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Temporal-spatial characteristics of severe drought events and their impact on agriculture on a global scale

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ABSTRACT

To identify the world's severely drought-prone areas, given that the corresponding ground area for a 0.5-degree grid in different latitudes is different, we proposed a more precise spherical area-based statistical method. The corresponding ground area per 0.5-degree grid is obtained by integral calculation in latitude and longitude directions. The analysis of the drought based on the global Standardized Precipitation Evapotranspiration Index dataset from 1902 to 2008, where global, Northern Hemisphere, Southern Hemisphere, and major crop-planting regions from six continents are treated as statistical units. The interannual variability characteristics of the severe drought area for each statistical unit are investigated. To study the spatial distribution characteristics of the global frequency of severe drought, the drought frequency was calculated based on drought events identified by continuous drought months on a grid level. Six major crops (wheat, maize, rice, soybean, barley, and sorghum) were chosen to study the impact of drought events on agriculture. The results suggested that severe droughts in global, Northern Hemisphere, and Southern Hemisphere areas have indicated a downward trend since 1990, but an upward trend overall in all continents except Oceania. The identified drought-prone areas show a patchy distribution and frequently drought-prone areas (with 10–20% occurrence probability of drought) were distributed in regions surrounding chronically drought-prone areas (with more than 20% probability). Global chronically drought-prone areas have increased significantly, from 16.19% in 1902–1949 to 41.09% in 1950–2008. Chronically drought-prone areas of agriculture are located in the center of southern Europe, South America, and eastern Asia.

1. Introduction

Drought is one of the costliest natural disasters (Wilhite, 2000; He et al., 2011), and it is also the most complex and the least understood natural disaster to affect humans (Hagman et al., 1984; Wilhite, 1996; He et al., 2013). Data from the Emergency Event Database (www.em-dat.net) show that the number of drought disasters accounts for only 5% of total disasters, but the losses can amount to 30% of the losses from all natural disasters. The effects of drought have recently evoked interest beyond the scientific community (Leuzinger et al., 2005).

Since the 1970s, characteristics of drought such as intensity, duration and affected area of droughts are increasing, the percentage of the world subjected to extreme drought will expand from 1% to 30% in the 21st century (Burke et al., 2006), and the number of severe drought events and drought duration are likely to increase (Blunden et al., 2011). In particular, severe drought can have devastating effects (Shen et al., 2007), such as significant crop yield losses, an increased risk of forest fires, exacerbated and intensified land degradation and desertification, and increased competition for resources and social violence (Bruins and Berliner, 1998; Quiring and Papakryiakou, 2003; Pausas, 2004; MacDonald, 2007), because of its long-lasting and wide areal extent. In 2002,

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26 states in the United States were affected by severe and extreme drought, and total losses exceeded $2.7 billion (Wilhite et al., 2007).

The complexity of the temporal-spatial characteristics of drought hampered works on drought impact assessment (Vicente-Serrano, 2007). On a global scale, the temporal-spatial characteristics of drought have been studied by analyzing the changing trend of drought area and the relationship between runoff and drought area, and Dai (2011) concluded that an increasing trend of global drought area has been evident after the 1980s. A special report of the Intergovernmental Panel on Climate Change suggests that some regions of the world have experienced more intense and longer droughts, particularly in southern Europe and West Africa, but opposite trends also exist since 1950 (Field et al., 2012). Sheffield et al. (2012) question the above conclusions of a global temporal-spatial pattern, and revealed that the global drought area has not been increasing with warming since the 1980s. A special report on the results of extreme events in the latest IPCC fourth assessment report was modified, as conclusions about an increasing number of global extreme drought events may be overvalued by calculation with the PDSI method (Field et al., 2012). On a continent scale, the temporal-spatial characteristics of drought events were investigated with the drought severity-area-duration (SAD) method (Sheffield et al., 2009). On a regional scale, the spatial variability of drought in severe drought years was analyzed (Hayes et al., 1999; Andreadis et al., 2005; Yoo et al., 2012). The spatial variability of drought frequency on a global and regional scale was rarely investigated, and although Spinoni et al. (2013) studied drought frequency over the course of nearly 50 years, they only considered the rainfall factor without considering the temperature factor.

Agriculture is always the first sector to be affected by the onset of drought, which is one of the major natural disasters that influence world food production (Dilley, 2005; Narasimhan and Srinivasan, 2005; Helmer and Hilhorst, 2006). In the 1930s, the severe drought in the American southern Great Plains led to the bankruptcy of 200,000 farms (Lehman, 1998) and 50% yield losses for wheat and maize (Warrick, 1984), and the most recent droughts in the south (2011) and central (2012) USA were quite devastating for agriculture (Kogan et al., 2013). The current drought research on agriculture has mainly focused on the influence of abnormal climate on agricultural production (Peltonen-Sainio et al., 2010; David et al., 2011; Kristensen et al., 2011), and the effects of severe drought events on agriculture mainly emphasized regional drought events' impact on the crop growth process and crop yield (Warrick, 1984; Trnka et al., 2007). The agricultural drought risk scenario will also increase in the future (Li et al., 2009.), and severe drought could considerably reduce agricultural production, creating an imbalance between grain production and consumption (Kogan al., 2013), which is also a crucial factor that influences world food security (Tubiello et al., 2007). Any contribution to understanding and predicting drought conditions will be a step toward minimizing the impacts of drought. Assessing the effects of severe droughts on agriculture might help to properly anticipate and adapt farming to maximize agricultural production (Potop, 2011). Therefore, it is necessary to carry out impact studies of severe drought on agriculture.

Over the past 150 years, the average global temperature has increased by 0.5–2 C° (Jones and Moberg, 2003). Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation of the Intergovernmental Panel on Climate Change (IPCC) suggests that there will be virtually certain increases in frequency and magnitude of unusually warm days and nights at the global scale in the whole 21st century (Field et al., 2012). Higher temperatures will increase the potential evapotranspiration and possibly result in an increased occurrence of drought (Sheffield and Wood, 2008). The current common drought monitoring indices include the SPI (Standardized Precipitation Index), the PDSI (Palmer Drought Severity Index), the ISDI (Integrated Surface Drought Index), the SPEI (Standardized Precipitation Evapotranspiration Index), the TCI (Temperature Condition Index), the VCI (Vegetation Condition Index) and the VHI (Vegetation Health Index) (Rhee et al., 2010; Wu et al., 2012; Banimahd and Khalili, 2013), and the SPEI (Vicente -Serrano et al., 2010), the SPI (McKee et al., 1993) and the PDSI (Palmer, 1965) are the three most widely used drought indices. The results of using SPI are comparable in space and time (Guttman, 1998; Hayes et al., 1999), and their multi-scale characteristics can help to identify different types of droughts. However, SPI only considers the precipitation factor, which does not reflect drought conditions caused by warming. PDSI reflects the drought effects caused by warming (Dubrovsky et al., 2009), and trends in drought areas can be investigated based on PDSI on a global scale (Sheffield et al., 2012). Although PDSI takes temperature factors into account, it lacks multi-scale characteristics for the evaluation of different types of drought. Taking the multi-scale convenience of the time and temperature effects for drought assessment into account, SPEI is very suitable for monitoring and research of drought characteristics under warming, and there have already been some studies conducted on SPEI drought analysis (Vicente-Serrano et al., 2010). Also, SPEI detects agricultural drought better than SPI does (Potop, 2011). Potop (2012) studied that the SPEI drought index is an effective approach to determine the impacts of increasing drought on the crops. Therefore SPEI is very suitable indicator for agricultural drought monitoring and assessment.

The goal of this study was to calculate the severe drought area and the severe drought frequency on a global and continental scale. The severe drought area is obtained by proposing a more precise spherical area-based statistical method, and the changing trend analysis of the severe drought area can identify serious drought years and drought regions in the year. Drought frequency was calculated based on drought events identified by continuous drought months on a grid level. The drought frequency was subsequently used to divide the world into three levels (the least drought-prone areas, frequently drought-prone areas, and chronically drought-prone areas) and to identify chronically drought-prone areas around the world. Drought-prone areas of different crop-planting areas are evaluated by the main crop-planting distribution, the study can provide a scientific basis for the adoption of countermeasures of global defense to adapt to severe drought, guide farmers in drought-prone agricultural areas to choose drought-resistant crops, and ensure the conditions for food security in the world.

2. Data and methods

2.1. Data

SPEI data are obtained from SPEI library (Vicente-Serrano et al., 2013). The Global SPEI database offers long-time from 1901 to 2009, robust information about drought conditions at the global scale, with the 0.5-degree spatial resolution and monthly temporal resolution. The data has a multi-scale characteristic with between 1 and 48 months. SPEI data based on CRU TS3.0 monthly rainfall and temperature data, CRU TS3.0 data were compiled and processed by the British Ministry of East Anglia's Climatic Research University (CRU). CRU data have the following advantages: strict time uniformity tests in the process of data reconstruction, higher spatial resolution, and a longer time series. The CRU temperature series were one of the adopted data series of IPCC Second Assessment Report, the CRU temperature series were approximately one hundred years, and its conclusions are mainly adopted in the IPCC Third Assessment Report (Houghton et al., 2001), and the data have been widely adopted in the study of climate change (Jones, 2001;

Vicente-Serrano et al., 2010). In our study, due to the lack of data for part of 1901 and 2009, the SPEI data of 12-month and 3-month scales were adopted from 1902 to 2008. The severe drought area and frequency of severe drought events can be obtained by basing the analysis on the data from global and regional scales.

Global land cover data in 2000 with a 5-min spatial resolution are divided into 22 types of land cover (Bartholomé and Belward, 2005). Based on deserts and glaciers of two types, we excluded Greenland, Antarctica, and desert regions from the land use map. An analysis of the spatial and temporal characteristics of drought makes little sense in these regions because rainfall is less than 0.5 mm/day in these regions such as desert and ice (Sheffield et al., 2012). The global land cover data in 2000 is only used to mask the desert and ice areas, which are excluded in the analyses. Global Crop-planting distribution data produced by the U.S. SAGE organization include the crop-planting distribution of 175 types of crops in 2000 with a 5-min spatial resolution on the grid-level percentage of the acreage data of six major crops (wheat, maize, rice, soybeans, barley and sorghum) with a 5-min spatial resolution clustered into crop acreage with a 0.5-degree spatial resolution. Crop areas with drought were analyzed by combining the spatial characteristics of severe drought, and we assume that the distribution of global crop-planting areas is stable. Crop-planting areas for each country can be extracted by overlaying the acreage data of six major crops and administrative boundaries data on a national scale. FAO crop production data on the country level are used for 1961–2008. The progress of science and technology, which brings out the increment trend yield, the estimated impacts of climate on yield trends, and the long-term trends can be separated by the detrend method (Warrick, 1984; Lobell et al., 2011). To quantitatively evaluate increased or decreased crop yields, the yield without a trend is processed by the percentage calculation of yield anomalies, the larger absolute value for the negative percentage, the greater crop production loss, and vice versa.

2.2. Methods

The multi-scale characteristics of time for SPEI is similar to the SPI and SPEI values on a 12-month scale for December of each year indicate the status of year-round water deficit caused by drought, and a 3-month scale of monthly SPEI value are used to depict the severe drought in the event of drought (Seiler et al., 2002). The detailed calculation process for SPEI is referenced in the study by Vicente-Serrano (Vicente-Serrano et al., 2010), and the classifications for the SPEI drought class are shown in Table 1.

Table 1
Classification used for SPEI (McKee et al., 1993; Paulo et al., 2012).

Drought class	SPEI values
Non-drought	SPEI ≥ -0.5
Mild	$-1<$SPEI < -0.5
Moderate	$-1.5 <$ SPEI ≤ -1
Severe	$-2<$SPEI ≤ -1.5
Extreme	SPEI ≤ -2

In this paper, we focus on the impact of drought on agriculture, particularly drought events including severe drought and extreme drought events. We extract drought events from a 3-month scale of monthly SPEI data from 1902 to 2008 based on SPEI drought classification criteria. Considering the continuity of drought properties, we define continuous months with SPEI values less than or equal to −1.5 as a severe drought event for each grid, where a severe drought event ends when one month's SPEI is greater than −1.5.

To study the interannual characteristics of severe drought on global and continental scales, December SPEI data on a 12-month scale for each year are used as the status of year-round water deficit caused by drought. The global, Northern Hemisphere, Southern Hemisphere, continental and major crop-planting regions for Iran, Brazil, Peru, Spain, and China are taken as statistical units, and the proportion of severe drought area of the total area of each unit is counted year by year from 1902 to 2008.

Area statistics based on that sum of the grid area that meets the condition, the corresponding ground area for a 0.5° grid has considerable differences in different latitudes. For the grid-area statistics of different latitudes, we consider that the corresponding ground area for a 0.5° grid in different latitudes is different, because the arc length is shorter in higher latitude than that of in lower latitude. They are the same for longitudinal arc length of 0.5° in higher and lower latitude region. Therefore, the area for 0.5° grid in higher latitude region is greater than in lower latitude. We proposed a more precise spherical area-based statistical method. The corresponding ground area per 0.5° grid is obtained by integral calculation in latitude and longitude directions. Taking the earth to be spherical with a radius $R_c = 6371$ km, the grid cell area between longitudesλ_1 and λ_2 and latitudes θ_1 andθ_2 is given by

$$\text{Area} = \int_{\theta_1}^{\theta_2} R_c \int_{\lambda_1}^{\lambda_2} R_c \cos\theta \mathrm{d}\theta \mathrm{d}\lambda \tag{1}$$

A linear regression method was applied to analyze trends in the time series. The slope of the regression indicated the mean temporal change in the studied variable. Negative slopes indicated decreasing trends, while positive slopes indicated increasing trends. We analyze the change of drought area based on slopes of percentage of drought area (unit: % per year), to quantitatively evaluate the tendency of percentage of drought area during 50 years. Both numerator and Denominator of slopes are multiplied by 50, so the unit is % per 50 years or % per 50 a.

The drought frequency can reflect the drought liability. Based on the proposed definition of a severe drought event, the drought frequency is calculated on grid level. We used the number of severe drought events divided by the number of years for the research period, and the frequency of severe drought events is counted for the global, continent and crop-planting regions during 1902–1902, 1950–2008 and 1902–2008, which are three periods based on the frequency distribution characteristics of global drought events. The global area is divided into three levels including the least drought-prone areas (the probability of occurrence of drought is less than 10%), frequently drought-prone areas (the probability of occurrence of drought is 10–20%) and chronically drought-prone areas (the probability of occurrence of drought is more than 20%) (Sarkar, 2010), and the spatial and temporal variations of the frequency of severe drought events are investigated.

3. Results and discussion

3.1. Interannual variability of severe drought areas

The interannual variability of severe drought areas can identify the severe drought year and spatial distribution of severe drought in the study area. December SPEI data on a 12-month scale for each year are used to study the interannual variability of the global percentage of the severe drought area in the northern and Southern Hemispheres and six continents.

Based on the proposed spherical area-based statistical method and traditional method, respectively, we calculated the percentage of global severe drought area for each year during 1902–2008. The

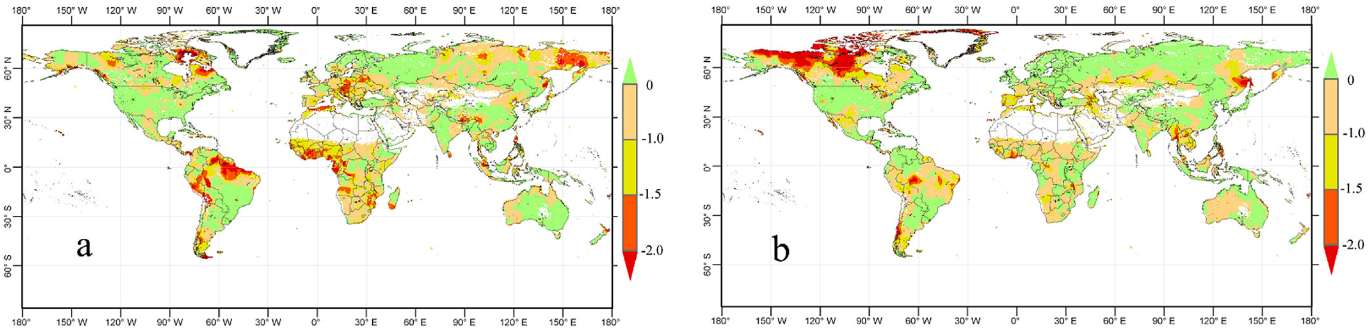

Fig. 1. Spatial distribution map of global drought in 1983 and in 1988(a shows spatial distribution of global drought in 1983; b shows spatial distribution of global drought in 1988, green color represents normal, yellow and red color represent drought, less than −2 is severe drought). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

results illustrate that the largest percentage of global severe drought area (8.16%) identified by our method occurred in 1983, whereas the largest percentage (8.06%) identified by the traditional method was in 1988. Spatial distribution maps of global drought are shown in Fig. 1.

Fig. 1a shows that global severe drought was mainly distributed in the mid-low latitude region in 1983. Fig. 1b illustrates that global severe drought was mainly distributed in the higher latitude region in 1988. According to our method, the calculated percentage by traditional method may be overestimated in higher latitude regions. Compared with 7.05% based on our method, the calculated percentage by traditional method is 8.06%, overestimated by 1.01% in 1988, so our method is more reasonable. Therefore, we adopt this method to calculate the percentage of severe drought area on global and continental scales.

The interannual variation of the percentage of global drought area is shown in Fig. 2, which suggests that the percentage of drought area is rising overall. The trend is 1.58%/50 y, with a downward trend since 1990 of 5.47%/50 y. The result indicates that the severe global drought area has had an obvious downward trend since 1990, and a severe drought in 1983 represented the largest drought in total area in the period between 1902 and 2008, accounting for 8.16% of the global land area (excluding glaciers and desert areas). The severe drought in 1983 mainly happened in Eastern Canada, northwestern Brazil, southern Peru, West Africa, most regions of Austria and Poland, eastern Russia, and southwestern China. This drought is mainly due to the El Nino phenomenon of 1982–1983, as El Nino leads to decreased precipitation in many land areas (Dai and Wigley, 2000). The year of the smallest drought area was 1903, only accounting for 0.6% of the global land area (excluding glaciers and desert areas), and the drought occurred in central western Russia and Ukraine. Dai (2011) and Sheffield et al. (2012) suggested that the global drought area has been increasing since 1980. Comparison with previous studies reveals the characteristics of severe drought areas, showing that mild drought and moderate drought areas are on the increase, and severe and extreme drought areas have no increasing trend on a global scale.

The interannual variability of the severe drought area in the Northern Hemisphere and Southern Hemisphere is shown in Fig. 3. The percentage of the severe drought area in the Northern Hemisphere and Southern Hemisphere showed an upward trend, with a

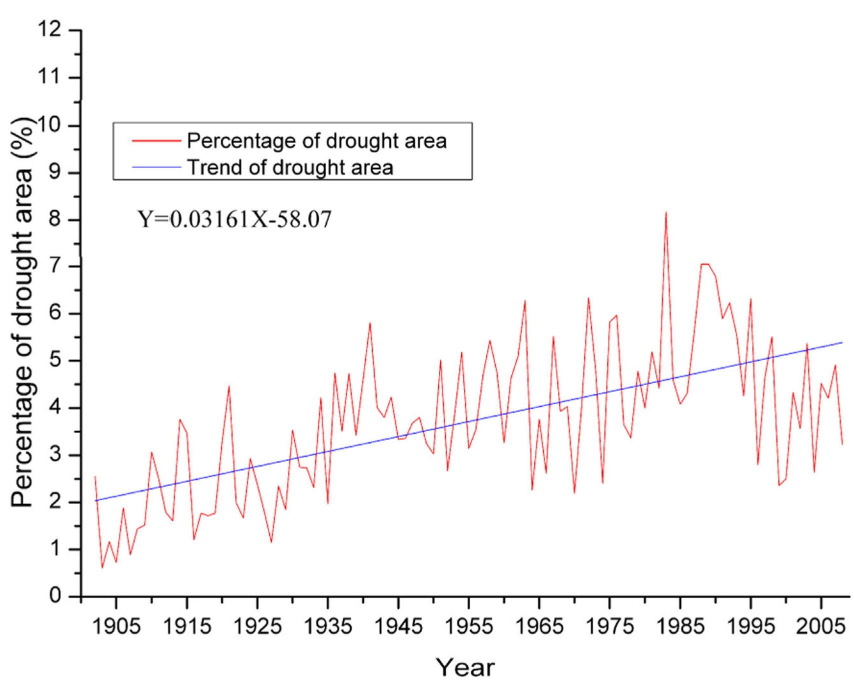

Fig. 2. Severe global drought area (the red curve represents the interannual variability of severe global drought area during 1902–2008; the blue line represents a changing trend of severe global drought area during 1902–2008). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

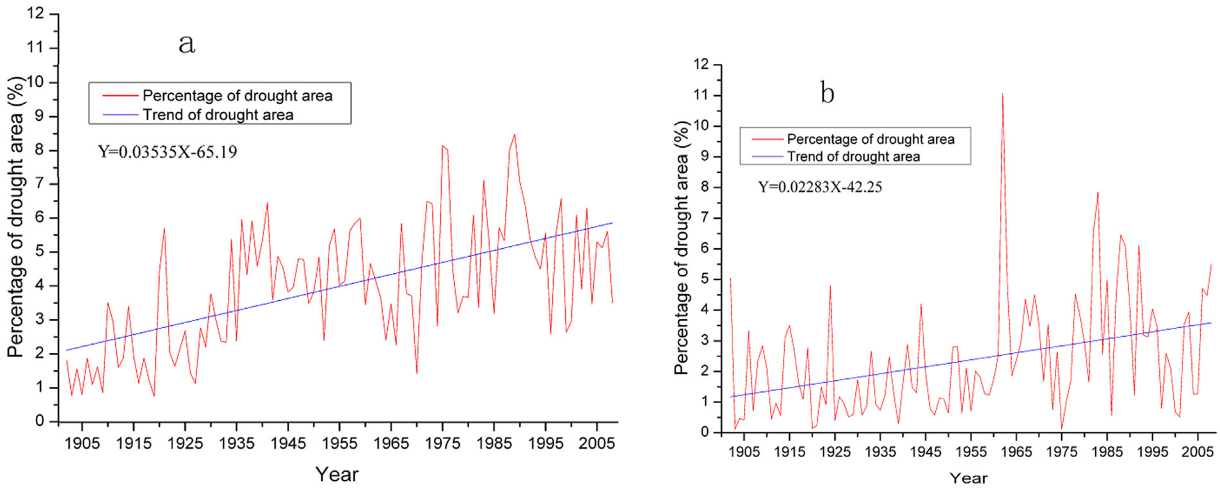

Fig. 3. Severe drought area in the Northern Hemisphere (a) and the Southern Hemisphere (b). (The red curve represents the interannual variability of the severe drought area during the period from 1902 to 2008; the blue line represents a changing trend of severe drought area.) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

trend of 1.77%/50 y in the Northern Hemisphere, which is above the trend of global change, and 1.14%/50 y in the Southern Hemisphere. Significant downward trends were shown in Fig. 3a for the Northern Hemisphere during 1914–1919, 1921–1927, 1941–1952, 1959–1966 and 1989–1996, with an overall downward trend since the 1980s. In the Northern Hemisphere, severe droughts in 1975 and 1983 marked the largest drought in terms of overall area during the 1902–2008 period, respectively accounting for 8.14% and 8.48% of the land area (excluding glaciers and desert areas). Severe drought in 1975 mainly occurred in western Russia and eastern Ukraine, and in 1985, severe drought mainly occurred in central Russia. Fig. 3b shows no obvious trend for the severe drought area in the Southern Hemisphere before 1962, and the severe drought area showed a significant downward trend from 1962 to 1975 and from 1983 to 2000. The area of severe drought has shown a significant upward trend since 2000. A severe drought in 1962 represented the largest drought in terms of area during the 1902–2008 period, accounting for 11.1% of the land area of the Southern Hemisphere (excluding glaciers and desert areas). The severe drought in 1962 mainly occurred in much of Bolivia, eastern Argentina, southern Brazil, and southern Madagascar.

To understand the interannual variability characteristics of severe drought areas in sub-global regions, we investigated the interannual variability of severe drought areas for North America, Oceania, Africa, South America, Europe, and Asia on a continental scale. As shown in Fig. 4, the result indicates that severe drought areas of five continents are on the rise, except for Oceania, which experienced a downward trend (−0.144%/50 y) from 1902 to 2008 and Asia's largest upward trend (2.69%/50 y), and South America 1.44%/50 y, Europe 1.36%/50 y, North America 1.08%/50 y, Africa 0.75%/50 y. Fig. 4 shows that Oceania and Africa are the continents with the least severe drought area. The years with the greatest drought area for each continent are identified, including 1948, 1954, 1973, 1976, 1981, 1987, 1988, 1998 with the greatest drought area (>10%) for North America, the year with the largest drought area was 1982 (with 5.18%) for Oceania, 1983 (with 12.71%) for Africa, 1963 (21.78%), 1983 (18.86%) for South America, 1975 (34.8%), 1959 (21.26%), 2003 (20.26%), 1921 (20.24%), 1972 (19.95%), 1938 (19.64%) for Europe, and 1986 (9.83%), 1967 (9.67%), 1989 (9.53%), 1991 (9.5%), 1997 (9.47%), 1990 (9.31%), and 1984 (8.77%) for Asia.

We compared the reported drought events on all continents to test the effectiveness of the identification of the years of the severe drought events. In North America, the most spatially extensive droughts were those in 1954–1957 (in the central United States and much of Canada), the 1976–1977 events (in the northern United States and central Canada) and the 1988 event (in the central United States and southern Canada) (Cook et al., 1999; Keyantash and Dracup, 2004; Sheffield et al., 2009). In Oceania, the 9-month 1982–1983 drought coincided with the centers of agriculture and population in the east and southeast (Nicholls, 2004; Mpelasoka et al., 2008). In Africa, droughts are dominated by events during the mid-1970s, 1980s (Hulme, 1992; Oba et al., 2001; Tarhule and Lamb, 2003; Dai et al., 2004) and the early 1990s (Rouault and Richard, 2005). The largest droughts were in the 1980s and 1990s. The 1982–1984 drought began in southern Africa in December 1982 and joined with a drought that started in central Africa to reach its peak extent in April 1983 (Sheffield et al., 2009). In South America, the 1963–1964 drought was the worst drought for durations of up to 12 months (Marengo et al., 2008), the 1982–1983 drought event extended over Peru, Colombia, Venezuela, and northern Brazil (Marengo et al., 1998). In Europe, the 1975–1976 drought was the most severe for this 12-month duration (Sheffield et al., 2009). In Asia, the 1984–1988 event persisted over central Siberia before migrating southeast to northern China and back. The 1997–1998 drought was the most spatially extensive, covering more than 8 million square kilometers from eastern China to central Asia (Sheffield et al., 2009). These drought events are consistent with the recognition based on our methods, which indicates that our methods for identifying the years of severe drought are reliable.

Table 2 shows that the maximum severe drought area percentage for six continents is greater than the comparable global percentage. The maximum reaches 34.8% in Europe, and the maximum for five other continents is all above 10%, indicating that the severe drought for each continent involves many regions in severe drought years. The average drought area percentage may indicate the mean spatial spread range of severe drought in regions. The greater the average value, the larger the average annual drought area in a region. Table 2 shows that the mean values of the severe drought area percentage for each continent imply a more obvious difference between the continents, with the highest mean in Europe and the smallest mean in Oceania. An average area of 5.04% of the total European continent experiences severe drought every year, while only 0.95% of Oceania

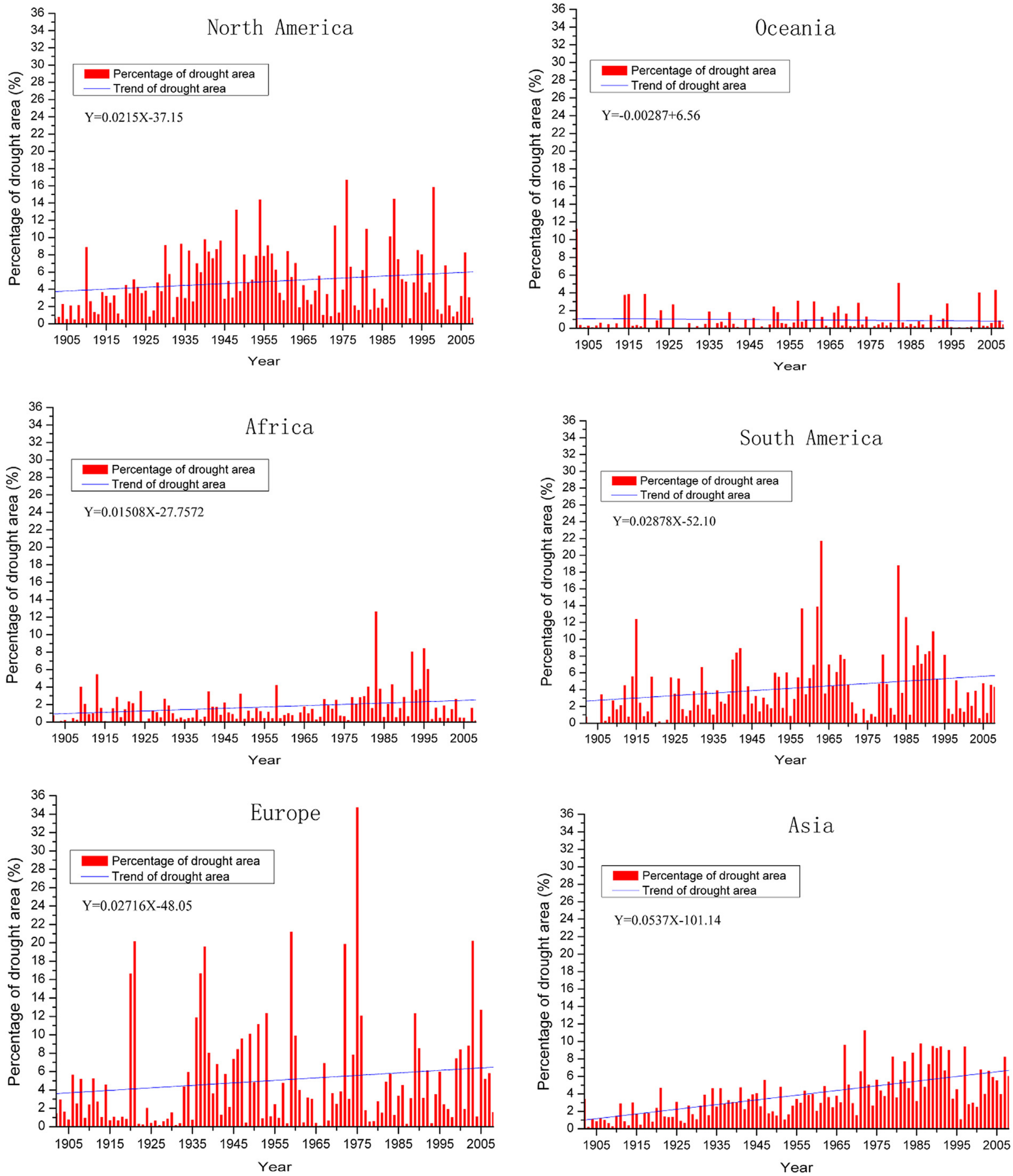

Fig. 4. The severe drought area in each continent. (The red histogram represents the interannual variability of the severe drought area for each continent during the period from 1902 to 2008; the blue line represents a changing trend of severe drought area.) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

experiences severe drought annually. The standard deviation of the percentage of the drought area may reflect the interannual variability of the severe drought area in regions, and a greater standard deviation indicates a greater degree of deviation from the mean and means that there are obvious differences in the severe drought area of a region. That is to say, when more severe droughts occur, many areas in the region will suffer from severe drought. Table 2 shows that the largest interannual variability of severe drought occurs in Europe, and the minimum occurs in Oceania. Table 2 shows that when the average area is larger, the standard deviation is also larger, and the mean and standard deviation are consistent, which suggests that when the annual average drought area for continents is larger, the interannual variation of the drought area is also larger. Therefore, any one indicator of the mean and standard deviation can reflect whether the region is prone to severe drought. Combining the above analysis, Europe is the most prone to severe drought, and Oceania is the least prone to severe drought.

Table 2
Statistical indicators of severe drought area on global and regional scales (unit: %).

	Global	Northern hemisphere	Southern hemisphere	Asia	North America	Europe	Africa	South America	Oceania
Maximum	8.16	8.48	11.07	11.34	16.73	34.8	12.71	21.78	11.28
Mean	3.71	4.00	2.38	3.85	4.88	5.04	1.72	4.16	0.95
Standard deviation	1.57	1.85	1.89	2.54	3.62	5.85	1.90	3.89	1.50

3.2. Severe drought frequency

To quantitatively evaluate the most drought-prone and least drought-prone regions based on the above spatial analysis method, we can obtain the frequency of severe drought at a grid-level scale, and Fig. 5 shows the spatiotemporal characteristics of the frequency of severe drought. Based on the frequency distribution characteristics of global drought events, the global area is divided into the least drought-prone areas, frequently drought-prone areas, and chronically drought-prone areas. Fig. 5a shows that most regions of the global area were categorized as frequently drought-prone areas during 1902–2008, which include eastern North America, Europe, western Russia, central South America, and central Africa. Chronically drought-prone areas are mainly distributed in southern Europe, eastern North America, and Central Africa. The least drought-prone areas are mainly distributed in fewer regions including fewer regions of Africa and North America, India, and Midwest Australia. Fig. 5b shows that most global areas are classified into the least drought-prone areas and frequently drought-prone areas during 1902–1949. The spatial pattern of chronically drought-prone areas during the 1902–1949 period are similar to that during the 1902–2008 period, which occurs mainly in the middle and high latitudes of the Northern Hemisphere and shows the distribution of clusters. The centers of distribution are in southern Canada, the Central and Eastern United States, southeast and northeast South America, central Africa, Europe, western Russia, eastern China, and eastern Australia, and frequently drought-prone areas are mainly distributed in and around chronically drought-prone areas. The Sahel, a semi-arid region in West Africa, experienced a drought of unprecedented severity in recorded history. Since the late 1960s and in the early and mid-1980s, the droughts that caused the most serious crop failure occurred from 1960 to the 1980s (Batterbury and Warren, 2001; Zeng, 2003).

Fig. 5c shows that most regions of the world are classified to frequently drought-prone areas and chronically drought-prone areas during the 1950–2008 periods. There are small regions that belong to the least drought-prone areas, which include South America, North America, small regions of Africa, central and Western Australia, and chronically drought-prone areas are mainly distributed in northern North America, central South America, central Africa, most of Asia, and Europe. Fig. 5d shows that 71.6% of all regions have experienced increasing drought frequency after 1949, and 28.4% show a decreasing trend. Our result is consistent with conclusions of recent studies. Sheffield et al. (2012) noted drying across much of the global land, particularly over Africa and eastern Asia, and it is probable to be attributed to increasing in evaporation driven by climate warming but also because of decreases in regional precipitation. The dominant least drought-prone areas were replaced by chronically drought-prone areas after 1950. Fig. 5d indicates that the regions of increasingly severe frequency are conversion regions directly from least drought-prone areas to chronically drought-prone areas. The results mainly attributed to most land areas warmed by 1–3 C° from 1950 to 2008, with the largest warming occurring over northern Asia and northern North America, during which the rains decreased most in Africa, southern Europe, southeastern Asia, eastern Australia, the Pacific coast of Central America, and some regions of South America (Dai, 2011). Chronic droughts in areas in the United States are likely attributable to the Pacific Decadal Oscillation (PDO) and the Atlantic Multi-decadal Oscillation (AMO) (McCabe et al., 2004). Prolonged dry spells and increased evaporation due to reduced precipitation may increase the frequency of droughts in southern European regions, while floods in northern Europe are more frequent with increased precipitation (Voss et al., 2002; Mishra and Singh, 2010). Severe drought frequency increased in many parts of Asia due to increasing water stress, increasing temperatures, the increasing frequency of El Niño events, and the reduction in the number of rainy days (Bates et al., 2008).

To study the spatial variability of the frequency of severe global drought in different periods, Table 2 shows the proportion of the global spatial distribution for three different levels of drought frequency during the 1902–1949, 1949–2008, and 1902–2008 periods. On a global scale, the least drought-prone areas and most frequently drought-prone areas dominated from 1902 to 1949, while chronically drought-prone areas accounted for only 16.19% of the total area. Frequently drought-prone areas and chronically drought-prone areas dominated from 1950 to 2008, and chronically drought-prone areas accounted for 41.09%, whereas the least drought-prone areas only accounted for 11.44%. Frequently drought-prone areas accounted for 71.32%, while chronically drought-prone areas accounted for only 15.59% from 1902 to 2008. Through studying the spatial distribution characteristics of drought frequency in several periods, the spatial variability of drought frequency and the spatial shift of drought frequency in several periods could be understood more comprehensively. Table 3.

Table 3
Statistics of severe drought frequency for three different levels in three periods.

Period (years)	Least drought-prone areas percentage(%)	Frequently drought-prone areas percentage(%)	Chronically drought-prone areas percentage(%)
1902–1949	47.45	36.36	16.19
1950–2008	11.44	47.47	41.09
1902–2008	13.09	71.32	15.59

3.3. Severe drought frequency in major crop-planting regions

Global crops are distributed throughout regions with different levels drought frequency to identify the global crop-planting regions located in chronically drought-prone areas. Wheat, rice, maize, soybeans, barley and sorghum are the six most widely planted crops in the world (Lobell and Field, 2007), accounting for 40% of the global planting area (FAO, 2006). Based on the frequency levels of severe drought in crop-planting regions, we evaluated whether the planting regions for each crop are prone to severe drought and which regions are prone to severe droughts. If crop-planting regions are in the higher frequency of severe drought, these planting regions are more vulnerable to the impact of severe drought.

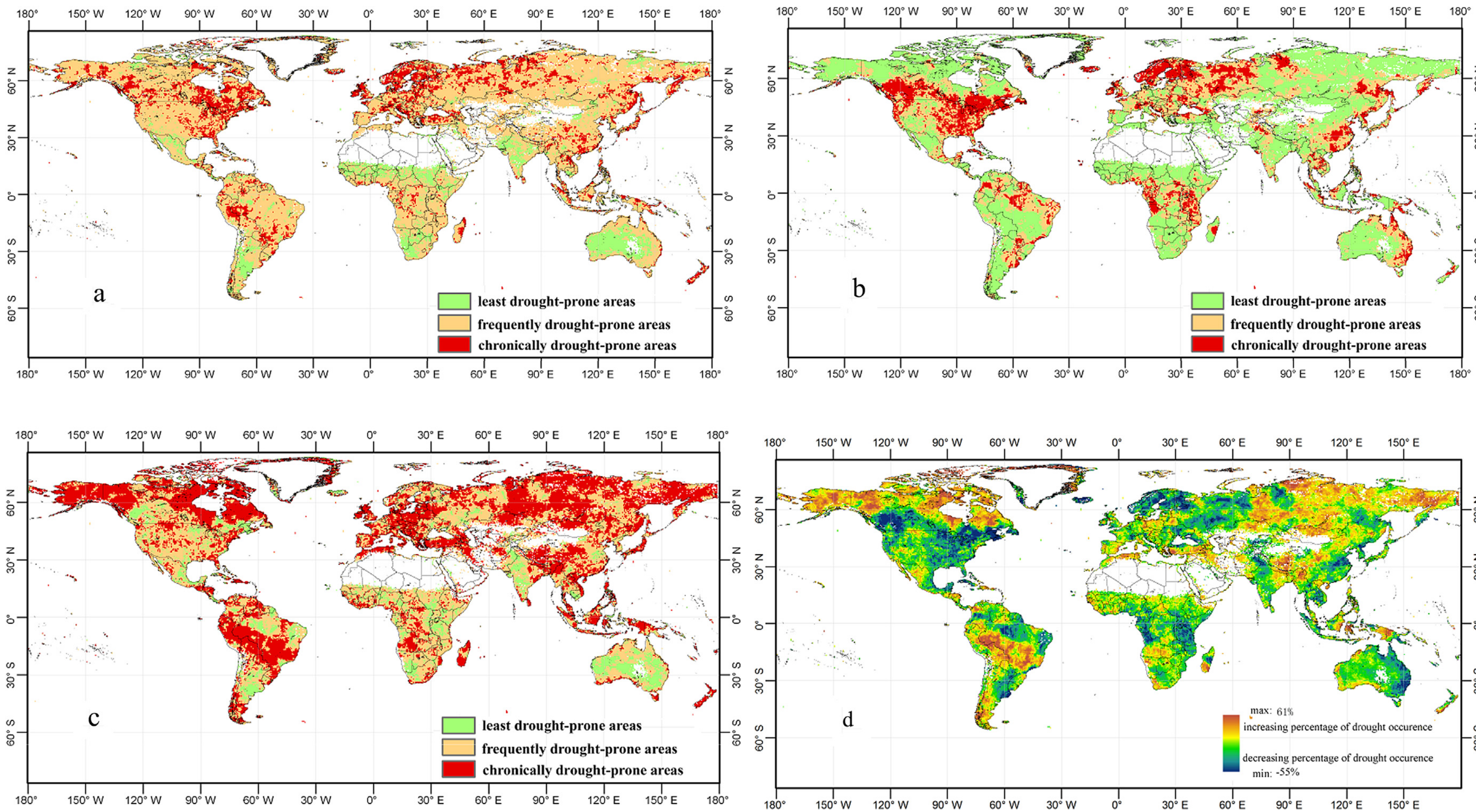

Fig. 5. a, b and c show the spatial distribution of the frequency of global severe drought events during the period from 1902 to 2008, 1902–1949 and 1950–2008, respectively. d shows the spatial distribution of the change in the frequency of severe global drought events after 1950.

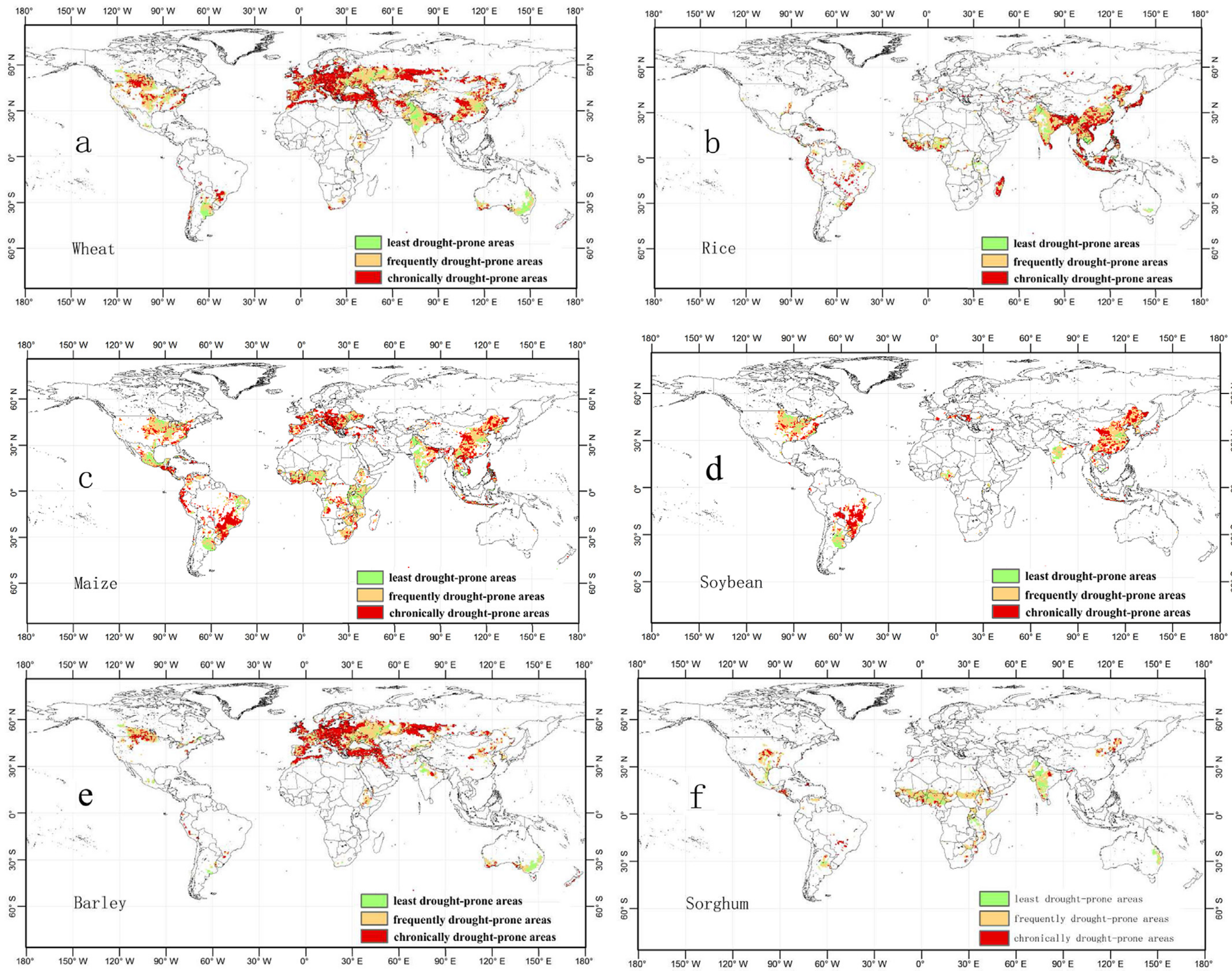

Fig. 6. The spatial distribution of the frequency of severe drought events for main crops during the 1950–2008 period(a,b,c,d,e and f show the spatial distribution of the frequency of severe drought events in Wheat, Rice, Maize, Soybean and Barley crop-planting regions, respectively).

Fig. 6a shows that wheat-planting regions are mainly distributed in much of Europe, Central America, India, and eastern China, and the regions that are the most prone to severe drought are in Southeast Asia and Central America. The regions that are the least prone to severe drought are eastern Argentina, northwestern India, and eastern Australia. Fig. 6b shows that rice-planting regions are mainly distributed in Southeast Asia, Central and South America, Western Africa and Madagascar, and the regions that are the most prone to severe drought are in Southeast Asia and Central America. Fig. 6c shows that maize-planting regions are mainly distributed in the eastern United States, southeastern South America, southern Europe, southern Africa and Southeast Asia, and the regions that are the most prone to severe drought are Southeast Asia, southern Europe and Central South America. Fig. 6d shows that soybean-planting regions are mainly distributed in the southwestern United States, eastern China and central South America, and the regions that are the most prone to severe drought are eastern China and southern Brazil. Fig. 6e shows that barley-planting regions are mainly distributed in Europe, Asia, North America, and southwestern Australia, and the regions that are the most prone to severe drought are southern Europe and western Asia. Fig. 6f shows that sorghum-planting regions are mainly distributed in Central Africa, the Indian subcontinent and the central United States, most of which are in frequently drought-prone areas and the least drought-prone areas, and only central China and the central United States are chronically drought-prone areas. The spatial distribution of drought frequency in these main crop-planting regions is not consistent with previous studies (Yinpeng et al., 2009; Spinoni et al., 2013) because previous studies ignored the temperature factor and only considered precipitation.

The statistical area ratio of different levels of drought frequency for each crop can be used to investigate which areas of the total global planting area are likely to suffer severe drought. The statistical area results of different levels of drought-prone areas for six crops are shown in Table 4, six planting crops are mainly distributed in frequently drought-prone areas, and fewer crop-planting areas are located in the least drought-prone areas, except for sorghum. For wheat, most of the planting regions are located in frequently drought-prone areas and chronically drought-prone areas, respectively. For rice, most of the planting areas are located in frequently drought-prone areas and chronically drought-prone areas. For maize, most are in frequently drought-prone areas. For soybeans, most are in frequently drought-prone areas. For barley, most are in frequently drought-prone areas and chronically drought-prone areas. For sorghum, most are in frequently drought-prone areas.

Table 4
Statistical area of different levels of drought frequency for six crops.

Crop name	Least drought-prone areas		Frequently drought-prone areas		Chronically drought-prone areas	
Type	Area (Mha)	Percentage	Area (Mha)	Percentage	Area (Mha)	Percentage
Wheat	28.63	14.28%	99.30	49.51%	72.63	36.21%
Rice	13.94	10.38%	71.81	53.46%	48.57	36.16%
Maize	16.05	12.53%	72.81	56.87%	39.18	30.6%
Soybeans	10.18	14.28%	40.83	57.28%	20.27	28.43%
Barley	3.24	6.49%	23.33	46.86%	23.23	46.65%
Sorghum	10.05	28.55%	21.80	61.95%	3.35	9.5%

3.4. The impact of severe drought events on crop yield

Based on the analysis of spatial and temporal characteristics of drought frequency, the main crop planting areas of southern Europe, South America, and East Asia can be found in chronically drought-prone areas. To quantitatively evaluate the impact of severe drought on agricultural yields, five countries that are prone to severe drought were chosen for the evaluation in chronically drought-prone areas, such as Brazil, Peru, Iran, Spain, and China. In Brazil, the agribusiness sector now accounts for more than one-third of the gross national product, and Brazil is a leading worldwide producer of soybeans, which is also one of the most important crops in Brazil (Morton et al., 2006). Brazil is a major producer, traditionally ranking third behind the United States and China in global production (Schnepf et al., 2001), and Brazil is the largest net exporter of food worldwide (Gauder et al., 2011). The region's rice-planting area is just below the Belt of Peru, and rice is one of the most main food crops in Peru (FAO, 2006), ranking second in the country. The field crop production area accounts for 18.5 million hectares in Iran. The most extensive cultivated area is devoted to wheat, which is grown on nearly 60% of the total country's area under cultivation (Faramarzi et al., 2010). Irrigation in Spain, covering only 17% of cultivable land, produces approximately 60% of its agricultural output (Vogt and Somma, 2000). In Iran, wheat occupies one of the largest crop-planting areas, representing 3.20 Mha (FAO, 2006). China also has the largest population in the world and stopped approving bioethanol projects using maize and wheat (Zhao et al., 2009). The degree of dependence on imported oil in China reached 49.0% in 2006, and this figure could reach up to 77% in 2030. Bioethanol derived from plant materials is now believed to be the most promising substitute for fossil energy and to have the potential to increasingly replace fossil fuels (Zhang et al., 2010). Sorghum is considered to be the most important and the most promising energy plant (Wang et al., 2009). Therefore, in our study, several crops in chronically drought-prone areas, including soybeans in Brazil, rice in Peru, wheat in Iran, barley in Spain, and sorghum in China, are chosen to analyze the relationship between severe drought areas and crop yields.

Four severe drought years are chosen in each crop-planting region, and the relationship between the percentage of drought area and the percentage yield anomaly under severe drought years are comparatively analyzed, and the percentage of drought area and the percentage yield anomaly for the main crop belts in severe drought years are shown in Table 5. Crops except wheat, which showed an obvious increase in 1995 and in 2002, showed different levels of yield loss in severe drought years. The 2000 drought event led to yield decreases of 5.11% for maize and 10.81% for soybeans, which are attributed to a severe drought caused by La Niña, which brought a high loss of life and crop failure in southeastern Brazil and Uruguay. The event led to government subsidies to affected areas (Rosenzweig et al., 2001). In Spain, the area affected by the 1995 drought accounted for 14.22% of the country's barley-planting regions, but the barley yield decreased by 35.86%, which is attributable to the drought lasting for five years, beginning in 1991 and ending in 1995. The surface water could not meet crop irrigation and led to crop failures. Throughout 1991–1995, approved funds for drought emergency relief reached approximately 600 million Euros. In the first eight months of 1995 alone, this figure rose to approximately 90 million Euros (Vogt and Somma, 2000). The extent of crop failures is not completely consistent with the size of the drought area, and to some extent, the effects of severe drought were most likely alleviated by intervention and mitigation plans led by governments. Although the decrease in crop yields is not entirely caused by drought and may also be affected by factors such as plant diseases, pests, freeze-up disasters and others (Warrick, 1984), severe drought is an important factor affecting crop yields. Li et al. (2009) concluded that drought explained >60% of the yield reduction. Therefore, crop-planting regions that are prone to severe drought should strengthen the construction of water conservancy irrigation facilities.

Table 5
Percentage of drought area and the percentage yield anomaly for each crop in severe drought years.

Crop (country)	Drought period	Drought area	Yield change	Crop (country)	Drought period	Drought area	Yield change
	Year	Percentage (%)	Percentage (%)		Year	Percentage (%)	Percentage (%)
Maize (Brazil)	1990	5.33	−14.9	Soybeans (Brazil)	1979	2.80	−6.18
	1993	15.92	−0.11		1993	33.46	−5.86
	1995	12.86	−1.31		1995	4.60	−7.37
	2000	9.56	−5.11		2000	6.41	−10.81
Rice (Peru)	1983	13.83	−10.04	Barley (Spain)	1961	63.99	−5.80
	1992	18.59	−10.48		1970	50.84	−9.01
	1993	30.83	−5.22		1989	60.51	−2.60
	1995	25.55	−5.43		1995	14.22	−35.86
Wheat (Iran)	1986	12.96	−5.16	Sorghum (China)	1989	60.08	−7.59
	1995	12.42	4.66		2001	37.99	−12.97
	1997	48.39	−4.25		2007	82.93	−14.29
	2002	17.28	6.85		2008	51.52	−18.11

4. Conclusions

The spatial-temporal analysis of drought is one of the most important aspects of drought disaster mitigation. We used the Standardized Precipitation Evaporation Index to study the spatial-temporal pattern of drought on a global scale and revealed the spatial and temporal variation of severe global drought since 1902. Using the area and event frequency of severe drought as the main indicators, we explored the spatial and temporal characteristics of severe drought on global, Northern Hemisphere, Southern Hemisphere, and continental scales. Because severe drought has a severe impact on socio-economic sectors, particularly on the agricultural sector, regions that are prone to severe drought for main crops can be identified on the basis of a global spatial-temporal pattern analysis, and the impact of severe drought events on crop yields were analyzed in several typical regions and on a national scale.

Our results suggested an overall rising trend (1.58%/50 y) for percentage of global drought area from 1902 to 2008, but since 1990, the percentage of global drought area showed a downward trend (5.47%/50 y). Overall downward trends have been exhibited in the Northern Hemisphere and the Southern Hemisphere since 1980. On a continental scale, the change in drought area presents a rising trend to some degree in all continents except for Oceania, and Europe is the most prone to severe drought. Since 1950, chronically drought-prone areas that experienced global drought events increased significantly, and the least drought-prone areas decreased. Chronically drought-prone areas showed a patchy distribution and were mainly distributed in high latitudes of the Northern Hemisphere and near the equator during the 1902–2008 and 1902–1949 periods, and frequently drought-prone areas are mainly distributed in regions surrounding chronically drought-prone areas. The areas that are the most prone to severe drought in main crop-planting regions showed a patchy distribution. The regions are mainly in southern Europe, South America, and eastern Asia. When severe drought events occur in crop-planting regions, yield reductions will appear on different levels.

These conclusions can provide a scientific basis for the management of drought mitigation strategies on a global or national scale. Identifying the drought-prone areas can help decision-makers to take drought into account in resource planning and help to select drought-tolerant crops in drought-prone agricultural areas. However, our study adopted the SPEI data with the lower 0.5-degree spatial resolution, which probably influences certain spatial description of drought characteristics in detail. If the soil water balance factor can be considered in SPEI, it would be much better for the agricultural drought assessment. In addition to the drought event frequency and drought area, comprehensive factors, including drought duration and severity should be used in future studies to reveal drought events, the characteristics of spatial and temporal shift should be analyzed, and a periodic analysis of drought events should be conducted.

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