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Prolonged dry episodes and drought over China

Yonghui Lei[a]* and Anmin Duan[b]

[a] *State Key Laboratory of Remote Sensing Science, Institute of Remote Sensing Applications, Chinese Academy of Sciences, Beijing, China*
[b] *LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China*

ABSTRACT: Prolonged dry episodes, defined by the 90th percentile of long durations without efficient precipitation (above the 0.1 mm/day threshold) in both the wet and dry seasons, have been investigated from 1958 to 2008 at 404 stations over China. Associated with droughts over northern China in summer, the enhancement of the prolonged dry episode duration is an essential feature, together with a lack of precipitation and the negative Palmer drought severity index (PDSI) in the wet season. In the dry season, durations of prolonged dry episodes have significantly increased over southern China and the Yellow River valley during the last 51 years. The prolonged dry episodes highlight the impact of a decrease in precipitation frequency, and are useful for representing short-term droughts, particularly over semi-arid regions and in the dry season. The occurrence of the maximum prolonged dry episodes over vulnerable regions in the early twenty-first century is suggestive of a greater risk of droughts during both the wet and dry seasons in a warmer climate over China. Copyright © 2010 Royal Meteorological Society

KEY WORDS prolonged dry episodes; droughts; precipitation frequency

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1. Introduction

The worst drought in half a century hit central China between November 2008 and February 2009. A 50–80% reduction in precipitation and a long dry spell duration during the previous winter season affected 10 000 000 ha of crops and human well-being over 12 provinces of China (Tao *et al*., 2009). Although the drought was alleviated by the occurrence of efficient precipitation in late February, a great loss had occurred in wheat production in the harvest season.

Drought has been a common feature over northern China in the last two decades because of precipitation deficiencies (e.g. Zhai *et al*., 2005; Zou *et al*., 2005). Simultaneously, China has also experienced a warming climate (e.g. Wang and Gong, 2000). A warmer and drier climate is not unique over northern China. The number of severe dry areas has increased globally since the late 1970s due to decrease in precipitation and increase in evaporation (Dai *et al*., 1998, 2004). Disproportionate changes in precipitation enhance the risk of droughts in a warmer climate, as well as the risk of flooding. For example, a tendency of increased precipitation in the south of China accompanies the northern drought, related to a weakening of the East Asian summer monsoon (e.g. Guo *et al*., 2003) and a southward shift of summer rainfall (e.g. Ding *et al*., 2008).

Observational evidence indicates that disproportionate changes in precipitation over China not only occur with spatial distribution but also with temporal characteristics (Lei, 2008). The rainfall intensity increased but the number of rain days (frequency) uniformly decreased during summer in the last 50 years (Zhai *et al*., 2005; Ding *et al*., 2008). In particular, light rainfall frequency decreases significantly (Lei *et al*., submitted). These changes in the temporal characteristics of precipitation tend to aggravate the extreme events (i.e. drought and flooding) in summer.

Associated with a general increase in surface air temperature and inhomogeneous changes in precipitation, the longer average duration of dry episodes without sizable precipitation (1 mm/day threshold) during the warm season (above 5 °C) has been reported as an emerging new tendency in the recent decades over the eastern and southwestern United States (Groisman and Knight, 2007, 2008). Over China, a homogeneous increase in the number of non-rain days (the counterpart of rainfall frequency) during summer also suggests that the average duration of dry episodes could increase in the last half century. The warm season has been of particular concern in previous studies. However, it is unclear whether the longer dry episodes, such as the 100 days' dry spell that occurred during the winter of 2008/2009 are indicative of a tendency in a warmer climate.

Drought is a gradual process and its impact accumulates as precipitation deficiencies persist over a considerable period of time. In severe cases (e.g. the 1984/1985 drought in the Horn of Africa), drought can last for years and can have a devastating effect on agriculture and human well-being. The monitoring of drought has focused on long-term dryness, particularly over several months or years. In addition to precipitation deficiency,

* Correspondence to: Yonghui Lei, Institute of Remote Sensing Applications, Chinese Academy of Sciences, Beijing, 100101, China.
E-mail: yonghui.lei@hotmail.com

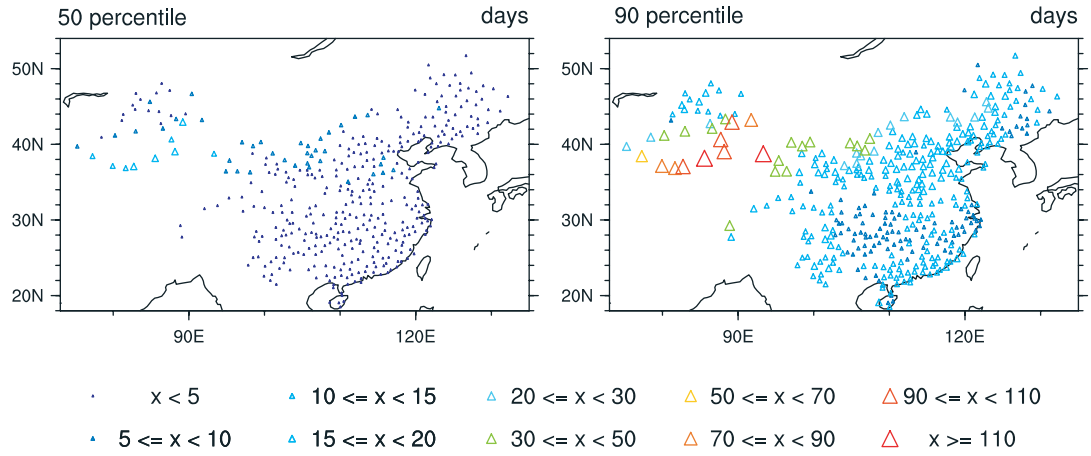

Figure 1. Climatology of the 50th percentile (a) and the 90th percentile (b) of dry spell duration (days) at 404 stations in the period 1958–2008. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

some drought indices focus on water balance between supply and demand. For instance, the Palmer drought severity index (PDSI) is calculated on the basis of historic precipitation and temperature data, with a complex format including evaporation, runoff, and other land surface processes (Palmer, 1965). The PDSI has been proven to be the most effective index for determining long-term meteorological drought, which has been used to identify the severity of droughts over northern China (Dai *et al*., 2004; Zou *et al*., 2005).

An individual prolonged dry episode indicates a temporal aberration related to the timing and effectiveness of precipitation. The monitoring of prolonged dry episodes is effective with short-term droughts that occur almost everywhere in the world. The main purpose of this paper is to document prolonged dry episodes and associated drought, using daily rain-gauge observations during the period 1958–2008 over China. The climatology of prolonged dry episodes and their variations are investigated during the wet and dry seasons. Records of precipitation and the PDSI are used to indicate long-term drought over China. Relations between prolonged dry episodes and long-term droughts are of particular concern and impacts of disproportionate precipitation on drought disasters are discussed.

2. Data and method

Dry spells, characterized by a long duration without measurable precipitation (above 0.1 mm/day threshold), are naturally related to temporal characteristics of precipitation. A dataset of daily precipitation over China, provided by the National Meteorological Center of Chinese Meteorological Administration, is used to identify dry episodes. During 1958–2008, daily observations at 404 rain-gauge stations are available and have been subjected to quality control procedures (Zhai *et al*., 2005). Over the 404 stations for which data is available, the total number of dry spells during the 51-year period varies from 456 to 2297, and the longest dry spell duration ranges from 17 to 330 days. Within China, regional characteristics of dry spells are distinct. The relatively large number of dry spells and small values of the longest dry spell duration occur over the southwest, the Yangtze Rive valley, and northeast of China, and vice versa over southern Xinjiang and the west of Inner Mongolia (figure not shown).

Figure 1 shows the spatial distribution of the 50th percentile and the 90th percentile of dry episode durations at 404 stations between 1958 and 2008, while probability density functions for the duration of dry episodes are calculated using all the dry spells over each station during 51 years. The 50th percentile of dry episodes are predominantly characterized by durations of 5–10 days over the whole country, while the 90th percentile of dry episodes shows a large range from less than 10 days in the south and 20 days in the northeast to over 60 days in the Tarim Basin. The distinguishing spatial feature of the 90th percentile of dry episodes is predominantly consistent with that of regional climates. The 90th percentile of dry episodes can last about a month or more over arid and semi-arid regions, such as north China, but about a week or two over wet regions in the south. Compared to an even distribution of the average dry episodes, the pattern associated with the 90th percentile of dry episodes has a larger impact on regional climate, terrestrial ecosystems, and agriculture when considering the impact of long durations without precipitation.

The East Asian monsoon determines patterns of precipitation over China in wet and dry seasons during the annual cycle (e.g. Ding, 1992). Rainfall predominantly occurs in June, July, and August, accounting for an average of 53% of the annual mean precipitation. Although the contribution to precipitation in spring (April and May) is also large over southeast of China, 3 months in summer are considered to be the wet season, while the dry season is defined as September to May of the next year. Dry episodes are investigated here in both the wet and dry seasons. At the season boundaries, dry spells are allocated to the season in which the larger part falls. In the case of a dry spell falling at a season boundary with an equal duration in both seasons, the dry spell is allocated to the

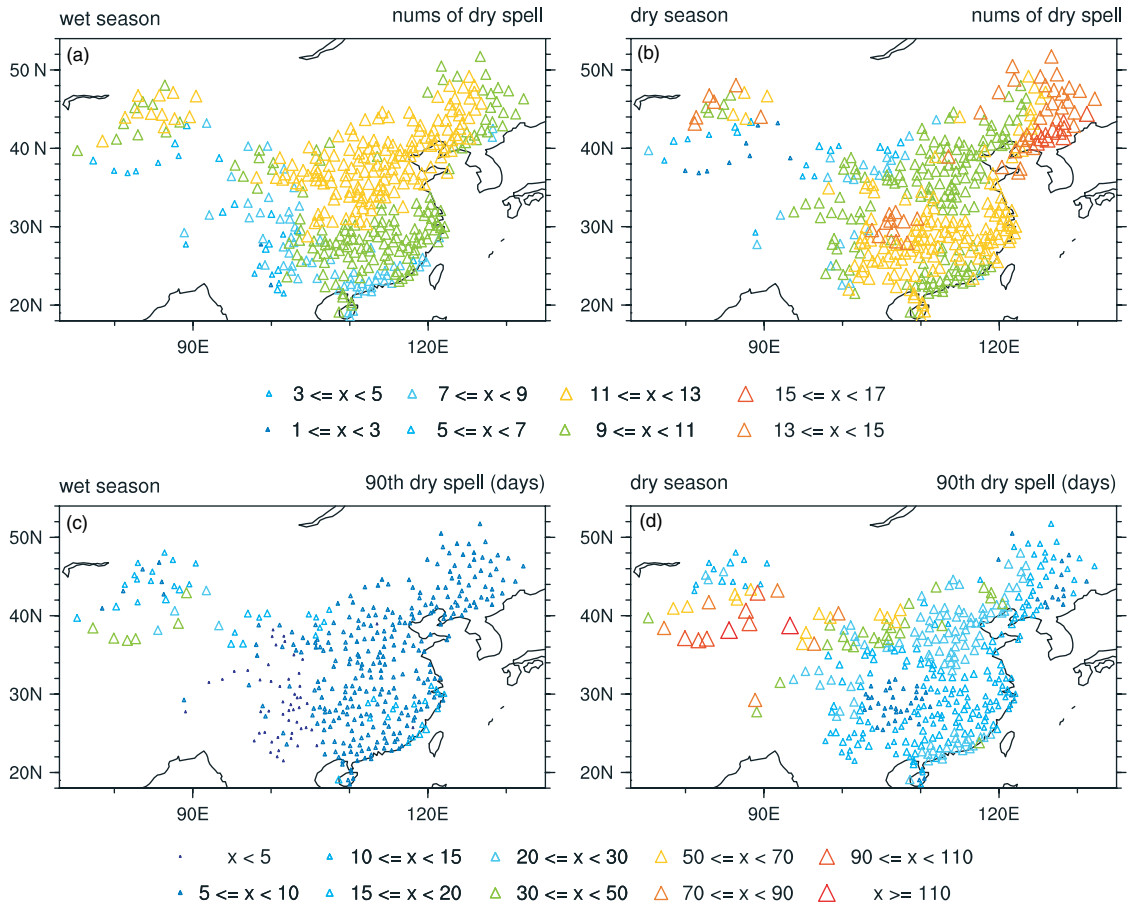

Figure 2. Climatology of number of dry spells during the wet and dry seasons in the period 1958–2008 (at the top), together with the 90th percentile of prolonged dry episode duration (days, at the bottom). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

later season. This work does not specifically discuss dry episodes in the natural warm season (above 5 °C) because prolonged dry episodes in cold conditions are also important for water supply and agricultural products (i.e. winter wheat) in China, as in the winter of 2008/2009.

Following previous studies (Dai *et al*., 2004; Zhai *et al*., 2005; Zou *et al*., 2005), precipitation at 404 stations in both the wet and dry seasons from 1958 to 2008 and the PDSI from 1958 to 2005 are used to indicate long-term drought over China. Because the PDSI does not reflect droughts over snow and frozen ground, the PDSI in the dry season is used with caution only over southern China. In addition, observed precipitation provides direct information for precipitation deficit. Relations of prolonged dry episodes with long-term droughts are evaluated on multiple timescales.

The presence of systematic change in the prolonged dry episodes over the past 51 years is detected using least squares regression (Draper and Smith, 1966) and Student's *t*-test. Empirical Orthogonal Function (EOF) analysis is used to identify the predominant variation in precipitation frequency in the wet and dry seasons during 1958–2008, which may suggest a natural connection with droughts described by the prolonged dry episode duration. Associated large-scale circulation anomalies are explored using regressions of 500 hPa geopotential height in the ERA-40 reanalysis (from 1958 to August 2002) on area-averaged prolonged dry episodes over key regions of China.

3. Results

3.1. Prolonged dry episodes and drought tendency

Climatologies of the number of dry spells during the wet and dry seasons in the period 1958–2008 are shown in Figure 2(a) and (b). There are around 10 dry spells in both seasons over most of China. The maximum is up to 17 dry spells, occurring over the Sichuan Basin and northeast China during the dry season. The minimum occurs over the Tarim Basin in both seasons, with around three dry spells. According to the average number of dry spells during each season, the 90th percentile of prolonged dry episodes generally indicates the longest dry spells in both the wet and dry seasons.

Figure 2(c) and (d) shows climatologies of the longest dry episodes in the wet and dry seasons during the period 1958–2008. The prolonged dry episodes show distinguishing spatial features in the wet and dry seasons. The durations of the prolonged dry episodes are generally longer in the dry season, implying a higher risk of short-term drought than in the wet season. The prolonged dry episodes generally last for about 1 month over central northern China during the dry season. In the wet season,

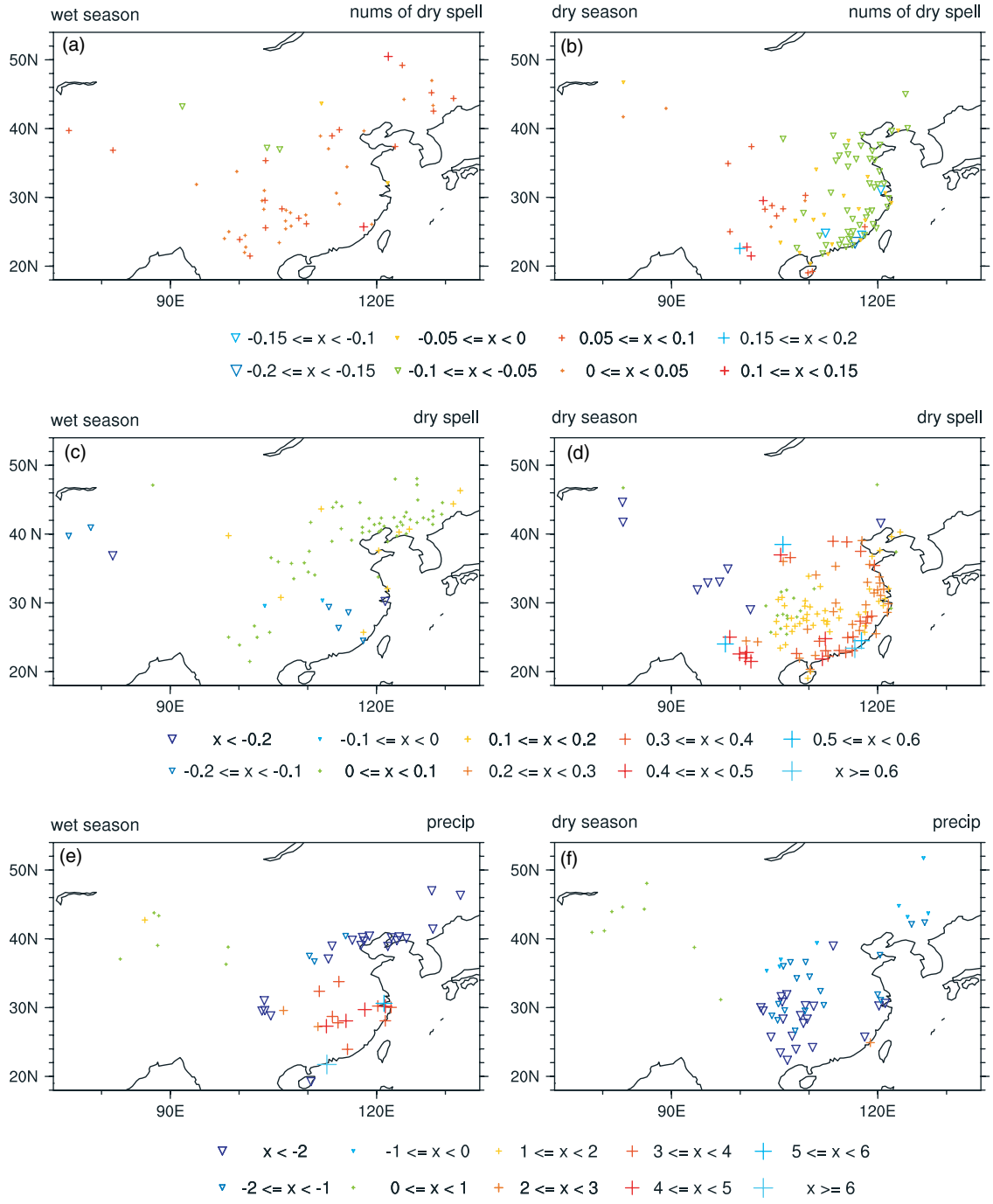

Figure 3. Significant ($p = 0.05$) coefficients of linear trends for the numbers of dry spells (numbers/year, at the top), the prolonged dry episode duration (days/year, in the middle) and precipitation amount (mm/year, at the bottom) in both the wet and dry seasons from 1958 to 2008.

the prolonged dry episodes are less than 15 days in duration over most of China apart from the northwest. The durations of the prolonged dry episodes and the numbers of dry spells in Figure 2 are anti-correlated. Longer durations correspond to smaller numbers of dry spells, such as those over the Tarim Basin.

Figure 3 shows statistically significant coefficients of linear trends for the number of dry spells (a, b), the prolonged dry episode duration (c, d), and precipitation amount (e, f) in both the wet and dry seasons from 1958 to 2008. The number of dry spells has increased slightly in the wet season, with sparse signals across the country. A decrease in the number of dry spells over east China is dominant during the dry season, although an increase occurs over the west.

The prolonged dry episode durations show increasing tendencies in both seasons, with distinct spatial distributions. The trends in prolonged dry episode duration in the wet season are consistent with the predominant pattern of southern flooding and northern drought in the last half century (e.g. Zhai *et al*., 2005). An increase in the duration of prolonged dry episodes is widespread over northeast China, and a sparse decrease appears over the Yangtze River valley. During the dry season, the

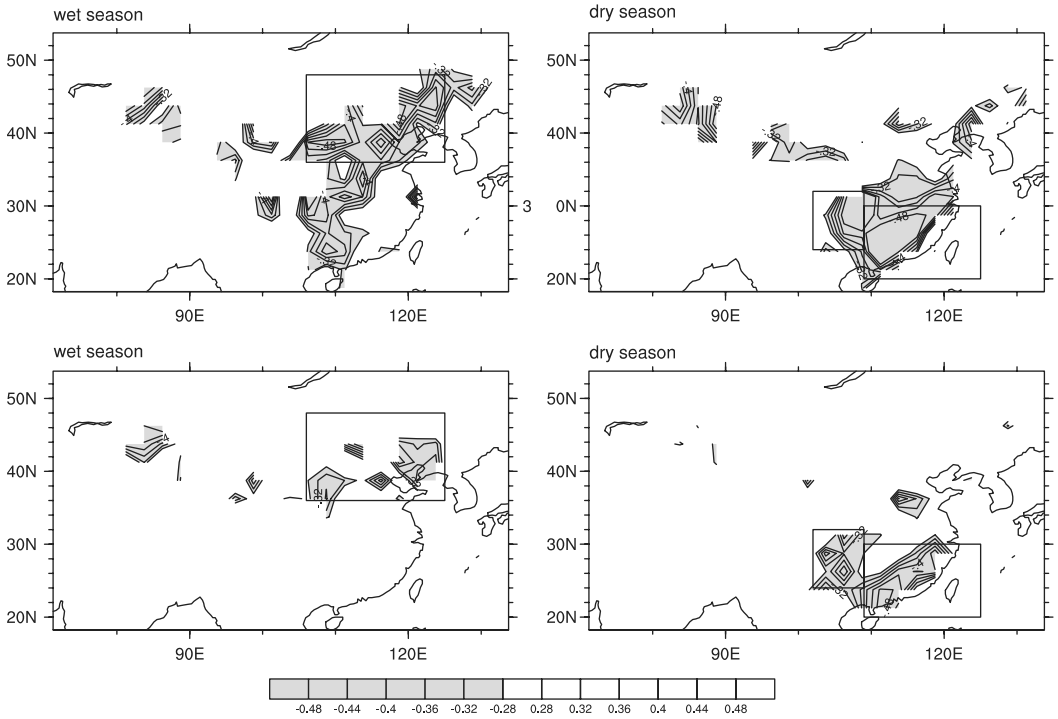

Figure 4. Correlation coefficients ($p = 0.05$) of the prolonged dry episode duration with precipitation in both the wet and dry seasons during 1958–2008 (the top panels), together with the PDSI in the period 1958–2005 (bottom). Significant correlations occurring over northeast China in the wet season and over southwest and southeast of China in the dry season are highlighted in boxes.

prolonged dry episode duration significantly increases over southeast China and the Yellow River valley, associated with a decrease in the number of dry spells. Further examination indicates that an increase in the duration of prolonged dry episodes over the southeast occurs in autumn (SON) and winter (DJF), but an increase over the Yellow River valley appears mainly in autumn (figure not shown).

Linear trends in precipitation amount show some similarity to those in the prolonged dry episode duration. Corresponding to the increase in the prolonged dry episode duration, the precipitation amount significantly decreases over the Yellow River valley in the wet season and over the southwest in the dry season. An increase in precipitation is related to a decrease in the prolonged dry episode duration, particularly over the Yangtze River valley in the wet season and over northwest of China in both seasons. However, the opposite signs of tendencies in the prolonged dry episode duration and precipitation amount do not always appear. An increase in the prolonged dry episodes is widespread over northeast China during the wet season and the southeast during the dry season, but significant negative trends in the precipitation amount over these regions are relatively sparse.

A systematic increase in the prolonged dry episode duration represents an enhancement of the risk of short-term droughts, which does not always correspond to a long-term decrease in precipitation. During the last 51 years, the duration of prolonged dry episodes has increased by about 5 days over northeast of China in the wet season, by about 10 days over the southeast and the Yellow River valley, and by 20 days over the south of Yunnan Province during the dry season.

Correlations of the prolonged dry episode duration in the wet and dry seasons with precipitation between 1958 and 2008 and with the PDSI during 1958–2005 are shown in Figure 4. The prolonged dry episode duration and precipitation are regridded on the grid of PDSI. Negative correlations are significant over northern China during the wet season and over southern China in the dry season. Highlighted areas in three boxes in Figure 4 show strong connections of an increase in the prolonged dry episode duration with a reduction in precipitation, together with a decrease in the PDSI. Negative correlations over northern China in the wet season are weak after removing long-term trends (figure not shown); however, negative correlations over south China in the dry season are almost same on inter-annual timescales.

Figure 5 shows the area-averaged prolonged dry episode duration over the highlighted regions (including northeast of China in the wet season and the southwest and southeast in the dry season) from 1958 to 2008, together with the corresponding precipitation and PDSI. Consistent with Figure 4, increasing tendencies in the prolonged dry episode duration are accompanied by the decline in precipitation and PDSI over the three regions. Compared to a gradual decrease in precipitation and the PDSI, a rapid increase in the prolonged dry episode duration occurring over the northeast during the wet season and the southeast during the dry season is suggestive of severe short-term droughts in the early twenty-first century. In particular, over southeast of China, the prolonged dry episode duration has been characterized

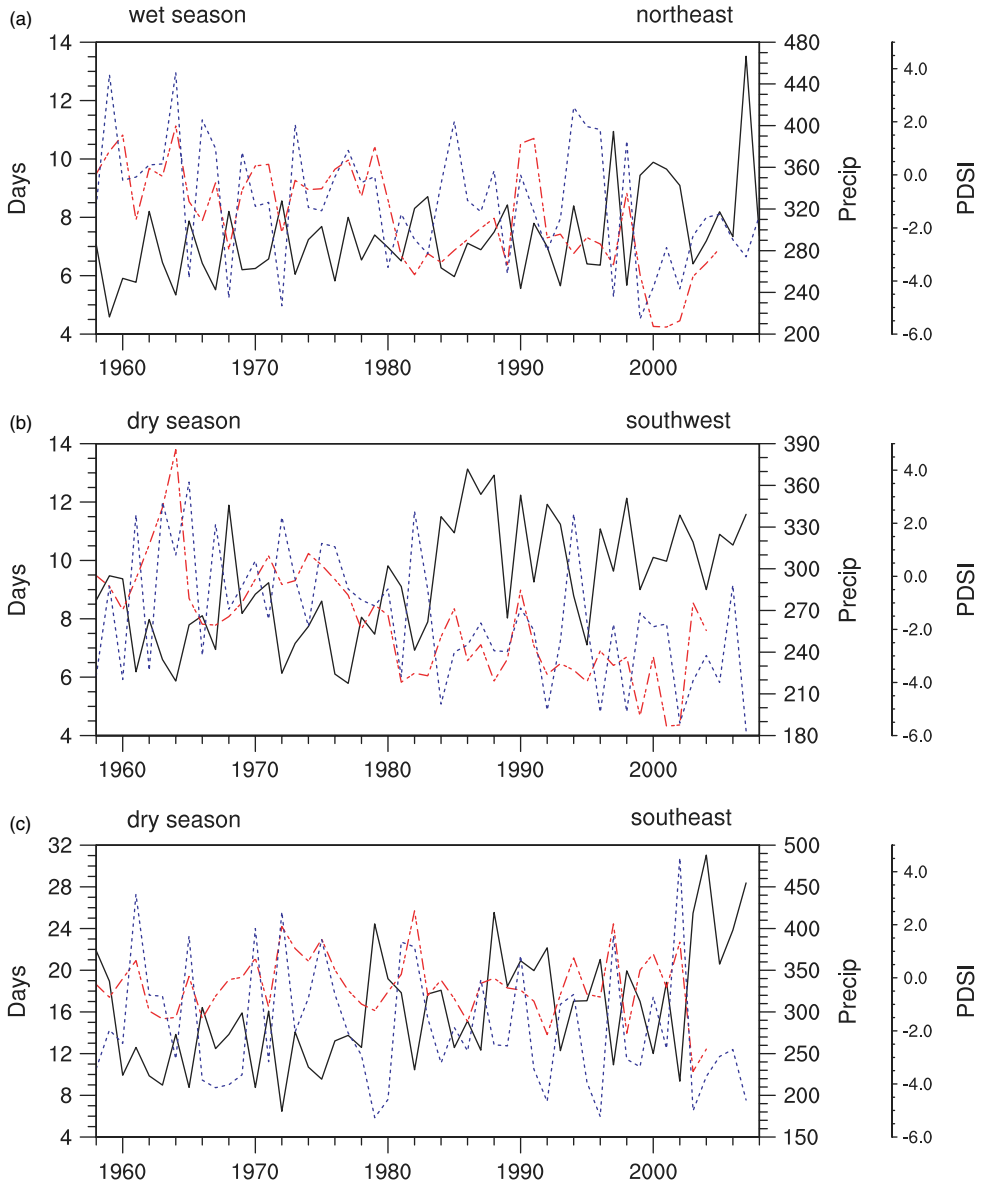

Figure 5. Solid lines show area-averaged prolonged dry episode duration over northeast China in the wet season, and southwest and southeast of China in the dry season (highlighted regions in Figure 4) from 1958 to 2008, together with the corresponding precipitation (dotted lines) and the PDSI (dashed lines). This figure is available in colour online at wileyonlinelibrary.com/journal/joc

by 20–30 days during the dry season in the recent years. A rapid increase in the prolonged dry episode duration over southwest of China in the dry season occurs in the mid of 1980s. On inter-annual timescales, negative correlations of the prolonged dry episode duration with precipitation/PDSI are statistically significant over the three regions with coefficients of −0.59/−0.45, −0.53/−0.16 and −0.66/−0.55, respectively.

3.2. Impact of precipitation frequency on prolonged dry episodes

A lack of precipitation is a major cause for the prolonged dry episodes and there is high negative correlation between the prolonged dry episode duration and precipitation amount over China in both the wet and dry seasons (Figures 4 and 5). According to Lei (2008), a lack of precipitation is associated with a reduction in precipitation frequency in summer. Naturally, a reduction in precipitation frequency can lead to an enhancement of the prolonged dry episode duration. Therefore, we further investigate connections between the prolonged dry episodes and precipitation frequency.

Figure 6 shows the leading mode of EOF analysis for precipitation frequency at 404 stations over China in both the wet and dry seasons from 1958 to 2008. The first leading mode of precipitation frequency in the wet season accounts for 15.3% of the variance. Distinguishing spatial and temporal features highlight the decline in rainfall frequency over northeast China in the last 51 years, consistent with the increasing trend in the duration of prolonged dry episodes (the left panel in the middle of Figure 3). After removing linear trends, the time series of EOF1 is significantly correlated with the area-averaged precipitation (−0.79), as well as the

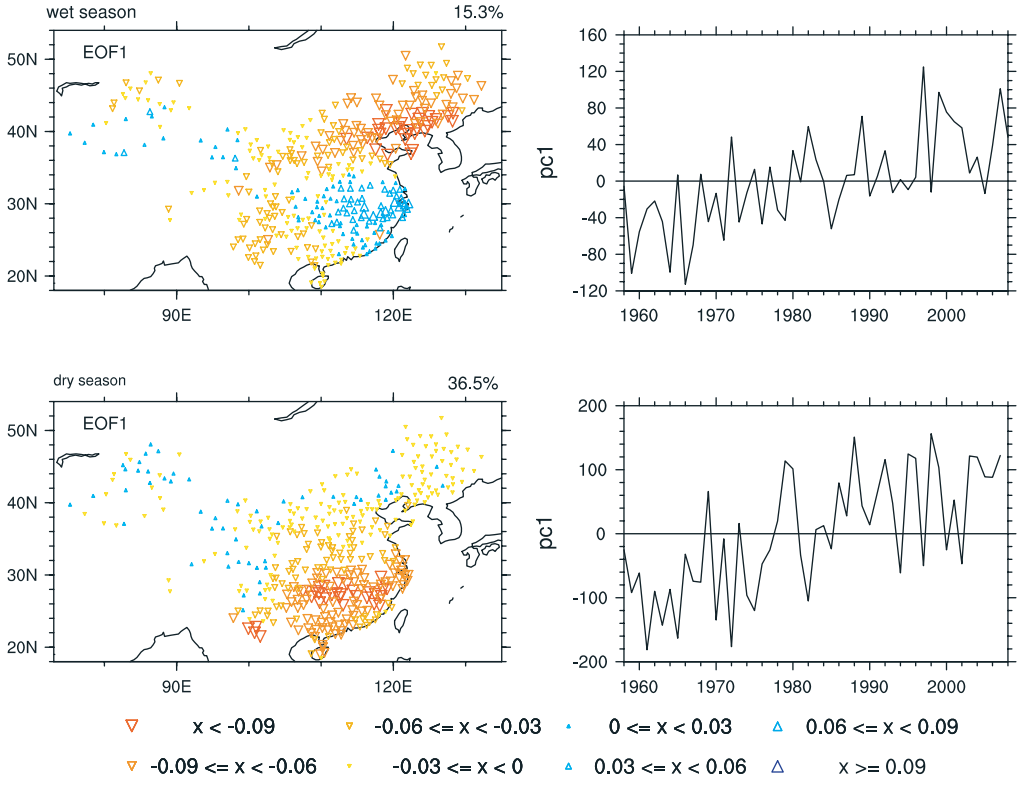

Figure 6. The first modes (EOF1 and PC1) of EOF analysis of precipitation frequency at 404 stations over China in the wet (the top panel) and dry seasons (bottom) from 1958 to 2008.

duration of prolonged dry episodes (0.74) and the PDSI (−0.44) over the northeast. High correlations suggest that the variability of the frequency, precipitation, and the prolonged dry episode duration are related on inter-annual timescales, in addition to the long-term trends associated with droughts over northern China in the wet season.

The leading mode of EOF analysis for precipitation frequency in the dry season accounts for 36.5% of the variance. The first spatial pattern and corresponding time series highlight a decrease in precipitation frequency over southern China, consistent with the increasing trend in the duration of prolonged dry episodes (the right panel in the middle of Figure 3). Area-averaged precipitation over both southwest and southeast of China is significantly correlated with the corresponding time series of EOF analysis on the inter-annual timescales, with correlation coefficients being −0.47 and −0.81 after removing linear trends. Coherent variability in precipitation frequency and the area-averaged prolonged dry episode duration is also evident with correlations of 0.27 and 0.69 over the two regions.

The leading modes of EOF analysis for precipitation frequency in both the wet and dry seasons highlight regional variability over northeast and southern China. Over these regions, enhancement of the prolonged dry episode duration is evident in each season during the last 51 years. High correlations among the time series of EOF analysis of precipitation frequency, the area-averaged precipitation and prolonged dry episode duration suggest that variations in precipitation frequency not only induce changes in precipitation amount but are also associated with variations in the prolonged dry episode duration on both inter-annual and long-term timescales. In view of the impact of disproportionate precipitation, prolonged dry episodes are likely to enhance the risk of droughts.

3.3. Impact of atmospheric circulation anomalies on prolonged dry episodes

Tao *et al*. (2009) suggest that the last winter drought in 2008/2009 over China was caused by the existence of quasi-stationary circulation systems in the mid-latitudes of the Northern Hemisphere. Persistent high pressure over the Tibetan Plateau and a trough over northeast Japan induce a prevailing northwesterly wind over China. Because of the stable trough in the mid-latitudes, the western Pacific subtropical high (WPSH) is strong but is mostly located at 10–20°N, suggesting less water vapour transportation into China.

We analysed large-scale circulation anomalies that might be associated with variability in the duration of prolonged dry episodes in the last decades. Figure 7 shows regression of 500 hPa geopotential height during summer (JJA) in the period 1958–2002 on the area-averaged prolonged dry episode duration over the northeast in the wet season (Figure 5(a)), together with the regression-removed linear trends. The circulation anomalies highlight patterns over the high-latitudes and widespread positive anomalies over the tropics. The signals over the tropics are associated with global warming trends, which are removed when linear trends are excluded. In the high-latitudes, anomalous circulation

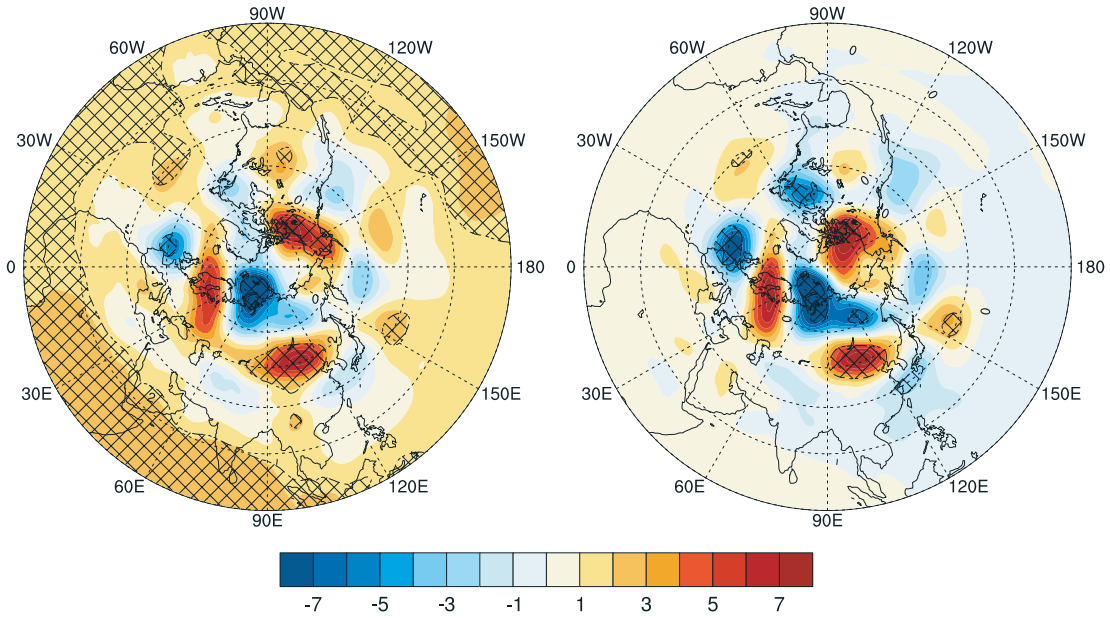

Figure 7. Regression of 500 hPa geopotential height in summer on the area-averaged prolonged dry episode duration over northeast China in the wet season (in Figure 5(a)), together with the regression-removed linear trends. Hatched areas represent significant ($p = 0.05$) regressions.

patterns persist on inter-annual timescales. A ridge over northeast Asia in summer is especially related to the prolonged dry episodes and droughts over northeast China, similar to Figure 4 in Zhou and Yu (2005). Dry conditions may develop in early spring when the ridge over Eurasia and trough over the Japan pattern induces northerly wind anomalies over northern China (figure not shown). Consistent with Tao *et al*. (2009), northerly wind anomalies reduce water vapour transport and cause prolonged dry episodes over northeast China in the wet season.

We estimated regressions of 500 hPa geopotential height in the preceding summer, autumn, winter, and spring seasons on prolonged dry episode durations over southern China in the dry season (Figure 5(b) and (c)). Regressions on the prolonged dry episode duration over the southwest are different from the counterparts for the southeast, suggesting independent mechanisms for the prolonged dry episodes over both regions during the dry season. Associated with the prolonged dry episode duration over the southwest, regressed high anomalies over the Tibetan Plateau and southern China in winter (DJF) are especially significant in Figure 8(a). After removing the linear trend, regressions still show significant signals over the Tibetan Plateau on inter-annual timescales.

Regressions of 500 hPa geopotential height based on the prolonged dry episode duration over southeast of China in the dry season suggest weak and localized circulation patterns over the surrounding areas. Figure 8(b) shows that the long-term negative trend in the prolonged dry episode duration over southeast China may be associated with a positive geopotential high over Tibet in autumn, but significant troughs over the South China Sea in autumn and over the Indo-China Peninsula in winter (figure not shown) may be important on inter-annual timescales.

4. Conclusions

Drought has been a common feature over northern China in the last two decades. Drought in northern China is particularly associated with a reduction in the rainfall amount during summer. Disproportionate changes in precipitation, such as a decrease in precipitation frequency, enhance the duration of dry spells. The prolonged dry episodes are likely an emerging tendency associated with droughts. The most severe drought in the half-century record, which affected a large area of China in the winter of 2008/2009, was characterized by a prolonged dry episode (around 100 days).

This study has focused on prolonged dry episodes described by the 90th percentile of dry spells without precipitation (0.1 mm/day) in the wet and dry seasons from 1958 to 2008 over China. The prolonged dry episodes have distinguishing spatial features in both seasons. The duration of prolonged dry episodes is spatially homogeneous in the wet season, but durations in the dry season are consistent with regional climate conditions with relatively large values over the arid and semi-arid regions (Figure 2).

Consistent with the trend in droughts over northern China during summer, the prolonged dry episodes in the wet season significantly increased in duration over the last 51 years, together with a reduction in precipitation and a decrease in the PDSI. During the dry season, significant positive trends in the duration of the prolonged dry episodes are widespread over southern China. Although significant negative trends in precipitation amount are not always consistent with trends in the prolonged dry episode duration, particularly over east of China (Figure 3), significant negative correlations are found between the prolonged dry episode duration, precipitation amount, and the PDSI over southwest and southeast

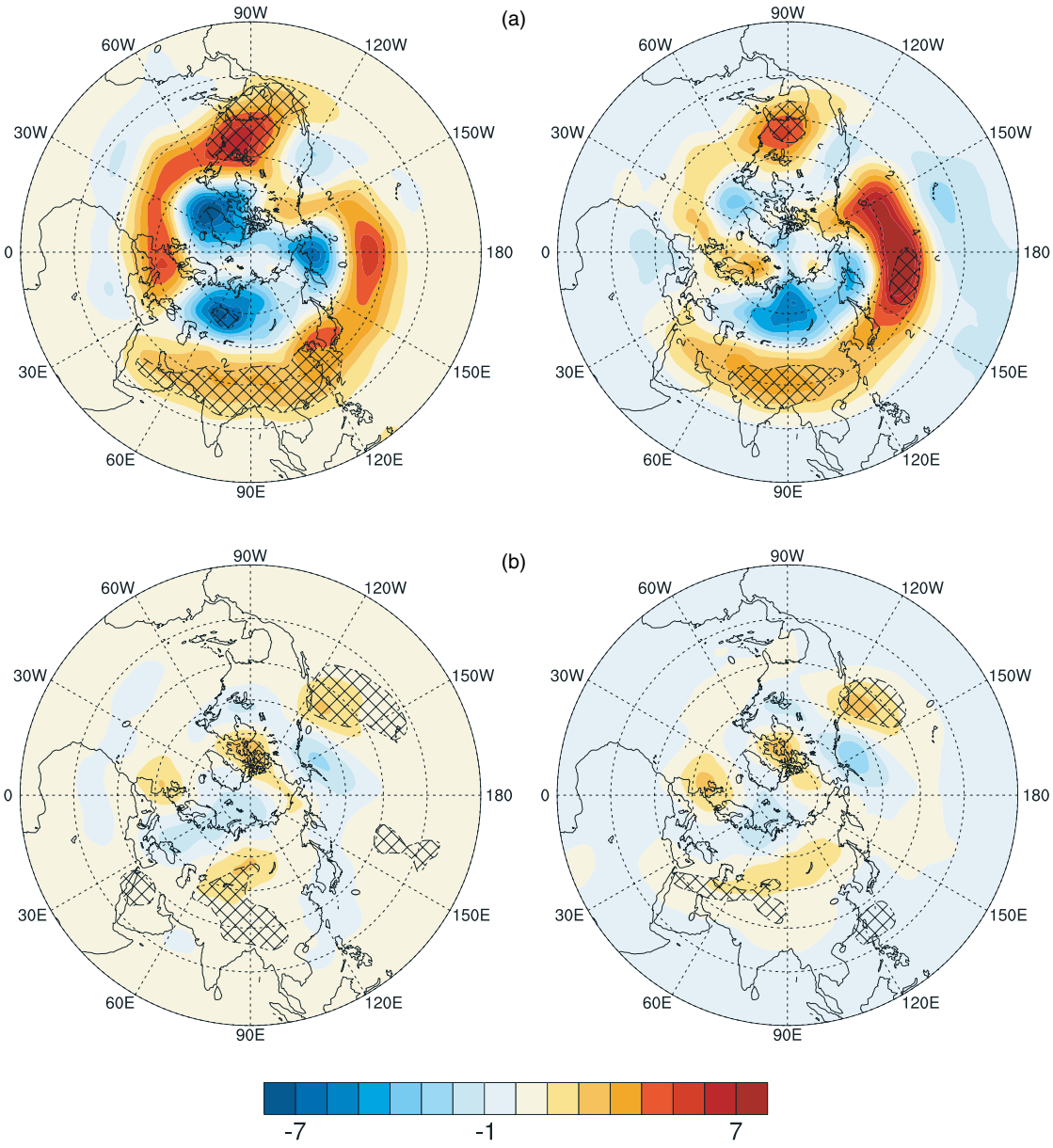

Figure 8. Regressions of 500 hPa geopotential height in winter (the top panels) and in autumn (bottom), based on the area-averaged prolonged dry episode duration in the dry season (left) and the counterparts removed linear trends (right) over southwest and southeast of China, respectively (in Figure 5(b) and (c)). Hatched areas represent significant ($p = 0.05$) regressions.

of China during the dry season (Figure 4). Over the vulnerable regions and in the particular season, positive trends in the prolonged dry episode duration suggest an enhancement of the risk of short-term droughts. In particular, the occurrence of the maximum prolonged dry episode duration within the early twenty-first century implies that extreme drought events are becoming worse over northern China during the wet season and over southern China in the dry season (Figure 5).

Further examination of precipitation frequency in both the wet and dry season indicates that a decrease in the precipitation frequency not only causes a decline in precipitation amount but also enhances the duration of prolonged dry episodes over northern China during the wet season and over southern China in the dry season (Figure 6). Disproportionate precipitation plays an important role in the prolonged dry episodes and associated droughts in a warming climate.

Compared to a deficiency in precipitation and the PDSI, the prolonged dry episode duration is a better index to represent both long-term and short-term droughts. Disproportionate precipitation changes, such as reduction in the precipitation frequency, are critical for inducing drought disasters by enhancing the duration of dry spells, with or without a significant decline in precipitation. Associated with variations in the duration of prolonged dry episodes over the key regions and, in particular seasons, ridges over the Eurasian continent are important circulation patterns that enhance atmospheric stability and induce northerly wind anomalies and reduction in moisture transport over regions of east China. However, further studies are needed to clarify mechanisms for

frequent occurrence of extreme cases of the prolonged dry episodes in the early twenty-first century.

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