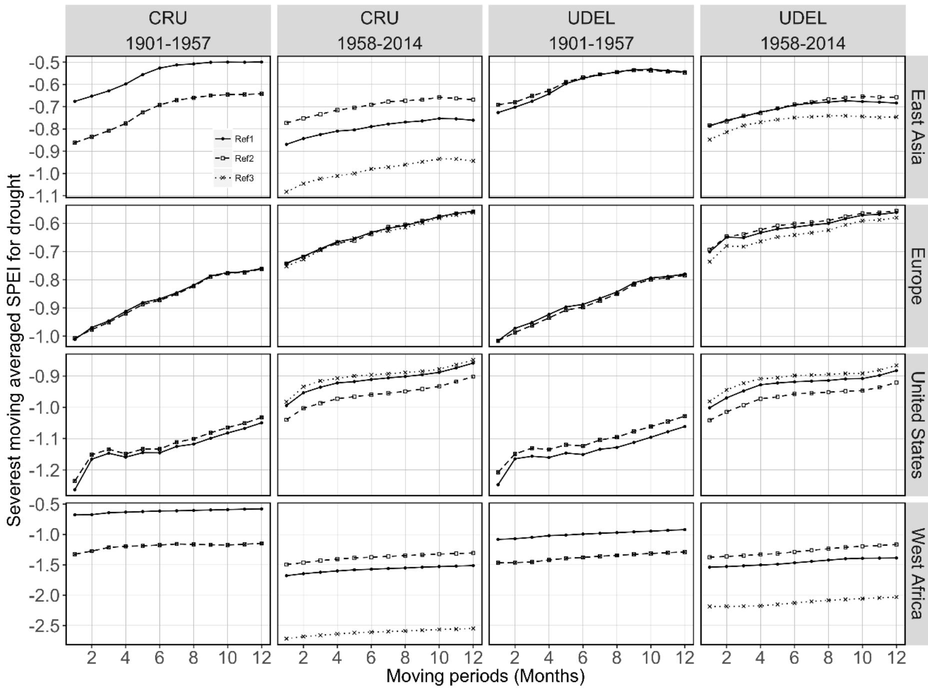

Figure 7. Severest moving average of regional average SPEI for 1–12 months for three different reference periods (Ref1, Ref2 and Ref3) for the CRU and UDEL datasets and the periods 1901–1957 and 1958–2014.

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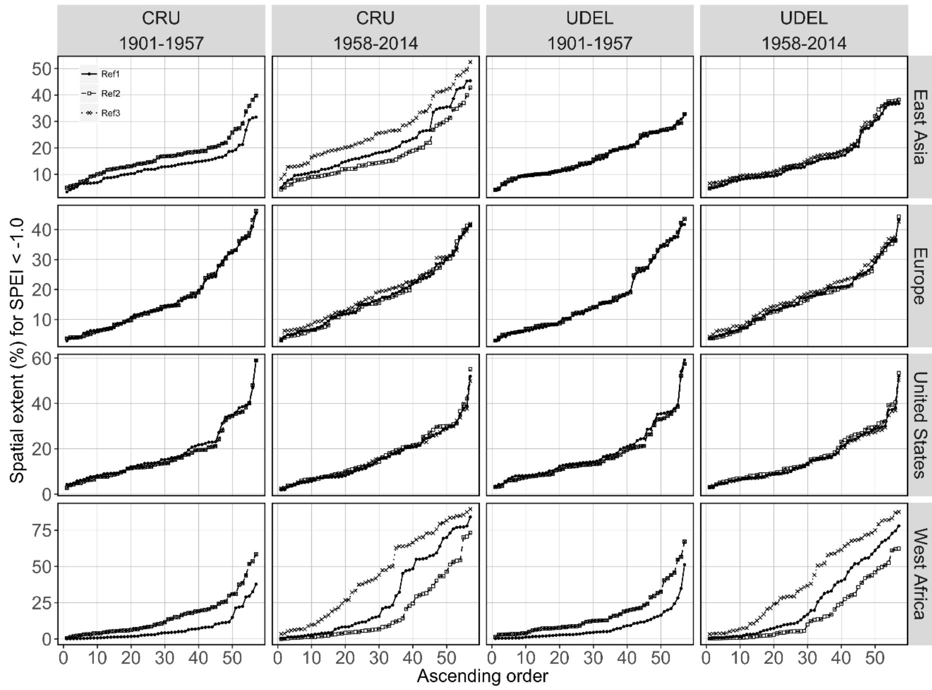

Figure 8. Spatial extent (%) for SPEI with 12-month lag < -1.0 for three different reference periods (Ref1, Ref2 and Ref3) for the CRU and UDEL datasets and the periods 1901–1957 and 1958–2014.

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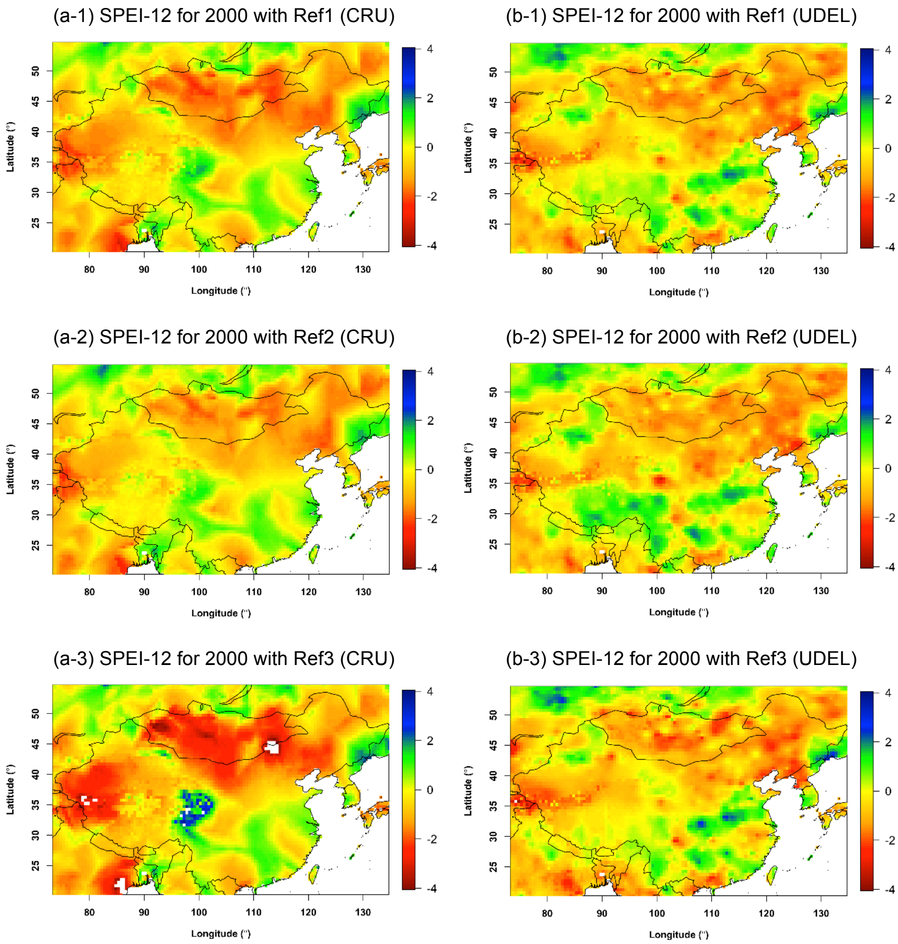

Figure 9. SPEI with 12-month lag (SPEI12) for three different reference periods (Ref1, Ref2 and Ref3) for the (a) CRU and (b) UDEL datasets in East Asia in 2000.

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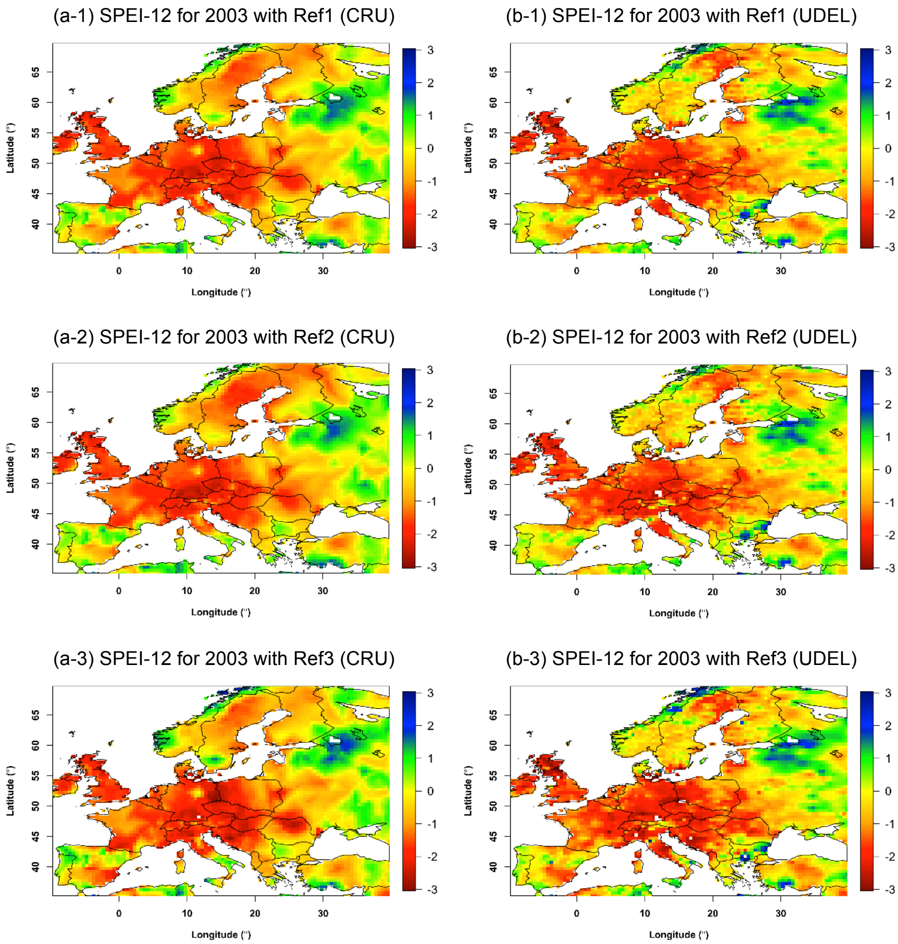

Figure 10. SPEI with 12-month lag (SPEI12) for three different reference periods (Ref1, Ref2 and Ref3) for the (a) CRU and (b) UDEL datasets in Europe in 2003.

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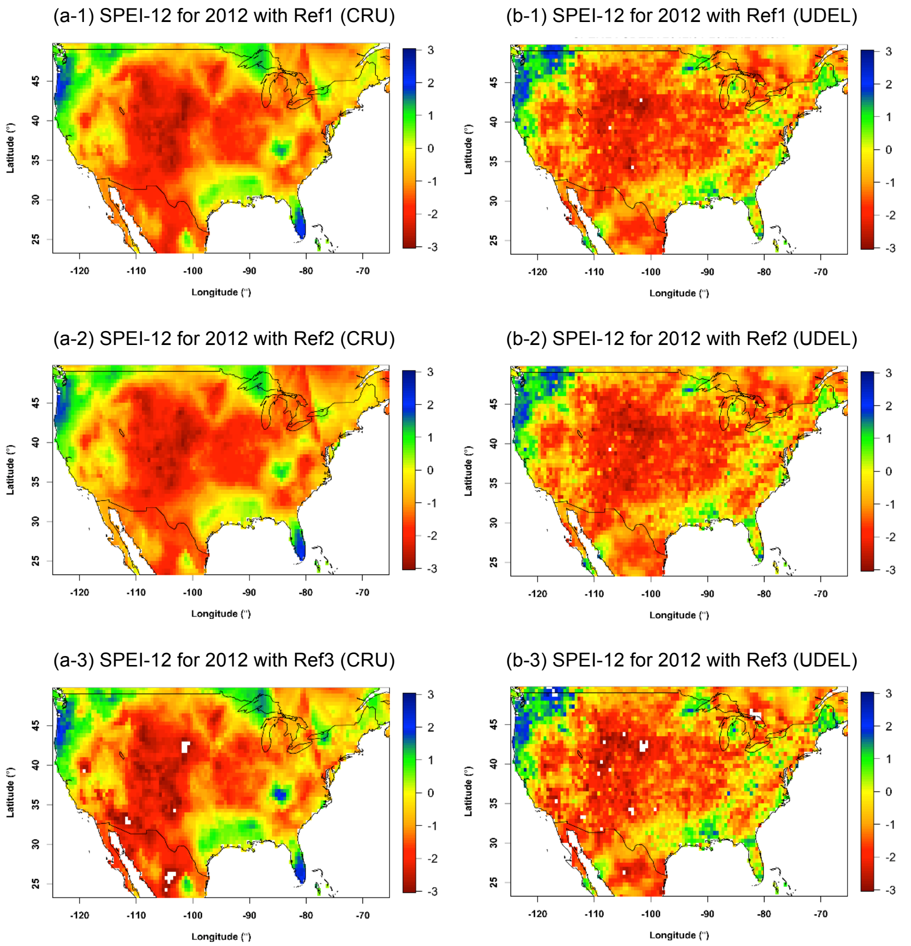

Figure 11. SPEI with 12-month lag (SPEI12) for three different reference periods (Ref1, Ref2 and Ref3) for the (a) CRU and (b) UDEL datasets in the United States in 2012.

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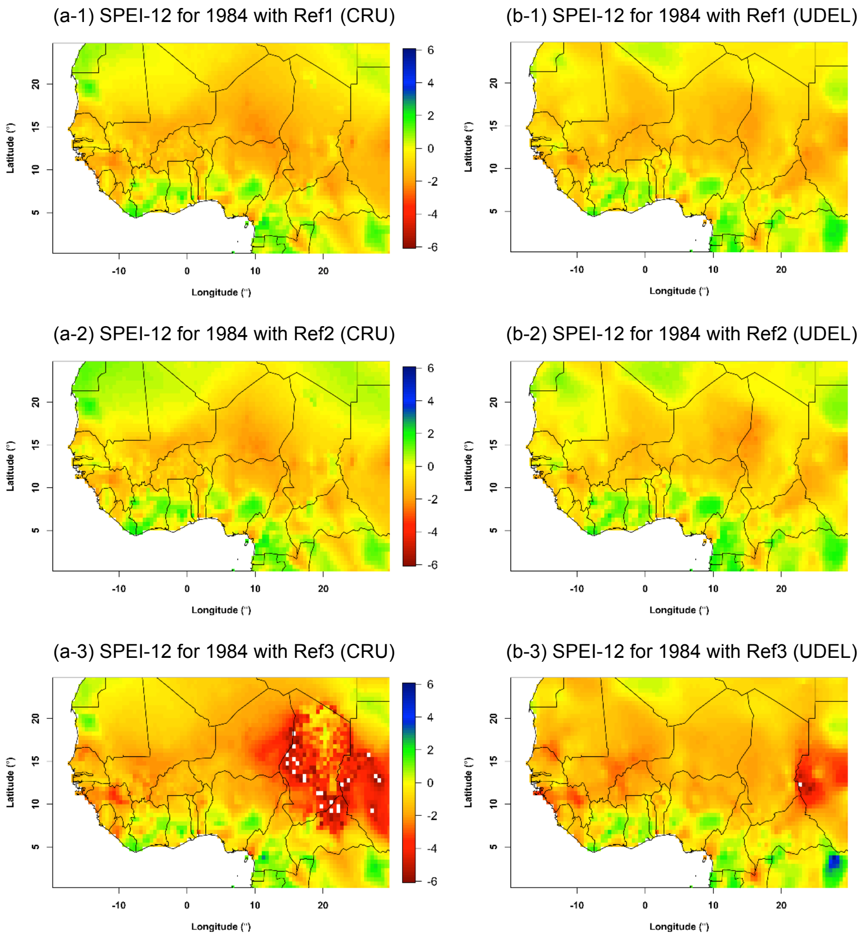

Figure 12. SPEI with 12-month lag (SPEI12) for three different reference periods (Ref1, Ref2 and Ref3) for the (a) CRU and (b) UDEL datasets in West Africa in 1984.

Table 1. Climate variables and conditions for SPEI.

Type	Estimation Period	Calibration Period
Ref1	1901–1957	1901–2014
	1958–2014	
Ref2	1901–1957	1901–1957
	1958–2014	1958–2014
Ref3	1901–1957	1901–1957
	1958–2014	

Table 2. Mean and standard deviation (STD) of precipitation and air temperature over the regions.

			CRU		UDEL	
			1901–1957	1958–2014	1901–1957	1958–2014
Annual Precipitation (mm)	EA	Mean	698.4	736.2	709.5	734.4
		STD	43.3	41.5	44.1	41.6
	EU	Mean	685.9	711.0	674.2	688.3
		STD	31.1	32.4	31.0	31.2
	NA	Mean	698.5	666.6	734.8	676.1
		STD	36.9	43.8	44.9	48.0
	WA	Mean	637.2	635.5	659.7	649.2
		STD	22.4	30.0	30.7	31.8
Air Temperature (°C)	EA	Mean	10.5	10.8	10.6	10.6
		STD	0.5	0.5	0.4	0.4
	EU	Mean	7.0	7.5	7.0	7.3
		STD	0.6	0.7	0.6	0.6
	NA	Mean	26.3	26.6	26.4	26.7
		STD	0.2	0.5	0.3	0.4
	WA	Mean	6.1	6.7	6.2	6.6
		STD	0.3	0.5	0.3	0.5

Table 3. Trend area (%) for the different models for SPEI-12.

Zone	CRU						UDEL					
	Ref1		Ref2		Ref3		Ref1		Ref2		Ref3	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
EA	2.5	36.3	0.0	8.0	2.5	36.5	3.4	23.2	0.0	7.7	3.4	23.2
EU	10.4	24.9	0.0	1.7	10.4	24.9	5.3	15.8	0.0	2.2	5.3	15.8
US	18.6	16.2	0.0	67	18.6	16.2	11.3	9.7	0.1	3.1	11.3	9.7
WA	0.0	90.2	0.0	40.4	0.1	89.8	0.0	90.9	0.0	19.5	0.0	90.9

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Table 4. Drought area (%) for the major drought events.

Zone	Period	Type	CRU			UDEL		
			Ref1	Ref2	Ref3	Ref1	Ref2	Ref3
EA	2000	D1	32.63	27.48	38.80	26.81	27.39	29.62
		D2	2.45	0.75	14.64	0.92	0.73	2.64
		D3	0.05	0.00	1.83	0.04	0.01	0.07
EU	2003	D1	37.58	39.10	36.68	35.30	34.67	36.61
		D2	5.33	3.97	7.68	5.93	4.82	8.50
		D3	0.00	0.00	0.02	0.02	0.10	0.22
US	2012	D1	52.16	55.01	50.02	54.69	56.32	52.92
		D2	11.97	11.90	15.74	10.36	11.76	11.63
		D3	0.02	0.00	0.53	0.09	0.05	0.87
WA	1984	D1	44.06	31.04	62.18	37.13	27.15	57.78
		D2	3.42	1.87	28.62	2.07	1.72	13.80
		D3	0.00	0.00	14.30	0.00	0.00	2.99

* D1, D2 and D3 denote the cases of SPEI < -1.0, SPEI < -2.0 and SPEI < -3.0, respectively.