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The day-to-day monitoring of the 2011 severe drought in China

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Abstract Dry/wet condition has a large interannual variability. Decision-makers need to know the onset, duration, and intensity of drought, and require droughts be monitored at a daily to weekly scale. However, previous tools cannot monitor drought well at this short timescale. The Palmer Drought Severity Index has been found dissatisfactory in monitoring because of its complexity and numerous limitations. The Standardized Precipitation Index (SPI) always asks for a timescale, and precipitation is averaged over the period of the scale. Because of this, the SPI cannot be used for short scales, e.g., several days, and what it tells is the overall drought situation of the period. The weighted average of precipitation (WAP) developed by Lu (Geophys Res Lett 36:L12707, 2009) overcomes the deficiency of the SPI; it does not require a timescale, and can provide the drought (and flood) extent of each day. Therefore, the WAP can monitor drought at scales from daily to weekly, monthly, and any longer scale, and is really "flexible and versatile for all timescales". In this study, the standardized WAP (SWAP) is used to monitor the 2011 drought over China. Drought swept the country during the year from north to south and from east to west. In spring, a once-in-a-fifty-year drought occurred over the Yangtze River basin and the southern region, causing serious shortage of drinking water for people and livestock, as well as tremendous losses in agriculture and the shipping industry. Results show that the SWAP, with its monthly mean plots, can well reproduce the seasonal shift of the 2011 drought across the country. The animation of daily plots demonstrates that the SWAP would have been able to monitor the day-to-day variation of the spring drought around the Yangtze River basin. It can provide the details of the drought, such as when the drought emerged over the region, how long it maintained there (though drought area may move back and forth with extension and contraction of the area), and when the drought relieved over the basin.

Keywords Drought monitoring · Day-to-day monitoring · Short timescale · At daily scale · The WAP index

1 Introduction

In 2011, severe droughts swept China from north to south and from east to west. Followed by the droughts in the last 2 years, there was drought again in the Southwest. Severe drought also plagued in North China, which is climatically a semiarid region. What is particularly abnormal in 2011 is that over the Yangtze River basin and the southern region, which is the major agricultural base and is generally in a wet condition, suffered its worst drought in the 50 years during the spring, with the lowest level of rainfall since 1961. The spring drought affected Jiangsu, Anhui, Jiangxi, Hubei, and Hunan provinces in the middle and lower reaches of the Yangtze River, with forty to 60 % less rainfall on average. Although cloud seeding was made to induce rain and the sluice gates of the Three Gorges were opened to minimize the impact, the severe drought still

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affected 34.8 million people, among which 4.2 million were short of drinking water. Drinking water was also short for 3.2 million farm animals. The crops on 3.7 million hectares of land were damaged or destroyed. The lingering drought made more than 1,300 lakes devoid of all water in Hubei province. The Yangtze River dropped to 3 m deep and its width dwindled by 50 m, which made thousands of shipping and fishing boats stranded in the heat-baked mud of the Yangtze littoral, and the vital Yangtze shipping industry had to be shut down.

To reduce losses caused by drought, reliable methods for monitoring and predicting drought are required. However, drought is difficult to monitor due to its complexity, which involves not only climatic factors but agricultural, economic, and human as well. A variety of studies have attempted to provide understandings, depictions, and definitions of drought (e.g., Dracup et al. 1980; Wilhite and Glantz 1985; Wilhite 2000; Redmond 2002), and numerous indexes have been developed to monitor drought (e.g., Palmer 1965; Gibbs and Maher 1967; Yevjevich 1967; Palmer 1968; Keetch and Byram 1968; Shafer and Dezman 1982; Bergman et al. 1988; Redmond 1991; Guttman 1991; Garen 1992; Kogan 1995; Heim 2000; Redmond 2000; Svoboda et al. 2002; Keyantash and Dracup 2002).

The Palmer Drought Severity Index (PDSI) had been thought the best drought index available and thus widely used (e.g., Palmer 1965; Alley 1984; Karl 1986; Heddinghaus and Sabol 1991; Guttman et al. 1992). It is based on the anomalies of the supply and demand components in the water balance equation. In addition to precipitation, the PDSI also needs temperature and other local hydrological quantities. Because of the complexity of the index and its numerous significant limitations, there have been dissatisfactions in the operational monitoring (e.g., Alley 1984; Kogan 1995; Guttman 1998). Hayes et al. (1999) pointed out that the PDSI, as well as some other drought indexes, have been used with limited success as operational drought monitoring tools and triggers for policy responses. The monitoring of the 1996 drought over the United States suggested that the PDSI values significantly lagged the drought-related impacts.

The lack of precipitation is the key factor to drought. The Standardized Precipitation Index (SPI), which uses only precipitation, has later been utilized as a main tool in the operational monitoring (e.g., McKee et al. 1993; McKee et al. 1995; Guttman 1999; Agnew 2000; Hayes et al. 2011). When examining the 1996 drought in the southern plains and southwestern United States, Hayes et al. (1999) illustrated that the SPI could have been used operationally to follow the progression of the drought from its development in late 1995 to its conclusion during the summer and fall of 1996, and might improve the timely identification of the emerging drought conditions.

Hayes et al. (1999) further hoped that the SPI could fill a void in the capability to monitor the onset and duration of droughts, and could be improved to monitor drought at shorter timescales, e.g., weekly scale. In order to better arrange mitigation activities, decision-makers need to know the drought situation in the present day and the drought tendency in the coming days (based on prediction of precipitation), rather than just knowing an averaged drought situation over a longer period. Thus, they do require drought be monitored at shorter scales, and it would be better the monitoring is in a day-to-day basis.

However, it may not be appropriate to apply the SPI in monitoring short timescales (e.g., 3 days), because of the inherent problem in the construction of the index. The problem is that the SPI always asks for a timescale, and gives a full and equal consideration to the precipitation days in the period of the scale, but does not consider the precipitation in the days before the period. The SPI, though may work well for long-timescale (e.g., one or several months) monitoring, may provide unrealistic results when applied to short-timescale (e.g., daily to weekly) monitoring. This will be explained in detail in Sect. 2. The SPI was claimed to be “flexible and versatile for all timescales”, but actually it is not. The droughts monitored by the National Climate Data Center with the SPI range from 1 to 24 months.

The weighted average of precipitation (WAP), developed by Lu (2009), can monitor drought at all timescales, from daily, weekly, monthly, to any longer scale. In this study, the standardized WAP (SWAP) is applied to monitor the 2011 severe drought in China. A brief introduction to the WAP and SWAP as well as the merit of this method over the SPI will be provided in Sect. 2. In Sect. 3, the plots of monthly mean SWAP are used to monitor the seasonal shift of the 2011 drought across the country. In Sect. 4, the animation of daily SWAP is presented to monitor the day-to-day variation of the spring drought around the Yangtze River basin, with examining how drought emerged, maintained, and relieved over the region.

Daily precipitation data from 2205 stations over the 61 years from 1951 to 2011 are used in this study. Quality control is made for the data. Those stations, which have too many missing data or whose sites have been changed, are not included.

2 The standardized WAP and its merit over the SPI

2.1 The WAP and the deficiency of the SPI

The WAP, proposed in Lu (2009), is based on the following simple physical model

$$\frac{df(t)}{dt} = -bf(t) + P(t), \tag{1}$$

with the consideration that the change of flood extent f is forced by precipitation P, as the supply, but dissipated by the demands of runoff, evapotranspiration, and percolation, with the overall effect of these demands being represented by the factor $-bf$, in which $b > 0$ measures the strength of the dissipation. Here we use "flood extent" since the role of precipitation in (1) is to "increase" the extent of "flood". This quantity can indicate both flood and drought, with the large and small values of f, respectively (see Figure 2 in Lu 2009).

After some mathematical processing (integrating the equation, discretizing the obtained integral for using daily precipitation data, and truncating the time series for practical use), the f is finally expressed explicitly with precipitation. Based on this derived f, the WAP is defined as

$$WAP \equiv \sum_{n=0}^{N} a^n P_n \Bigg/ \sum_{n=0}^{N} a^n, \tag{2}$$

where $a = \exp(-b\Delta t) < 1$ ($\Delta t = 1$ day) measures both the contribution and the decay effects of the earlier precipitation.

The WAP is calculated for each day. For a specific day, though WAP measures the flood extent of the day, it is a weighted average of the precipitation of the day (P_{o}) and all the earlier days (P_n). The weight decays with the number of the days past. Because of the decay effect, the N, the number of the earlier days whose precipitation data are needed to calculate the daily WAP, can be limited, depending on the value of the parameter a and the precision that is necessary.

The SPI can be compared with the WAP. It is actually, from (2), a special case of the WAP, when parameter a is taken as 1 and N varies. Since $a = 1$, the precipitation of the earlier days no longer has the decay effect. All the days in (2) are treated equally, and the weights are the same. Correspondingly, a time period, the $N + 1$ days, must be given so that the simple average of the precipitation could be made over the period. This is the reason why the SPI always needs a timescale.

While the SPI requires a timescale to do the simple average of precipitation over the time period, the precipitation before the period is not considered. This can be accepted if the timescale is sufficiently long, e.g., one or several months. However, if the scale is very short, e.g., several days, this may cause problem. For a 3-day period, for example, if there is no precipitation during the period, it may be regarded as a drought period when compared with historical records (the method used by the SPI); however, if there was a heavy precipitation just prior to the period, then the 3-day period actually remains the flood state.

Since the timescale of the SPI should be sufficiently long and a simply average is made for precipitation, what the SPI tells is merely the overall flood/drought situation of the period. Differently, the WAP considers the decay effect of the earlier precipitation (with $a < 1$), therefore no timescale is required. What the WAP tells is the daily flood/drought situation, although the precipitation of the earlier days is used. This is more realistic in physics, since in reality the "flood extent", as a quantity describing the objective hydro-meteorological state of the land–atmosphere system, should possess a value at every moment.

With the output of the daily WAP, the flood/drought situation of a week, month, and any longer period can be evaluated through simply averaging the WAP over the periods. So, the merit of the WAP over the SPI is that it can monitor drought (and flood) at all timescales, from daily to weekly, monthly, and any longer scale. The WAP is therefore really "flexible and versatile for all timescales".

Lu (2009) showed, both analytically and from data, that the identifications of drought and flood, especially the severe ones, are not very sensitive to the choice of the parameter a. The value of the parameter can be given, based on the overall bio-hydro-meteorological characteristics of the regional land surface-atmosphere system, with the knowledge of, e.g., how long it needs to take for the impact of a heavy rainfall to reduce to half. In this study, the parameter a is taken as 0.95, and the related N is taken as 60.

2.2 The standardized WAP

The SPI is constructed with the standardization approach, since the probability density function (PDF) of the precipitation the SPI uses generally follows the gamma (Γ) distribution (rather than the normal distribution). The WAP, which is a linear combination of precipitation, also follows the Γ distribution. We thus use the same standardization approach to convert the WAP to the standardized WAP (SWAP). For a given value of WAP, the principle of determining the corresponding SWAP is that the probability of having lower (or higher) values of SWAP (than the specific SWAP to be determined) should be equal to the probability of having lower (or higher) values of WAP (than the specific WAP given).

The SWAP can thus be obtained through solving, numerically, the equation

$$\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{SWAP} e^{-z^2/2} dz = \frac{1}{\beta^\gamma \Gamma(\gamma)} \int_{0}^{WAP} x^{\gamma-1} e^{-x/\beta} dx, \tag{3}$$

where $\beta > 0$ and $\gamma > 0$ are, respectively, the scale and shape parameters of the Γ distribution, and have been determined by using the Γ distribution to fit the PDF of the WAP data.

For a specific value of WAP, the right side of Eq. (3) is the probability of having lower values than this specific

WAP ($x < WAP$) under the Γ distribution. This probability is then used to determine the corresponding SWAP in the left side of Eq. (3), which is the probability of having lower values than this specific SWAP ($z < SWAP$) under the normal distribution. Like the SPI, the SWAP is negative for drought (and positive for flood). When dry condition becomes more severe, the SWAP becomes more negative. For practical use, thresholds can be given to classify the severities of drought. For different time scales, e.g., daily or monthly, the thresholds can be different.

3 The severe drought monitored with the SWAP

3.1 Variations of P, WAP, and SWAP

Precipitation anomaly, which is also an indicator of drought, is negative and strong over the Yangtze River basin and the southern region in the spring (Fig. 1a). In the summer, the anomaly becomes positive over the middle and lower reaches of the Yangtze River basin, while negative over the Southwest (Fig. 1b). What the precipitation

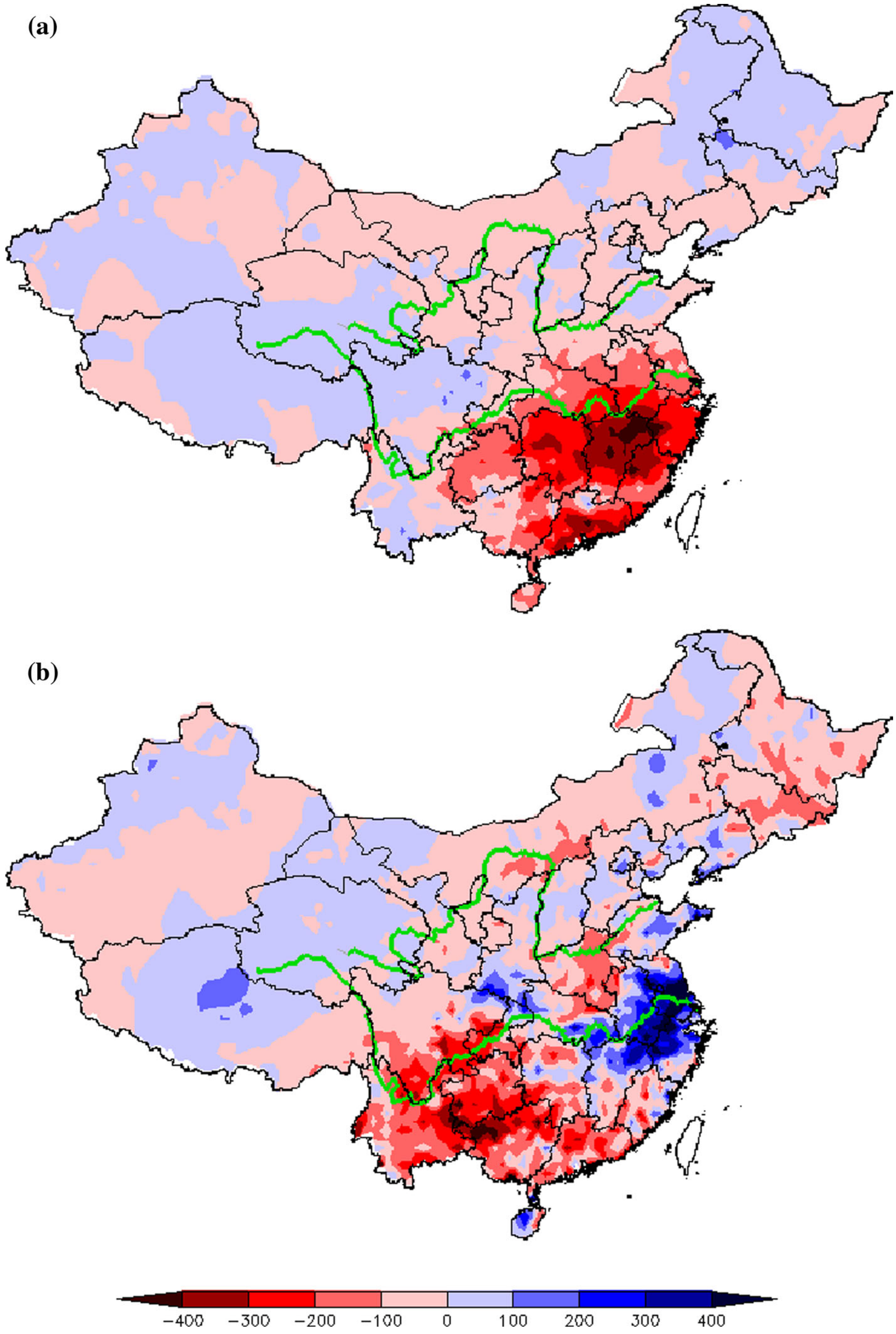

Fig. 1 Anomaly of the precipitation (mm) in **a** spring and **b** summer of 2011, relative to the averages of the springs and summers, respectively, during 1981–2010

anomaly provides here is the overall drought situation of a season. In addition to this, the details of the drought, such as the day-to-day variation of the drought area as well as the start and ending times of the drought over a specific area, are also required.

Figure 2 shows the day-to-day variations of the P, WAP, and SWAP during the first 6 months of 2011 and the climatic year, averaged over the middle and lower reaches of the Yangtze River basin. These plots can help understand how P is converted to WAP and how WAP is converted to SWAP, and examine the difference between P and WAP and the difference between WAP and SWAP.

The daily variation of precipitation (Fig. 2a) illustrates that during the first 5 months, the precipitation of 2011 is less-than-normal in most of the days. However, there are still days when precipitation is more-than-normal, and these days are roughly in a low-frequency mode. From this plot, it is difficult to gain the drought/flood information of each day, which is the purpose of this study, since it depends on not only the precipitation of the day but the precipitation of the earlier days as well. It is also hard to locate when the drought starts and ends. In June, there are more days when precipitation is more-than-normal, and the anomaly can be very large.

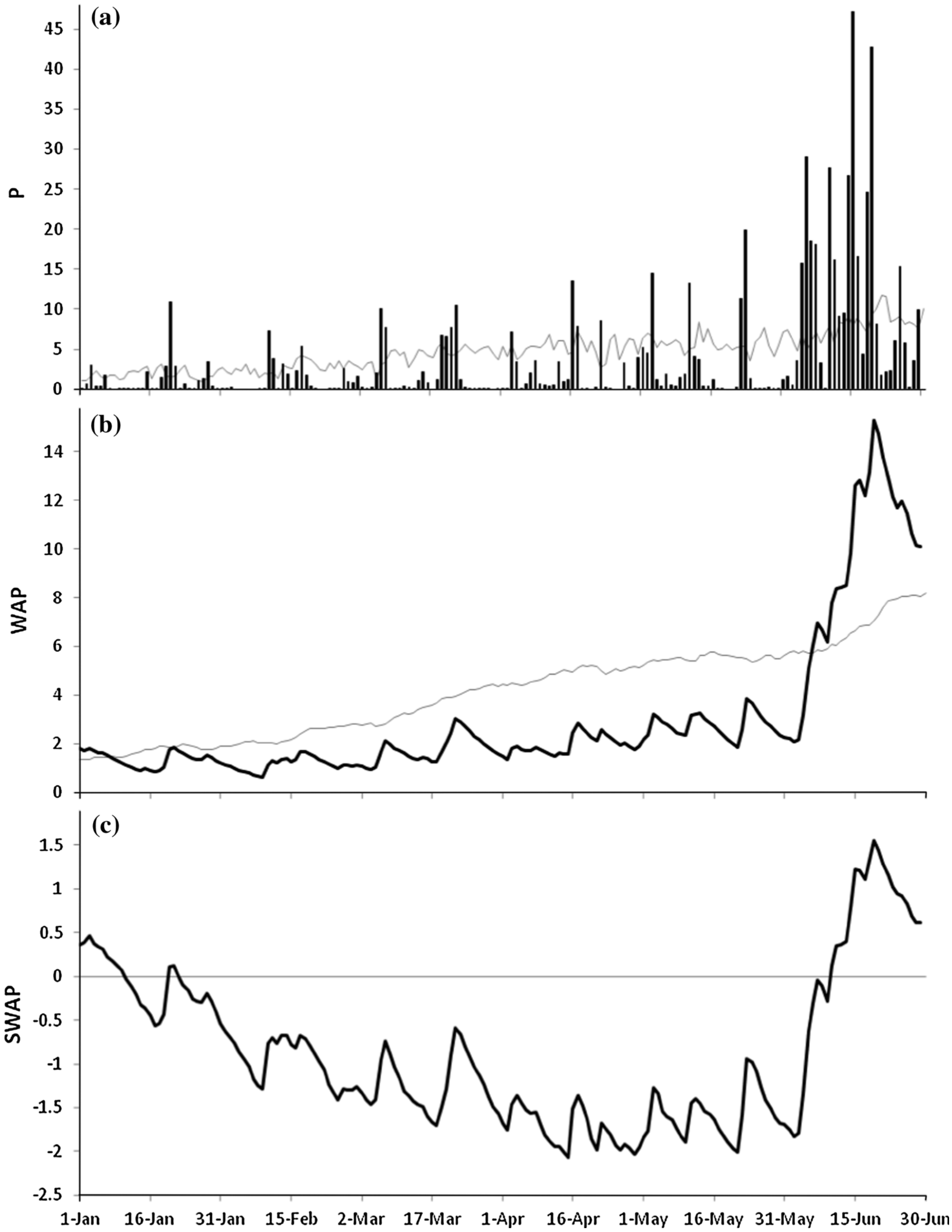

Fig. 2 **a** Daily precipitation (mm/day) in spring of 2011 (*bar*) and the climatic year (*curve*), and daily **b** WAP (mm/day) and **c** SWAP in spring of 2011 (*thick*) and the climatic year (*thin*), averaged over the 291 stations located within the middle and lower reaches of the Yangtze River basin (110–125°E, 27–32°N)

It is shown in Fig. 2b that after the conversion of the daily P to the daily WAP, the start and ending times of the drought can be readily identified. Starting from middle January, the WAP of 2011 is lower-than-normal in all of the days, including the entire spring, and the drought ends in early June. During the rest of June, the WAP is higher-than-normal, and it turns into a flood state over the region.

In Fig. 2c, which presents the daily SWAP that has been converted from the WAP, the daily flood and drought situation can simply be indicated by the positive and negative values of the daily SWAP. The drought revealed from the SWAP also starts in middle January and ends in early June. The drought is strong during the spring, especially in April and May.

3.2 Seasonal shift of the drought across the country

In addition to the visible events such as the impacts on the drinking water of people and livestock, crop harvest, and shipping industry, as mentioned in the introduction, the major reported events of precipitation during the year across the country include: (1) In the beginning of the year, severe meteorological drought occurred over the wide area of North China; (2) During the spring, severe meteorological drought maintained around the Yangtze River basin and the southern region; (3) Starting from early June, heavy rainfall appeared in the middle and lower reaches of the Yangtze River basin, which relieved the drought and caused flooding in some areas; (4) In the fall, drought formed over the Southwest. Though the visible events may belong to agricultural or hydrological droughts, their preliminary reason is the much-less-than-normal precipitation. The monitoring should have the capability to capture these visible and reported events.

Before doing the day-to-day monitoring, we would like to examine how drought area shifts seasonally across the country. The monthly means of the SWAP are calculated, with the daily output, and used to illustrate the seasonal change of drought. Figure 3 presents the plots of monthly mean SWAP for December 2010 and all the 12 months of 2011. Since we focus on drought, the positive values of SWAP are not highlighted and shown as blank in the plots. Severe drought maintained over North China, north of the Yangtze River, from late 2010 to January 2011. Drought moved southwards to the middle and lower reaches of the Yangtze River basin in February. In March, drought continued to stay along the basin, but with an increase in intensity. In April, drought became stronger, and extended from the Yangtze River basin to the entire South China. Then, the strong drought retreated back to the Yangtze River basin and the area immediately south of it in May. The drought around the Yangtze River basin started to relief in June because of the heavy summer rains. In July, drought disappeared over the middle and lower reaches of the Yangtze River basin, and started to form over the Southwest. In August, the drought became severe over the Southwest. Strong drought continued in the region in September. The drought over the Southwest was relieved in October, and almost disappeared in November and December. Comparing the geographical regions and intensities of the droughts in the Decembers of 2010 and 2011, we can observe a significant interannual variation.

The seasonal shift of the major drought area across the country revealed in Fig. 3 is fairly consistent with the above-mentioned visible and reported events, with severe drought moving overall from north to south and from east to west. This demonstrates the reliability of the SWAP as a new drought monitoring tool. In the following section, day-to-day monitoring will be made in more detail for the severe drought occurred during the spring over the Yangtze River basin and the southern region.

3.3 Day-to-day variation of the spring drought around the Yangtze

Through animating the daily plots of SWAP from January to June, the day-to-day variation process of the spring drought over the Yangtze River basin and the southern region, including the sub-periods before and after the drought, can be classified into the following 9 stages. Figure 4 presents the results of the daily monitoring, with each of the stages being represented by two plots.

Before moving to the Yangtze River basin, drought stayed for a fairly long time over North China, from late 2010 to February 9, 2011 (Fig. 4a). It then relieved for several days till February 17. Drought started to appear in the middle and lower reaches of the Yangtze River basin for 8 days from February 18 to 25 (Fig. 4b). The drought later moved southwards, and stayed for another 8 days from February 26 to March 5 with drought belt over the Yangtze River and the area immediately south of it (Fig. 4c). During the 15 days from March 6 to 20, the drought belt returned to the Yangtze River (Fig. 4d). It then extended again to the area immediately south of the Yangtze River, and stayed there for 11 days from March 21 to 31 (Fig. 4e). During the 15 days from April 1 to 15, drought continued to extend to the south, covering the entire South China, and the intensity became rather strong (Fig. 4f). During the later 16 days from April 16 to May 1, the drought area was separated into two parts, with one around the Yangtze River and one over South China, and they still had strong intensities (Fig. 4g). The drought area contracted gradually and moved back to the Yangtze, and maintained for over a month from May 2 to June 3 (Fig. 4h). Starting from June 4, the drought around the

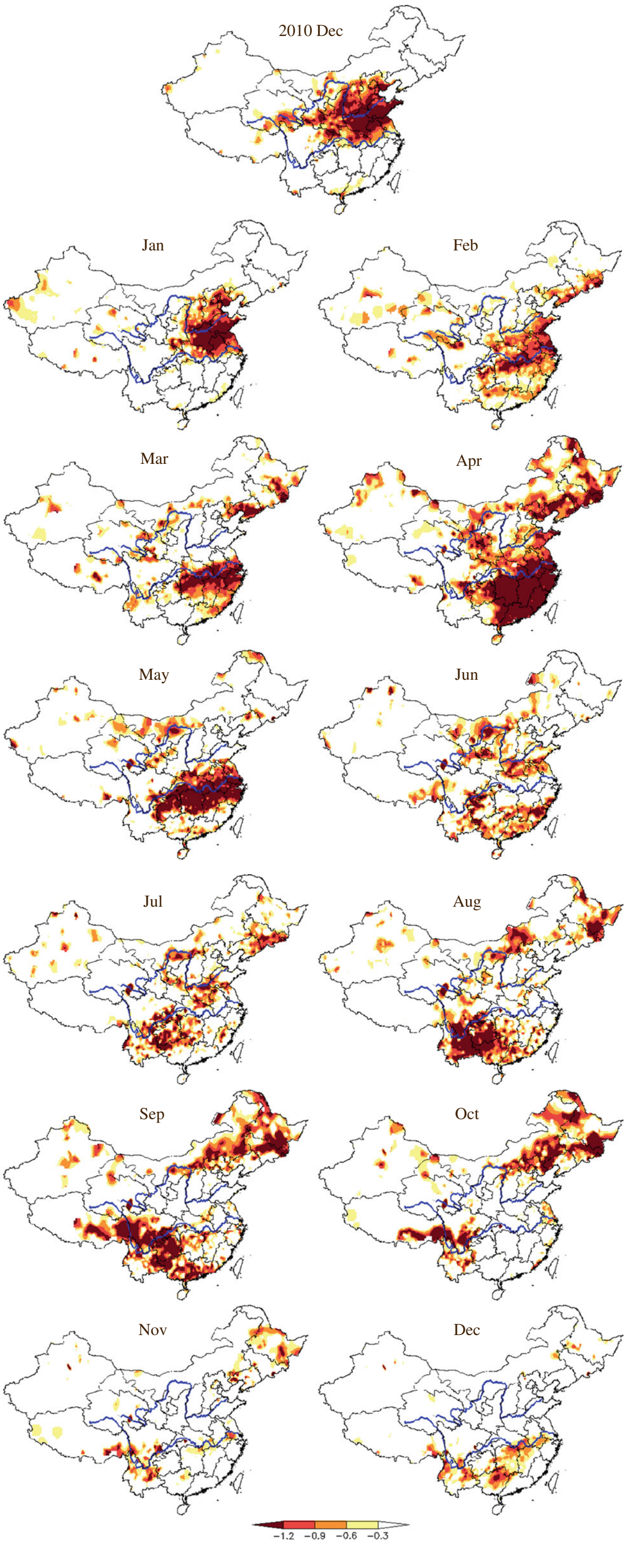

Fig. 3 Monthly mean SWAP for December 2010 and all the 12 months of 2011

middle and lower reaches of the Yangtze River basin disappeared due to the heavy rains in the early summer (Fig. 4i).

The above day-to-day monitoring suggests that although drought is relatively stable over the Yangtze River basin and the southern region during this spring, the drought area may have slight variations at a weekly scale. This reminds us that monitoring at a short scale, like the daily, is necessary, in order to obtain more detailed information on the onset, duration, intensity, and breaks of the drought, and examine how drought area moves north and south and how it extends and contracts. For each specific location, the drought may have breaks during the period. The serious impacts result from the persistence of the daily drought throughout the several months.

4 Summary and discussion

Corresponding to the large spatial change and interannual variability of precipitation, wet/dry condition varies greatly from place to place and from year to year. Decision- and policy-makers need to know the onset, duration, and intensity of drought, and require a reliable tool to monitor and detect droughts at a daily to weekly scale. However, the tools currently used are not so satisfied. The PDSI, though designed in a complex form to include more related factors, was found to have significant limitations and cannot provide timely identification of drought onset (Hayes et al. 1999). The SPI is, though simple, not appropriate to be used to monitor droughts at short scales, like the daily to weekly. It always needs a timescale, and can only tell the averaged drought situation over the period of the longer scale, hence is also not an effective tool for identifying the drought onset. The SPI is simply a mathematical index; it uses only the statistics of simple average, and there is no physics involved in the construction of the index.

The new index WAP, however, is physically-based, though it is simple and uses only precipitation either. It considers the overall effect of the demand components with a parameterization, which makes the drought and flood measured by this index have a memory of the earlier precipitation, with the influence of the earlier precipitation being decayed with time. Because of this decay effect, the WAP can eliminate the issue of the timescale, which is required by the SPI. It was demonstrated that the seasonal processes of the 1988 drought and the 1993 flood in the central United States can be well illustrated with the WAP (Lu 2009). The purpose of this study is to examine whether this new tool would have been able to monitor the 2011 drought over China and, especially, the spring severe drought over the Yangtze River basin and the southern region.

We use the monthly mean SWAP to monitor the seasonal shift of the drought across the country. Drought area

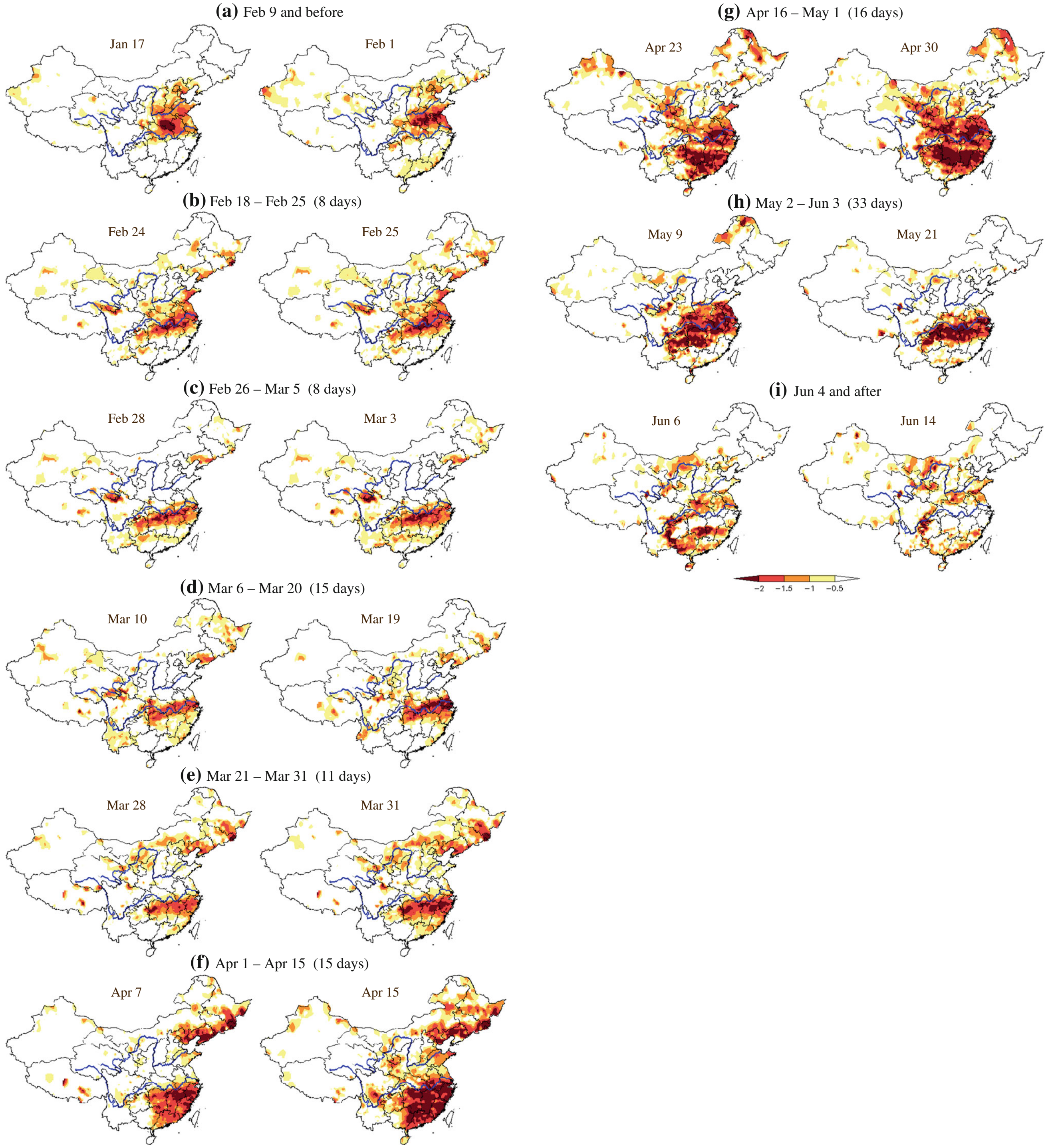

Fig. 4 Daily SWAP for the 9 stages of the spring drought over the Yangtze River basin and the southern region, including the development, maintenance, and relief of the drought, with each stage being represented by 2 plots

stayed in North China at the beginning of the year, then moved to the Yangtze River basin and the southern region in the spring, and later shifted to the Southwest in the fall, and this process is consistent with the visible impact events. The animation of daily SWAP is used to display the day-to-day variation of the spring drought and examine the details of the drought process. It can show when the spring drought emerged over the Yangtze River basin and when it relieved over the region. It also shows that while drought maintained stably over the Yangtze River basin during the season, the drought area may move back and forth, with extensions and contractions of the area. The SWAP is therefore an effective tool for drought monitoring, especially for the day-to-day monitoring, and holds the capability to tell reliably the onset, duration, and intensity of the drought over each specific area.

In addition to the success in drought monitoring, the SWAP may also be utilized to monitor floods of any timescale (even the hourly). It was hoped that the SPI might be able to monitor conditions leading up to a major flooding event (Hayes et al. 1999). The summer heavy rains starting from early June, which relieved the worst spring drought in the Yangtze River basin and caused flooding in some areas, can also be monitored when focusing on the positive values of the SWAP.

As a possible improvement in the future studies, the effects of evapotranspiration and snowmelt may be considered in the SWAP, which might be better for the monitoring of the droughts over the wet and cold regions. In addition to precipitation, the near surface air temperature may also be used for this purpose. Some parameterizations can be developed to include these effects. However, the temperature and precipitation may generally have a strong negative relation at the interannual timescale, and the effect of the temperature on drought might partially be represented by precipitation.

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