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The changing characteristics of drought in China from 1982 to 2005

Bin Li · Hongbo Su · Fang Chen · Jianjun Wu · Jianwei Qi

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Abstract Drought is one of the most detrimental natural disasters. Studying the changing characteristics of drought is obviously of great importance to achieve the sustainable use of water resources at river basin scales. In this paper, the satellite-based Vegetation Condition Index (VCI) and Vegetation Health Index (VH) were firstly calculated by using NDVI and brightness of the Global Vegetation Index dataset derived from Advance Very High Resolution Radiometer for China in growing seasons over 1982–2005. Then, the long-term VCI and VH data were employed to study the variation of droughts in the ten basins covering the whole country. The linear trend of each pixel showed that most parts of China were getting wetter in growing seasons, and the drought areas defined by the number of drought pixels have decreased in most basins. The increasing trend of basin averaged values of VCI and VH also indicates the whole country was generally getting wetter. At last, to better understand the two remote sensing drought indices, the response of the growing-season VCI and VH was compared to that of the Palmer Drought Severity Index and 6-month Standard Precipitation Index. Significant spatial variability of the relationship between the VCI, VH, and the station-based meteorological drought indices was shown, and some more closely related areas were found. The study will be useful for water resources management for each basin in the future.

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1 Introduction

Drought is considered to be one of the most serious natural hazards in the world. In recent decades, a lot of large droughts were reported on almost every continent and led to great loss. For example, droughts have cost more than $144 billion for the United States from 1980 to 2003. And for Europe, 1976, 1989, 1991, 2003, and 2005 are all drought-related years with large drought occurrence on the continent (Mishra and Singh 2010). Drought can be especially damaging for Asian countries because of the large population and the less developed economy. It is especially obvious for China and India (Mishra and Singh 2010).

Many studies regarding drought have been conducted in China recently. According to Yin et al. (2009), the aridity index significantly changed in the 1970s in China as a whole. Most regions showed a wetting trend. For example, an abrupt change occurred in 1986 for the arid Northwest China, the aridity index was getting significantly lower and the region was getting wetter since that year. Another study conducted by Wang and Huangyao (2008) found that the land surface in most regions of the Northeast China, particularly in Heilongjiang Province and eastern Jilin Province, showed wetting tendency from 1980 to 2005 due to an increase in precipitation and a decrease in potential evapotranspiration. The decreasing trend of potential evapotranspiration was attributed to the decreasing of wind speed and net radiation. The satellite-based drought indices were also used to study the changing pattern in China as a whole in recent decades. For example, based on the NOAA–AVHRR data, Qi et al. (2006) studied the spatio-temporal characteristics and occurrence frequency of droughts in China during 1982–2001 with the Water Deficit Index (WDI), the results indicated that Northwest China, North China, and South China showed high drought occurrence frequency in spring and winter. They also found a linear relationship between the drought occurrence frequency and the annual precipitation when the latter was less than 500 mm.

As drought studies have received so much attention, it is well developed especially in terms of monitoring methods or indices (Table 1). Generally, classical drought monitoring

Table 1 Several drought indices and their sources

Drought indices	Sources and reference
(1) Normalized Difference Vegetation Index (NDVI)	Tucker (1979) and Tucker and Choudhury (1987)
(2) Anomaly of Normalized Difference Vegetation Index (NDVIA)	Anyamba et al. (2001)
(3) Vegetation Condition Index (VCI)	Kogan (1995a, b, 1997)
(4) Temperature Condition Index (TCI)	Kogan (1995a, b, 1997)
(5) Vegetation Health Index (VH)	Kogan (1997)
(6) Palmer Drought Severity Index (PDSI)	Palmer (1965)
(7) Rainfall Anomaly Index (RAI)	Van Rooy (1965)
(8) Bhalme and Mooly Drought Index (BMDI)	Bhalme and Mooley (1980)
(9) Surface Water Supply Index (SWSI)	Shafer and Dezman (1982)
(10) Standardized Precipitation Index (SPI)	McKee et al. (1993, 1995)

approaches are calculated at the point scale using routine meteorological and hydrological observations. These processes are strongly limited in both space and time. In recent decades, with the rapid development of the remote sensing techniques, the satellite-based drought indices were also gradually proposed and used in both scientific studies and practical applications. Satellite remote sensing-based drought monitoring methods, as pointed out by Mishra and Singh (2010), "have proved to be a valuable source of timely, spatially continuous data with improved information on monitoring vegetation dynamics over large areas". Two of the most widely used remote sensing drought indices including the Vegetation Condition Index (VCI) (Kogan 1990, 1995a, b) and the Vegetation Health Index (VH) (Kogan 1995b, 1997, 2001) are all introduced in this study for analyzing the drought variation in China for the period of growing seasons.

As the Palmer Drought Severity Index (PDSI) and Standardized Precipitation Index (SPI) were two most widely used and representative meteorological drought indices, they were employed in this study. The PDSI is physically based and effective in reflecting the surface moisture conditions, for example, the soil moisture deficit or surplus (Zou et al. 2005; Dai et al. 1998, 2004). The Standardized Precipitation Index (SPI) was also used because it was based entirely on monthly precipitation accumulations and the standardized processes making the values comparable across different climatic and geographic regions. It can be calculated across different timescales so the lag response of monitoring indices to precipitation deficit and drought can be effectively reflected, which makes the SPI a widely used drought index (Mishra and Singh 2010).

Although drought detection has been widely conducted in different regions in China, most studies were based on a certain unique drought index or focused only on a certain region, province, or climatic zone. However, at the basin level, drought can greatly affect the water resources system and differ from one basin to another. Drought variation analysis by dividing the whole country into ten basins based on multiply indexes is very important for the government to get more reliable and comparable information and to have a better understanding of drought in China, which was also helpful to take effective measures for the sustainable development of water resource management. The aim of this study is to apply the satellite-based VCI and VH to identify the spatial pattern of the multi-year averaged drought index values, the linear temporal trend of drought at pixel and basin level, and the spatial variability of the coefficient of determination between VCI, VH, and meteorological drought indices during the growing seasons of 1982–2005 in China. Data and methodology used are described in Sects. 2 and 3, respectively. In Sect. 4, the detail results from the calculation are shown, and discussion and conclusions are presented in Sect. 5. This study will be of great significance for understanding the variations of droughts in growing seasons over the 1982–2005 periods in China and evaluating the two large global scientific datasets for drought detection across different climatic zones.

2 Study area and datasets

2.1 Study area

According to the Ministry of Water Resources and Zhai et al. (2010), China can be classified into ten river basins: the Songhuajiang River basin (Song), the Liaohe River basin (Liao), the Haihe River basin (Hai), the Yellow River basin (Yellow), the Huaihe

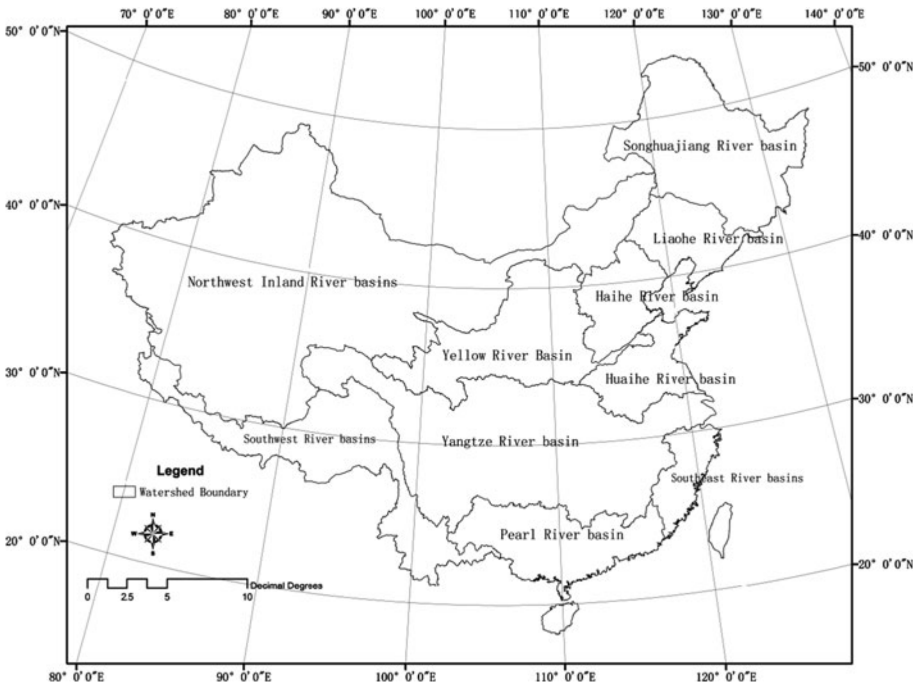

Fig. 1 Ten river basins of China

River basin (Huai), the Yangtze River basin (Yangtze), the Pearl River basin (Pearl), the Southeast River basins (SE), the Southwest River basins (SW), and the Northwest Inland River basins (NW) (Fig. 1). The ten river basins belong to different climatic zones and landscapes, making them prone to different levels of water shortages and drought. For example, many arid regions located in western and northern China are water limited and drought is directly related with less precipitation, while drought in some semi-humid or humid regions in eastern China is mainly controlled by East Asia monsoon. Studying the spatial and temporal trends of drought in China based on this geographic division becomes more and more important because different countermeasures are needed for each basin for efficient and sustainable water management.

2.2 Datasets

2.2.1 NOAA–AVHRR data

The Global Vegetation Index (GVI) dataset (ftp://orbit.nesdis.noaa.gov/pub/corp/scsb/wguo/GVIx/GVIx_VH_16km/) from 1982 to 2005 was used in this study. It was a standard NOAA product with a spatial resolution of 16 km and a temporal resolution of 7-day period, which was due to the maximum composite processing on the daily maps of GVI parameters. In this study, the similar maximum composite processing was employed to the 7-day composite product to generate the monthly data. This procedure reduced the atmospheric effects and minimized the cloud contamination in the monthly composite datasets (Kogan 1997, 2001).

2.2.2 SPI data

The global Standardized Precipitation Index (Guttman 1999) datasets were used in this study. The data library was obtained from the International Research Institute for Climate Prediction Lamont-Doherty Earth Observatory (Guttman 1999; http://iridl.ldeo.columbia.edu/SOURCES/.IRI/.Analyses/.SPI/). The available temporal resolution was 1-, 3-, 6-, 9-, and 12-month resolution, and in our study, the 6-month resolution was selected because of the lag-time effect. The spatial resolution was 2.5°, the same as the PDSI data.

2.2.3 PDSI data

The monthly PDSI data from 1982 to 2005 were retrieved from the IRI/LDEO Climate Data Library (Dai et al. 2004; http://iridl.ldeo.columbia.edu/SOURCES/.NCAR/.CGD/.CAS/.Indices/PDSI2004+.PDSI/). The long-term monthly air temperature and precipitation datasets were used to derive the monthly PDSI over global land areas from 1870 to 2005. The spatial resolution was 2.5° for each grid. These data have been widely used in many climate-related studies in the world. The details of the data can be found in Dai et al. (2004).

3 Methods: drought indices

3.1 SPI

The Standardized Precipitation Index (SPI), defined based on the concept of standardized precipitation and representing the number of standard deviations the cumulative precipitations deviates from the long-term average, was widely used in the world recently to characterize drought patterns (http://iridl.ldeo.columbia.edu/maproom/.Global/.Precipitation/SPI.html; McKee et al. 1993). The Pearson Type III distribution was usually used as the cumulative probability distribution based on the analysis of long-term precipitation datasets (Guttman 1999). Multiple timescales, such as 1-, 3-, 6-, 9-, 12-, and 24-month timescales, were applicable, making the index very important because different timescales suitable for different types of droughts (McKee et al. 1993, 1995; Guttman 1999). In this study, the 6-month timescale (April–September) was used based on previous analyses of the NDVI-SPI co-variability (Lotsch et al. 2003, 2005) and the relationship between the meteorological and satellite-based drought indices (Steven M. Quiring and Ganesh 2010).

3.2 PDSI

The Palmer Drought Severity Index (PDSI) was a meteorological drought index developed by Wayne Palmer (1965). Different from SPI, the calculation of PDSI was based on the water balance theory using data of precipitation, air temperature, and the available water content of soil. The index was suitable for reflecting the surface moisture conditions and analyzing the agricultural droughts (Dai et al. 1998, 2004). The standardized calculation process made the comparisons of results between different climatic zones possible. The PDSI was probably the most widely used drought index in the world, and it had been employed for assessing the drought variations in China successfully (Zou et al. 2005). More details can be found in references (Dai et al. 1998, 2004; Mishra and Singh 2010).

3.3 VCI

The Vegetation Condition Index (VCI) is one of the most widely used satellite-based drought indices in the world. Its calculation is based on the Normalized Difference Vegetation Index (NDVI) and represented as the NDVI anomaly relative to the long-term climatology average (Kogan 1995a, b, 1997; www.star.nesdis.noaa.gov). It is written as:

$$\mathrm{VCI} = 100(\mathrm{NDVI} - \mathrm{NDVI}_{\min})/(\mathrm{NDVI}_{\max} - \mathrm{NDVI}_{\min})$$

where NDVI, $\mathrm{NDVI}_{\max}$, and $\mathrm{NDVI}_{\min}$ are the smoothed monthly NDVI, multi-year maximum and minimum NDVI, respectively (Singh et al. 2003). The values from 0 to 100 represent the vegetation condition from severe drought stress to favorable conditions. As the calculation of VCI is strongly dependent on the vegetation conditions, the growing season is believed to be the most appropriate one to use VCI to monitor drought (Quiring and Ganesh 2010). In this study, the monthly VCI values were averaged to obtain the comparable VCI for growing season (April–September) in different years. More information can be found in references (Wang et al. 2001; Heim 2002; Ji and Peters 2003; Vicente-Serrano 2007).

3.4 VH

The Vegetation Health Index (VH) characterizes the vegetation health taking into account of both moisture and thermal conditions. It is based on the reflective and emissive properties of the vegetation and calculated using the combination of NDVI and Brightness Temperature (BT) (Jensen 2000). The VH is defined as:

$$\mathrm{VH} = \alpha * 100 * (\mathrm{NDVI} - \mathrm{NDVI}_{\min})/(\mathrm{NDVI}_{\max} - \mathrm{NDVI}_{\min}) + (1 - \alpha) * 100 \\ * (\mathrm{BT} - \mathrm{BT}_{\min})/(\mathrm{BT}_{\max} - \mathrm{BT}_{\min})$$

where α is a coefficient determining contribution of the two parts and was generally given a value of 0.5. NDVI, $\mathrm{NDVI}_{\max}$, $\mathrm{NDVI}_{\min}$, BT, $\mathrm{BT}_{\max}$, and $\mathrm{BT}_{\min}$ are the smoothed monthly NDVI or BT values and their maximum and minimum for 1982 to 2005. Similar to VCI, the VH also ranges from 0 to 100, quantifying severe drought to favorable conditions (Kogan 1997). For the same reason as VCI, only growing season (April–September) VH was calculated. More details can be found in references (Kogan 1997, 2001; www.star.nesdis.noaa.gov).

3.5 Statistical methods

The simple linear regression model (LM) and the rank-based nonparametric Mann–Kendall statistical test (MK) were used in this study. The output of the trend analysis using the LM method is map of r-values and slopes. This LM technique provides a simple yet robust way to analyze and discover trends. Using this model, the resulting inclination and intercept values at the pixel level can easily be compared (Fensholt et al. 2009) The MK method is widely used in climate-related studies due to its robustness, especially for abnormally distributed data. At the 95 % confidence level, the absolute value of the M–K statistics Z larger than 1.96 means significant increasing or decreasing trend.

4 Results

4.1 The spatial pattern of drought

The spatial pattern of the multi-year averaged values of VCI and VH is shown in Fig. 2a, b. The Northwest Inland River basins, the middle reach of the Yellow River basins, the southeastern Tibet Plateau, and the juncture regions between the upper and middle reaches of the Yangtze River basin have low values, while the upper reaches of the Yellow River basin and the Yangtze River basin, the Songhuajiang River basin, and the Huaihe River basin have high values. It should be noted that there are discrepancies in results found using VCI and VH (e.g., between Fig. 2a, b; over the eastern Yangtze River basin, Southeast River basin and Pearl River basin). The discrepancies should mainly be caused by the difference of the calculation methods of VCI and VH. The VCI is based only on the vegetation, and the VH takes both vegetation and temperature into account. In Fig. 2, it is noted all the eastern Yangtze River basin, the Southeast River basin, and Pearl River basin are located in relative warm and wet environment. And the water-energy condition is reflected in our drought indices. Other important factors, such as underlying landscape, human activities, etc., all have an impact on the drought condition to some extent.

4.2 The linear temporal trend of drought at each pixel

Linear temporal trends of VCI and VH were estimated by ordinary least squares at each pixel. In Fig. 3, the negative pixel value indicates a drying trend, and the positive pixel value indicates a wetting trend. The drying trend mainly occurred in western Songhuajiang River basin, eastern Northwest Inland River basins, the Yangtze River basin, and eastern Pearl River basin. The largest value was 3.81 year^{-1} for VCI and 2.6 year^{-1} for VH. Generally, most parts of China were getting wetter, and this trend was more obvious in southwestern Northwest River basins, western Southwest River basins, the middle reach of the Yellow River basin, and the western Liaohe River basin. The largest value was 3.98 year^{-1} for VCI and 2.90 year^{-1} for VH.

4.3 The linear temporal trend of drought area for each basin

As two widely used drought indexes, values of VCI and VH were generally classified into different groups to represent extreme drought, severe drought, moderate drought, middle drought, and no drought (Kogan 2001). This paper focus on the relative serious droughts in China over the study period to identify the most drought stressed areas. So the extreme

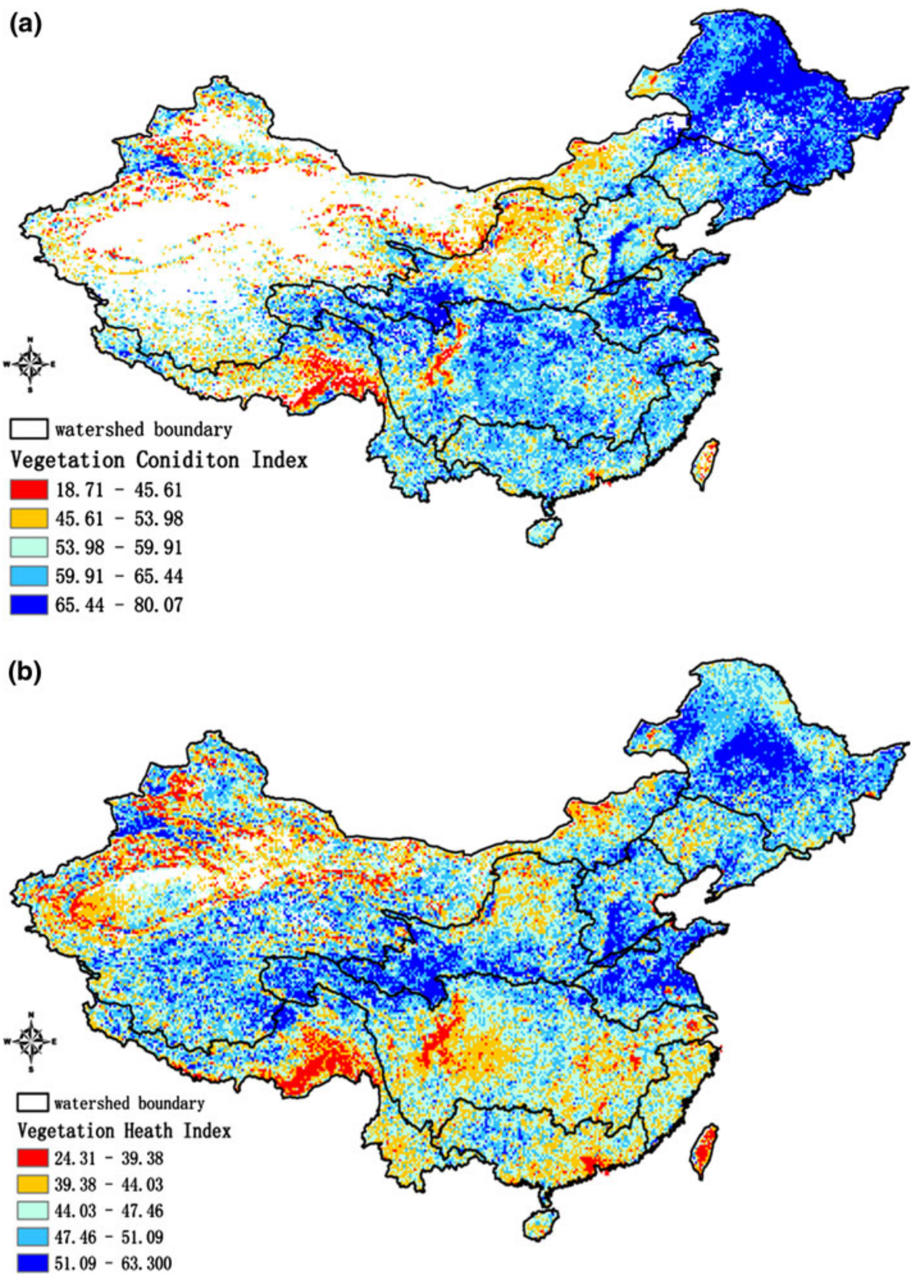

Fig. 2 **a** Spatial distribution of multi-year averaged VCI. **b** Spatial distribution of multi-year averaged VH

drought (VCI,VH < 15) and severe drought (15 < VCI,VH < 30) were chosen to be further investigated.

Changes in the total serious dry areas (VCI, VH < 30) during 1982–2005 vary over different regions of China. The grid cells with values less than 15 represent extreme

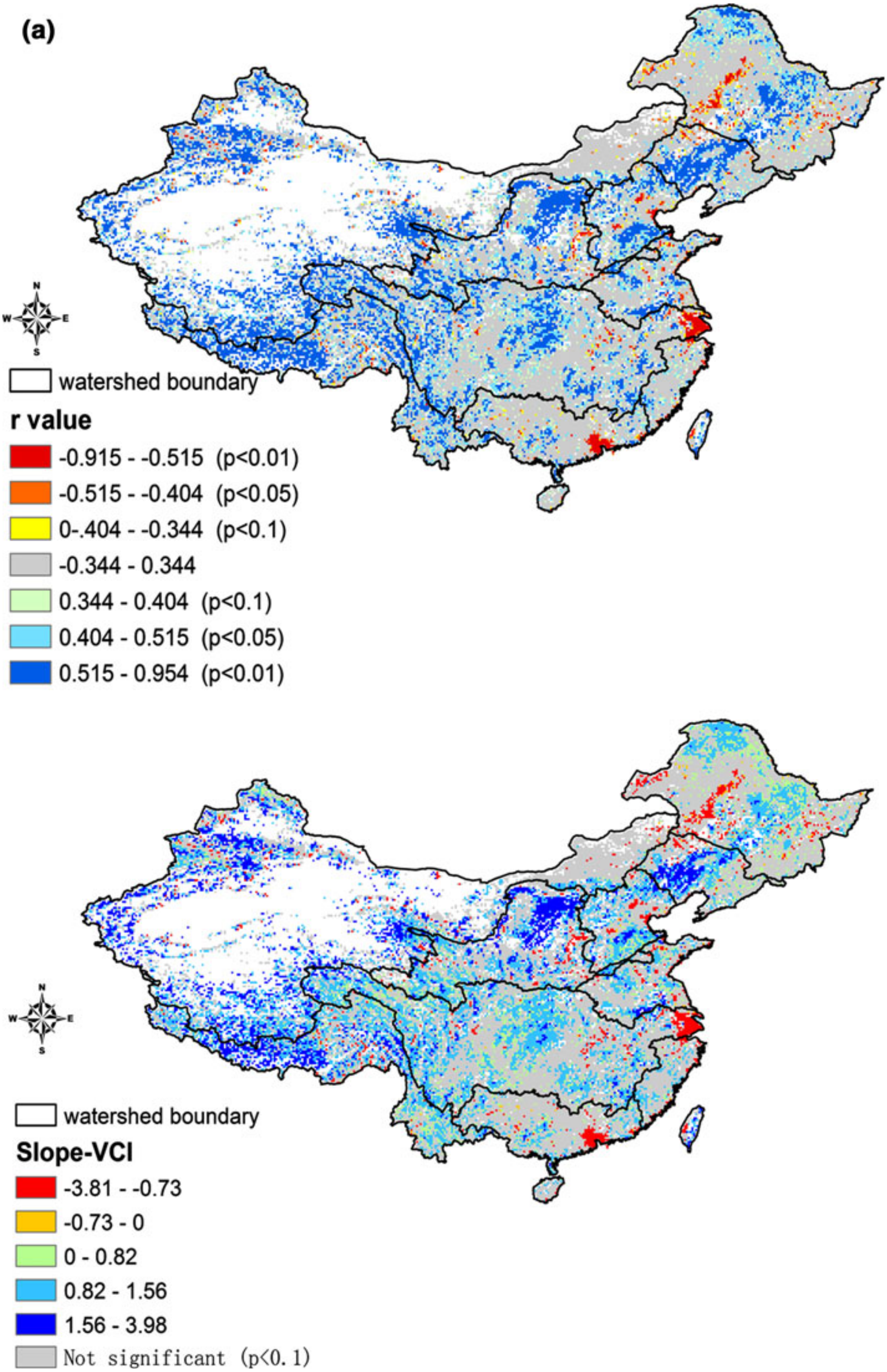

Fig. 3 **a** The linear temporal trend of VCI at each pixel over 1982–2005. **b** The linear temporal trend of VH at each pixel over 1982–2005

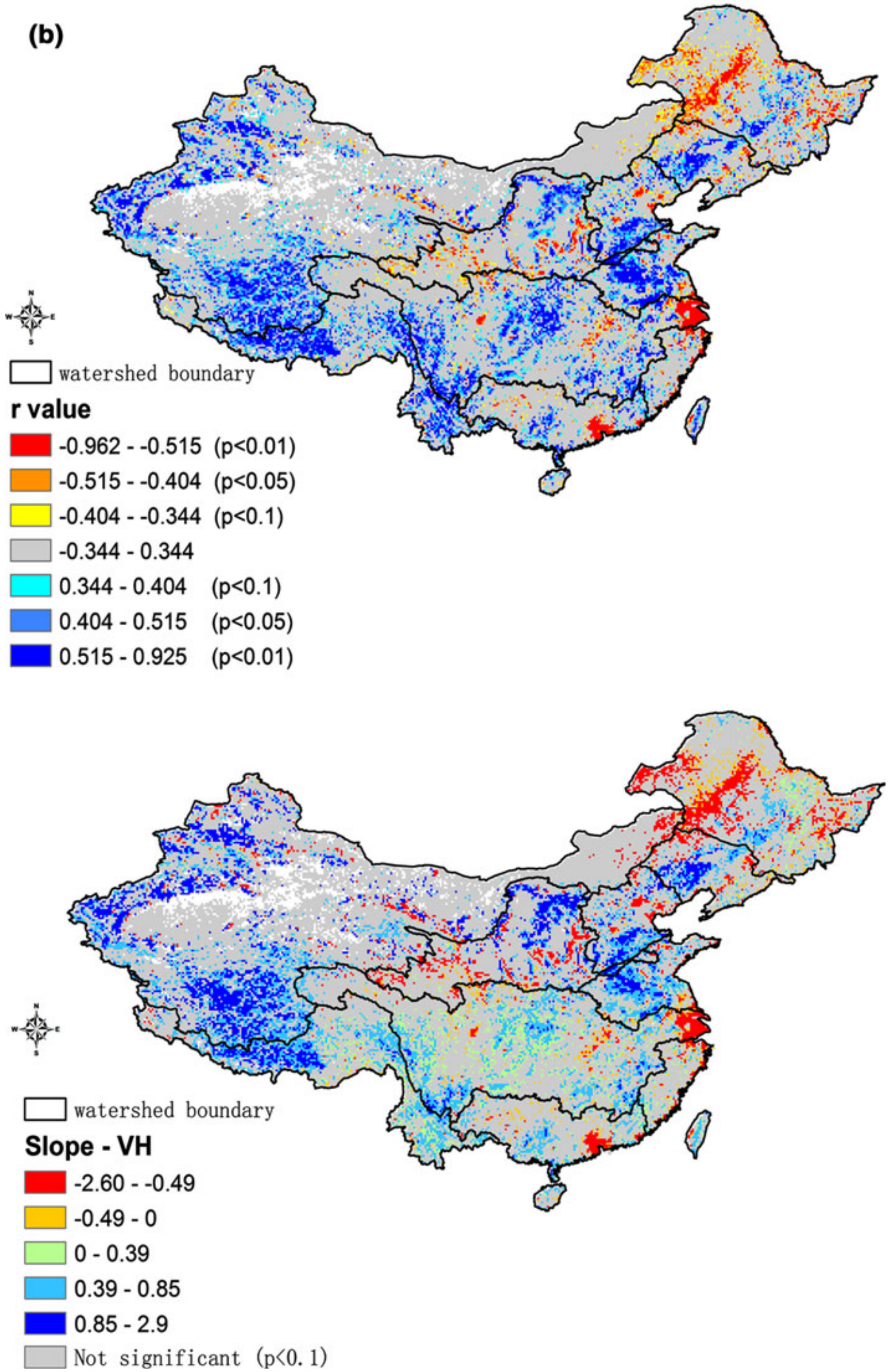

Fig. 3 continued

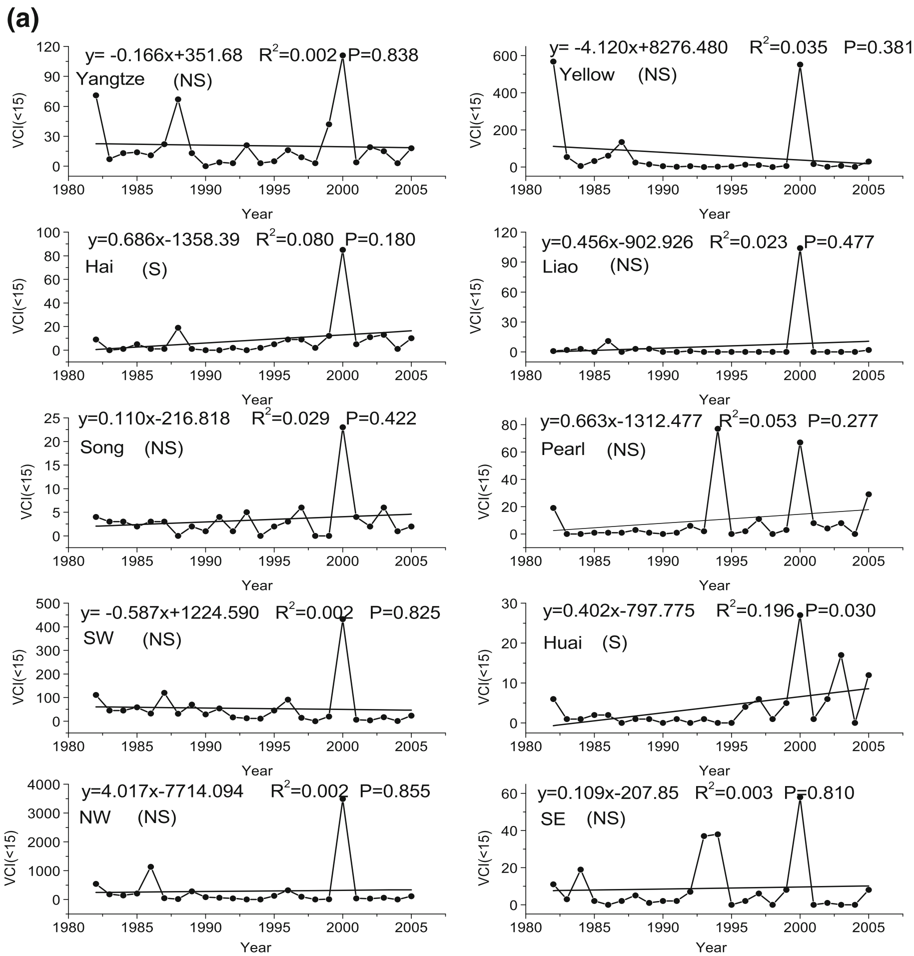

Fig. 4 **a** Trends of the number of VCI pixels with values less than 15. (S) indicates the trend is significant at 95 % confidence level by the MK test, while (NS) indicates not significant at this confidence level. **b** Trends of the number of VH pixels with values less than 15. (S) indicates the trend is significant at 95 % confidence level by the MK test, while (NS) indicates not significant at this confidence level. **c** Trends of the number of VCI pixels with values between 15 and 30. (S) indicates the trend is significant at 95 % confidence level by the MK test, while (NS) indicates not significant at this confidence level. **d** Trends of the number of VH pixels with values between 15 and 30. (S) indicates the trend is significant at 95 % confidence level by the MK test, while (NS) indicates not significant at this confidence level

drought and were analyzed firstly. For VCI (Fig. 4a), the Yangtze River basin, the Yellow River basin, and the Southwest River basins showed a slight decreasing tendency with trends of 0.166 year^{-1} ($r^2 = 0.002$, $p = 0.838$), 4.12 year^{-1} ($r^2 = 0.035$, $p = 0.381$) and 0.587 year^{-1} ($r^2 = 0.002$, $p = 0.825$), respectively, while all other basins increased. For VH (Fig. 4b), downward trends of dry areas occurred in the Huaihe River basin, the Yellow River basin, the Southwest River basins, and the Northwest Inland River basins. A p value of 0.05 is used as a threshold to determine whether the formulation is significant or not.

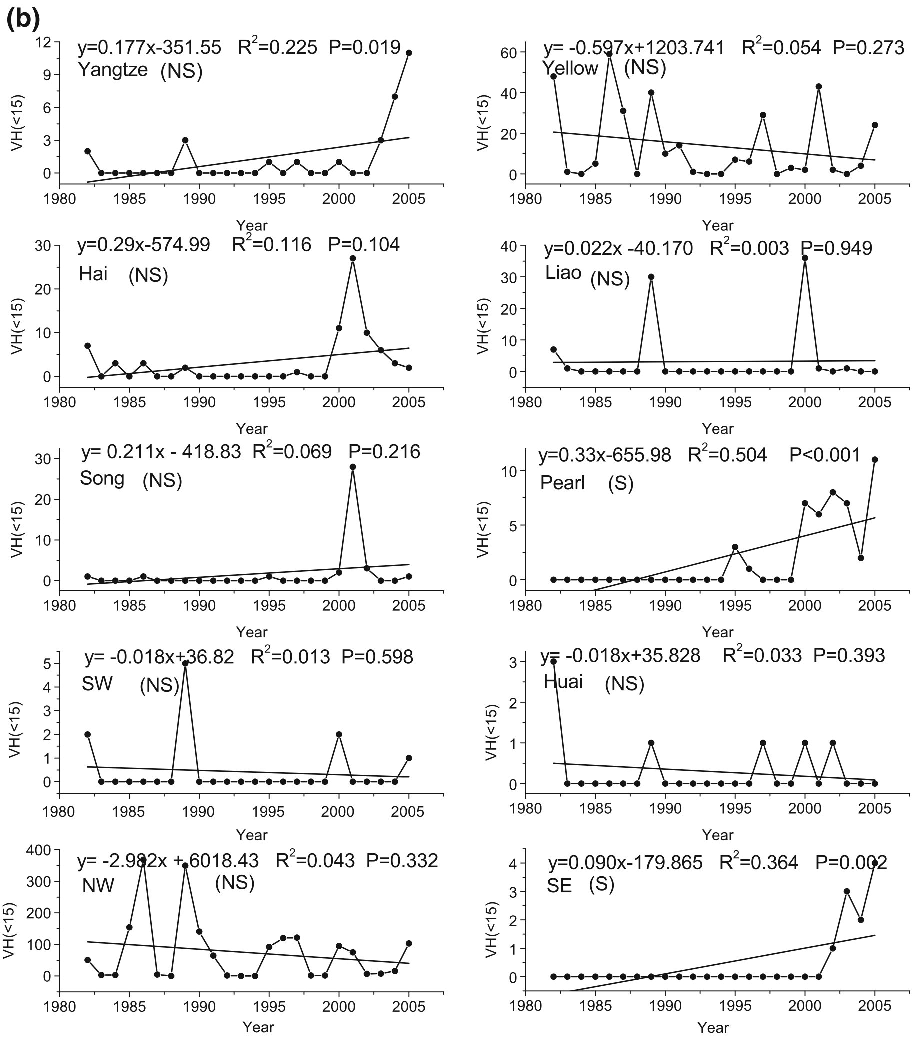

Fig. 4 continued

The grid cells with values less than 30 represent severe drought. For VCI (Fig. 4c), the number of this kind of cells decreased in all the basins except for the Songhuajiang River basin, which increased weakly with a rate of 0.076 year^{-1}. Significant decreasing trends were found in the Yellow River basin, the Liao River basin, the Northwest River basins, and the Southwest River basins. The slope values were -17.452 year^{-1} ($r^2 = 0.176$, $p = 0.041$), -4.389 year^{-1} ($r^2 = 0.155$, $p = 0.057$), -77.190 year^{-1} ($r^2 = 0.222$, $p = 0.020$), and -20.936 year^{-1} ($r^2 = 0.419$, $p = 0.001$) for each of them.

For VH (Fig. 4d), the decreasing trend of the severe drought areas calculated by the numbers of the grid cells with values less than 30 is showed. Only the Songhuajiang River basin, the Yangtze River basin, the Southeast River basins, and the Pearl River basin

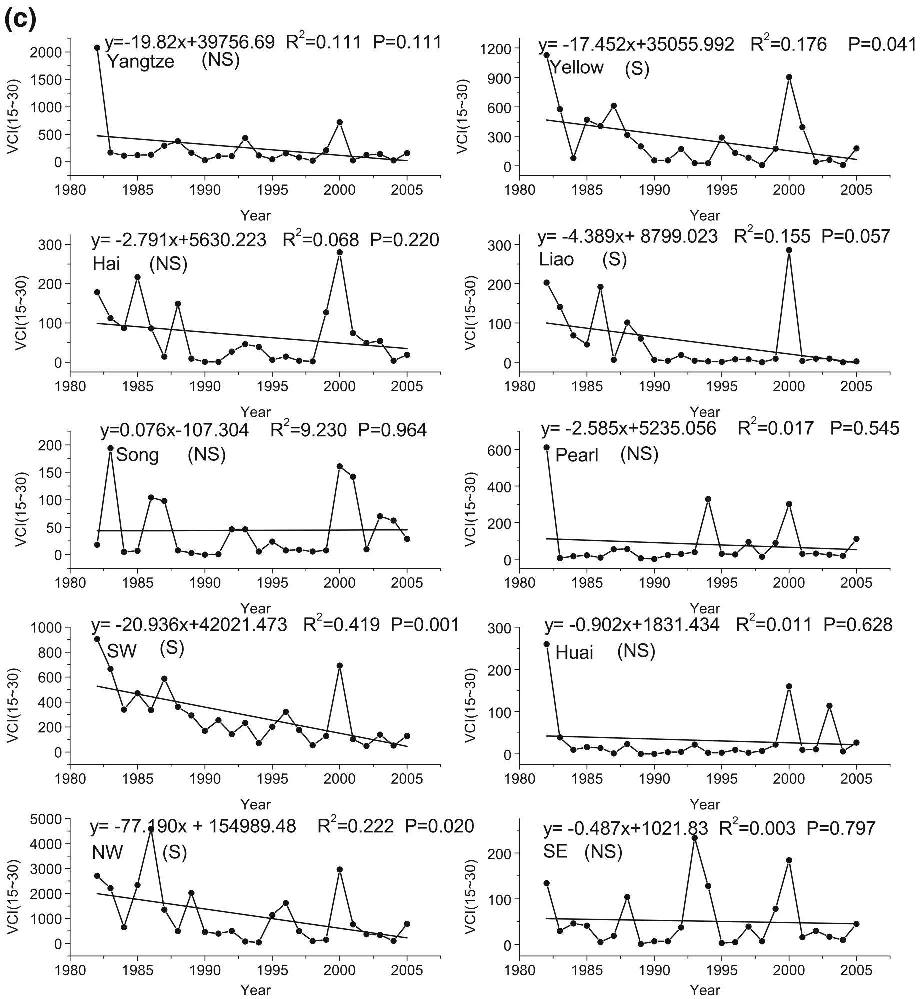

Fig. 4 continued

increased while all other basins decreased. Among the increased four basins, only the Southeast River basins increased relatively significantly with a rate of 1.602 year^{-1} ($r^2 = 0.178$, $p = 0.040$).

Although the number of extreme drought cells for both VCI and VH increased in most basins, the total drought areas decreased in most regions. The reason is that the number of grid cells with values less than 15 was quite small compared to the total number of drought cells for each basin. The drought areas were generally determined by the severe drought (15 < VCI, VH < 30) cells, not the extreme drought (<15) cells, because the number of the former was much larger than the latter in all basins (Table 2). The shrinking trend of the drought areas was consistent with the trends shown by Fig. 3, which clearly indicated the general wetting trend in the whole country.

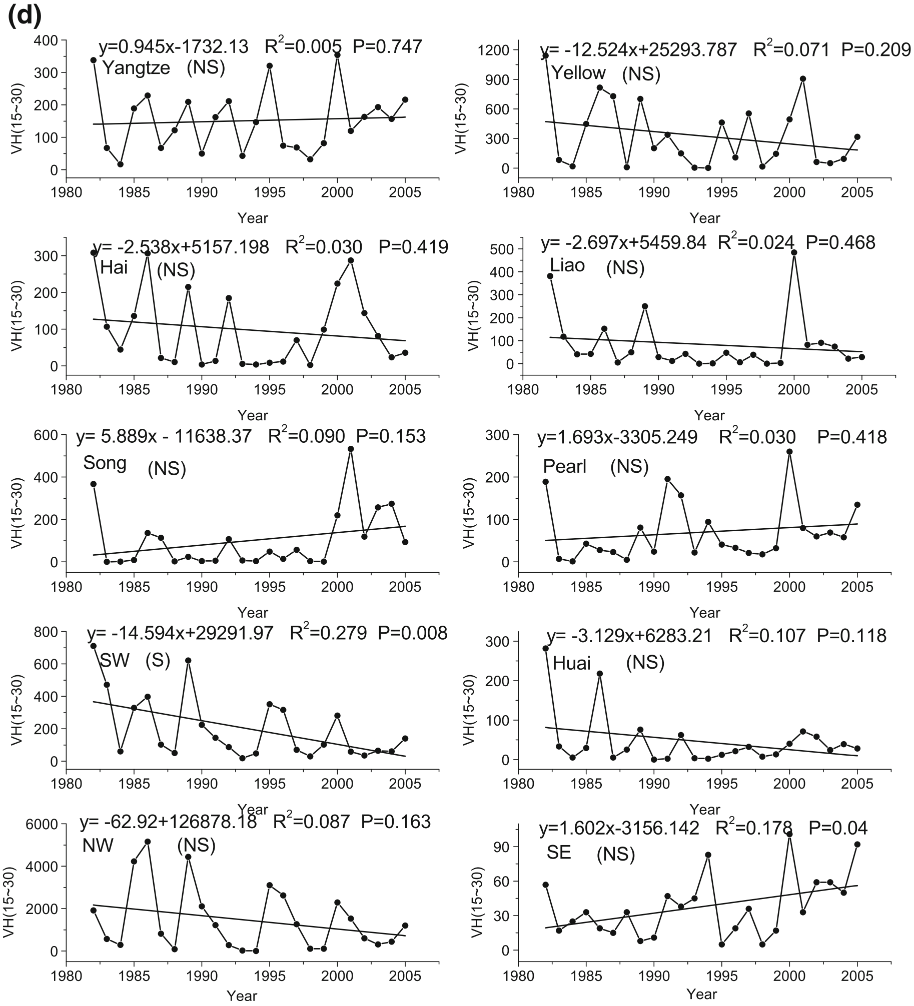

Fig. 4 continued

4.4 The linear temporal trend of the averaged VCI and VH for each basin

The averaged values of VCI and VH in every year over the study period from 1982 to 2005 are estimated for each basin. For VCI (Fig. 5a), all the basins tend to increase. For instance, the two largest single basin located in central China, the Yangtze River basin and the Yellow River basin increased at a rate of 0.581 year^{-1} ($r^2 = 0.225$, $p = 0.019$) and 0.765 year^{-1} ($r^2 = 0.237$, $p = 0.016$) respectively. In west China, the increasing trend was even larger, with a rate of 0.838 year^{-1} ($r^2 = 0.169$, $p = 0.046$) for Northwest Inland River basins and 0.885 year^{-1} ($r^2 = 0.484$, $p < 0.001$) for Southwest River basins. For VH (Fig. 5b), most basins increased except that the Southeast River basins and the Songhuajiang River basin decrease slightly, with trends of -0.018 year^{-1} ($r^2 = 0.001$,

Table 2 Numbers of drought cells and their proportion in total

Basin	Averaged annual number of drought cells		Total cell numbers for each basin	Proportion (%)	
	VCI,VH < 15	15 < VCI,VH < 30		VCI,VH < 15	15 < VCI,VH < 30
Yangtze	20.58	247.25	8,039	0.26	3.07
Southeast	8.83	51.08	1,002	0.88	5.10
Haihe	8.46	66.63	1,589	0.53	4.19
Huaihe	3.96	32.08	1,515	0.26	2.12
Yellow River	64.13	265.08	3,876	1.65	6.84
Liaohe	5.42	49.29	1,638	0.33	3.01
Songhuajiang	3.33	44.38	5,154	0.06	0.86
Northwest	293.71	1,112.08	16,511	1.78	6.74
Southwest	53.63	286.25	3,630	1.48	7.89
Pearl River	10.17	82.29	2,401	0.42	3.43

$p = 0.862$) and -0.138 year^{-1} ($r^2 = 0.044$, $p = 0.326$), respectively. The results indicate the whole country was generally getting wetter during 1982–2005.

4.5 Spatial variability of the coefficient of determination

The VCI and VH were compared against PDSI and 6-month SPI using the grow seasons representing the period of maximum vegetation growth. The reason was that the VCI and VH were both closely related with vegetation health, and therefore, they were only meaningful for drought monitoring during growing seasons (Quiring and Ganesh 2010; Vicente-Serrano 2007).

Figure 6a shows great spatial variability in the relationship between the satellite-based VCI and the routine meteorological 6-month SPI. Much stronger relationships are detected in western Liaohe River basin, central Yellow River basin, eastern Northwest River basins, and western Songhuajiang River basin than other basins. For example, the coefficients of determination in many of the regions in other parts of the country are near zero, while exceeding 0.3 (in some regions, the value was even larger than 0.7) in the regions mentioned above (e.g., western Liaohe River basin). This means the 6-month SPI explains more than 65 % of the variance in the VCI for regions with such a high coefficients of determination. Similar spatial patterns of the coefficient of determination for the VCI and PDSI (Fig. 6b), the VH and 6-month SPI (Fig. 6c) and the VH and PDSI (Fig. 6d) are also detected. In Fig. 6b, regions in Huaihe River basin, parts of the Yellow River basin, eastern Northwest River basins, and western Songhuajiang River basin have the strongest relationship between the VCI and PDSI, and regions in other parts have the weakest relationship. Figure 6c, d is nearly identical to Fig. 6a, b, indicating the high consistency of spatial pattern of drought in China. The difference generally was found in Songhuajiang River basin and northern Northwest Inland River basins, where the areas with larger coefficients of determination were larger in Fig. 6c, d.

After a comparison between the satellite-based drought indices and PDSI and 6-month SPI in the whole country which is classified into ten basins, some general conclusions can

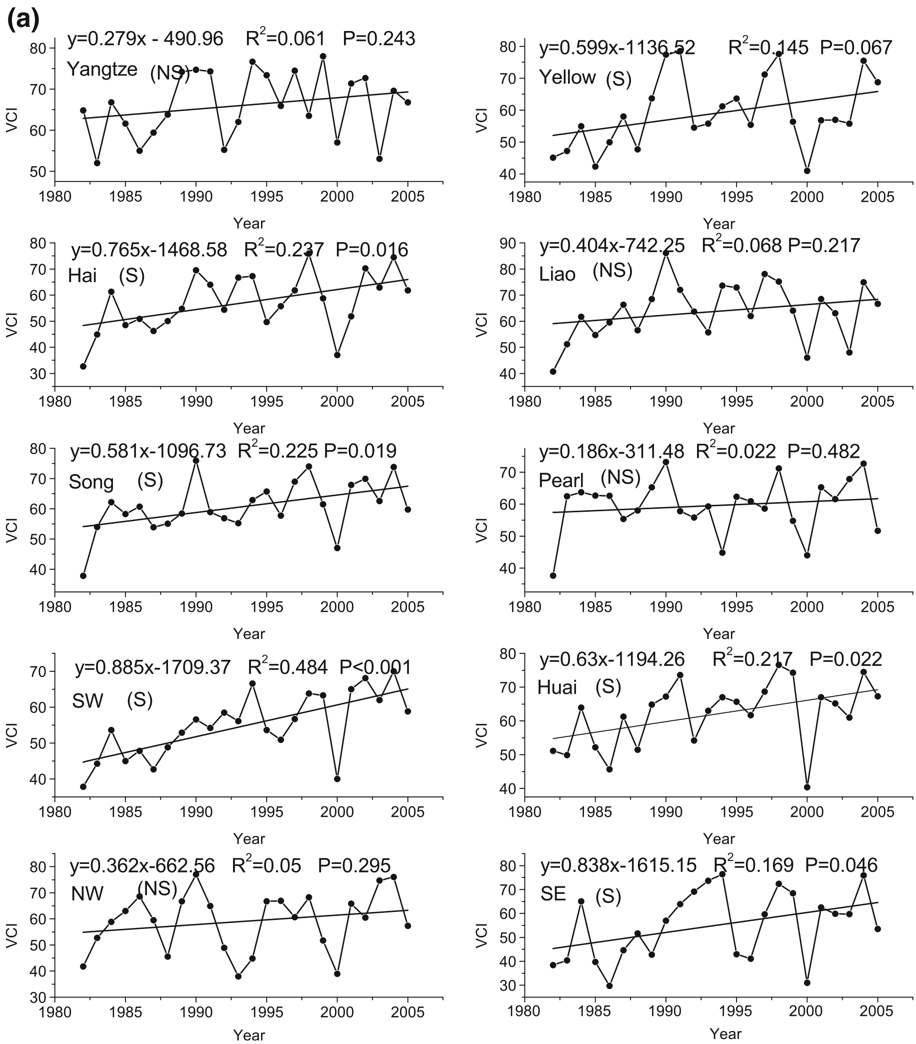

Fig. 5 **a** The linear temporal trend of the basin averaged VCI. (S) indicates the trend is significant at 95 % confidence level by the MK test, while (NS) indicates not significant at this confidence level. **b** The linear temporal trend of the basin averaged VH. (S) indicates the trend is significant at 95 % confidence level by the MK test, while (NS) indicates not significant at this confidence level

be drawn. Significant spatial variability for the relationships between the satellite-based VCI, VH, and the meteorological drought indices was detected. Generally, regions in northern China (especially parts of northeast China) had much higher correlations ($R^2 > 0.3$) than other regions. In those areas with high values of coefficients, the growing-season VCI and VH respond to prolonged moisture stress evidently. The spatial variations of the relationships between different drought indices indicate there are some underlying factors modulating it and forming the pattern. The possible factors include vegetation and

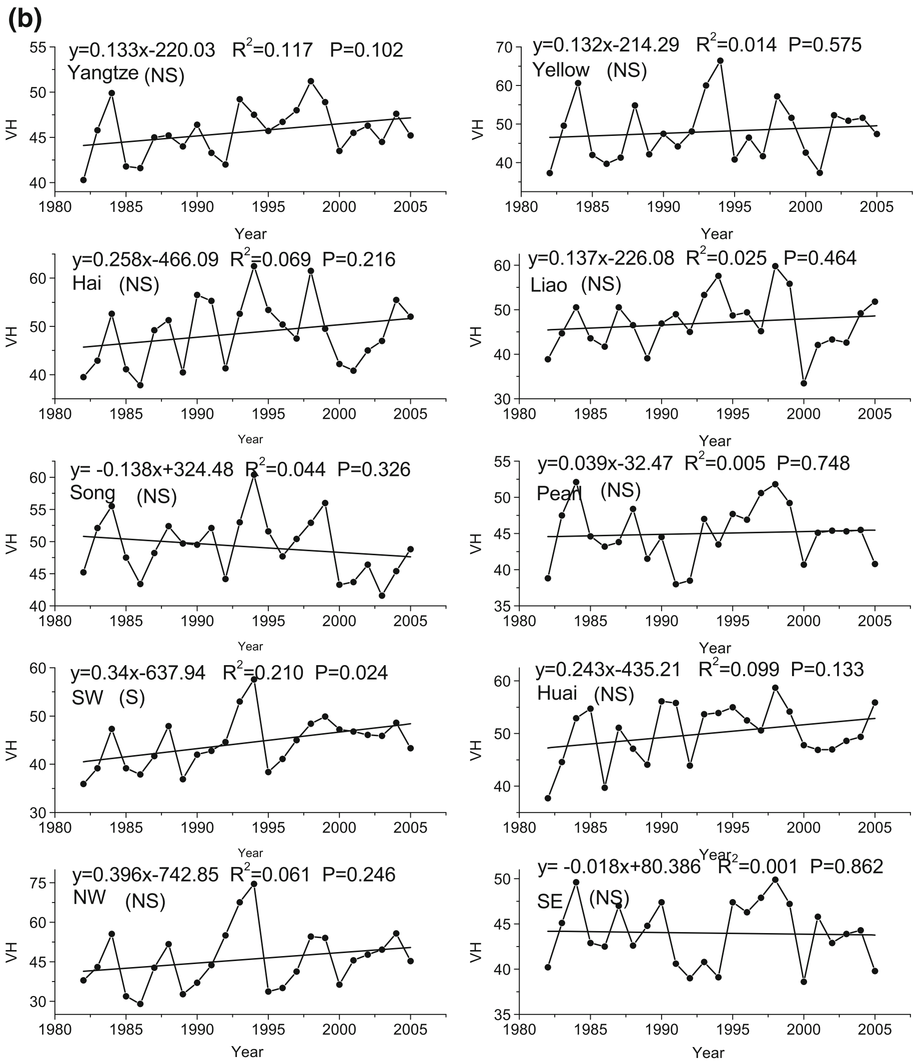

Fig. 5 continued

soil distribution, climate- and water-related human activities (Vicente-Serrano 2007; Wang et al. 2001; Quiring and Ganesh 2010). For example, the spatial distribution of the coefficients of determination between the satellite-based drought indices and meteorological drought indices indicate that the wettest regions in China (e.g., southern and eastern China) are also regions with the weakest relationship between the two kinds of indices. Therefore, local climate linked to the vegetation response to drought obviously (Quiring and Ganesh 2010). The findings also agree with studies of Vicente-Serrano (2007) which indicated that the correlations between the VCI and SPI were generally higher in dry regions and lower in wet ones.

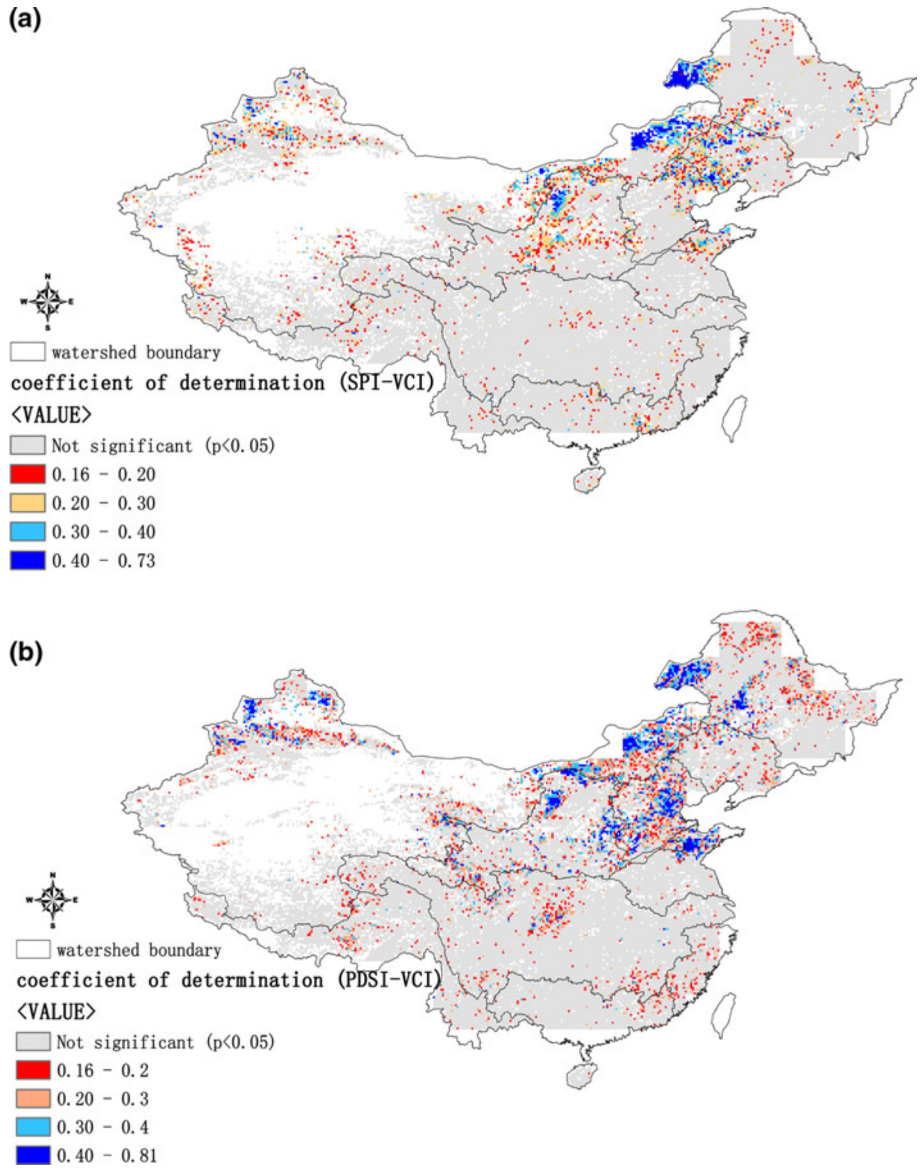

Fig. 6 **a** Spatial variation of the coefficient of determination (R^2) for VCI and SPI. **b** Spatial variation of the coefficient of determination (R^2) for VCI and PDSI. **c** Spatial variation of the coefficient of determination (R^2) for VH and SPI. **d** Spatial variation of the coefficient of determination (R^2) for VH and PDSI

5 Conclusions

Four different drought indices were employed in ten basins in China. They were the satellite-based VCI, VH, and the meteorological drought indices as PDSI and SPI. The

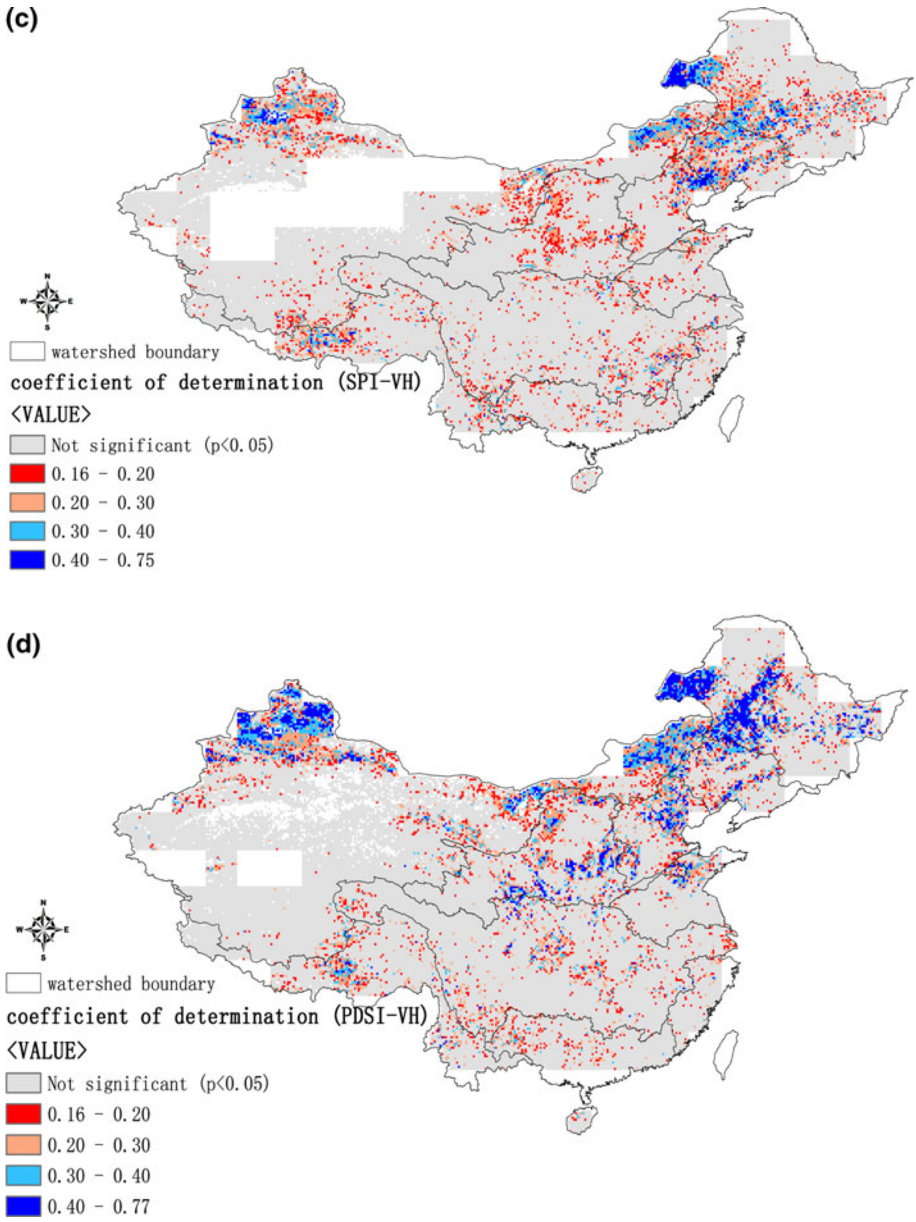

Fig. 6 continued

former two indices were used to study the characteristic and variation of drought in China while PDSI and SPI used for evaluation. As far as we have concerned, there are no such kinds of studies with multiple drought indices (especially combined both satellite information and routine observations) have been reported in detecting the trends and variation of droughts in the ten river basins in China. The calculation and cross-validation make the work scientific and practically valuable. The study is also important for developing reliable large scientific datasets for drought detection across different climatic zones or basins. Some general conclusions can be drawn:

Firstly, the spatial pattern of the multi-year averaged values of VCI and VH is similar. The Northwest Inland River basins, the middle reach of the Yellow River basins, the southeastern Tibet Plateau, and the juncture regions between the upper and middle reaches of the Yangtze River basin have low values, while the upper reaches of the Yellow River basin and the Yangtze River basin, the Songhuajiang River basin, and the Huaihe River basin have high values. The discrepancies in different regions should mainly be caused by the difference of the calculation methods of VCI and VH.

Secondly, generally most parts of China were getting wetter in the growing season over 1982–2005 calculated pixel by pixel, and this trend was more obvious in southwestern Northwest River basins, western Southwest River basins, the middle reach of the Yellow River basin, and the western Liaohe River basin.

Thirdly, the drought areas generally have decreased in the study period. The numbers of grid cells with values less than 30 were used as the main determinate factor of drought area. For VCI, the number of this category of cells decreased in all the basins except for the Songhuajiang River basin, which increased slightly with a rate of 0.076 $year^{-1}$. Significant decreasing trends were found in the Yellow River basin, the Liao River basin, the Northwest River basins, and the Southwest River basins. For VH, the decreasing trend of the severe drought areas calculated by the numbers of the grid cells with values less than 30 are also dominant for the whole country; only the Songhuajiang River basin, the Yangtze River basin, the Southeast River basins, and the Pearl River basin increased, while all other basins decreased. Among the increased four basins, only the Southeast River basins increased significantly.

Fourthly, the averaged values of VCI and VH of each year over the study period from 1982 to 2005 are estimated for each basin. For VCI, all the basins tend to increase. For VH, most basins increased except the Southeast River basins and the Songhuajiang River basin decrease slightly. The results indicate the whole country was generally getting wetter in the growing season over 1982–2005.

At last, the VCI and VH were compared against the two most representative meteorological drought indices including 6-month SPI and PDSI. The study showed there are much stronger relationships between the VCI and 6-month SPI in western Liaohe River basin, central Yellow River basin, eastern Northwest River basins, and western Songhuajiang River basin than other basins. The similar spatial pattern of the coefficient of determination was also found between the VCI and PDSI (Fig. 6b), the VH and 6-month SPI (Fig. 6c), and the VH and PDSI (Fig. 6d).

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References

Anyamba A, Tucker CJ, Eastman JR (2001) NDVI anomaly patterns over Africa during the 1997/98 ENSO warm event. Int J Remote Sens 22:1847–1859

Bhalme HN, Mooley DA (1980) Large-scale droughts/floods and monsoon circulation. Mon Weather Rev 108:1197–1211

Dai AG, Trenberth KE, Karl TR (1998) Global variations in droughts and wet spells: 1900–1995. Geophys Res Lett 25(17):3367–3370
Dai A, Trenberth KE, Qian T (2004) A global data set of Palmer Drought Severity Index for 1870–2002: relationship with soil moisture and effects of surface warming. J Hydrometeorol 5:1117–1130
Fensholt R, Rasmussen K, Nielsen TT, Mbow C (2009) Evaluation of earth observation based long term vegetation trends: intercomparing NDVI time series trend analysis consistency of Sahel from AVHRR GIMMS, Terra MODIS and SPOT VGT data. Remote Sens Environ 113(9):1886–1898
Guttman NB (1999) Accepting the standardized precipitation index: a calculation algorithm. J Am Water Resour As 35(2):311–322
Heim RR Jr (2002) A review of Twentieth-Century drought indices used in the United States. Bull Am Meteorol Soc 83:1149–1165
Jensen JR (2000) Remote sensing of the environment: An Earth resource perspective. Prentice Hall, Upper Saddle River
Ji L, Peters A (2003) Assessing vegetation response to drought in the northern Great Plains using vegetation and drought indices. Remote SensEnviron 87:85–89
Kogan FN (1990) Remote sensing of weather impacts on vegetation in nonhomgeneous areas. Int J Remote Sens 11:1405–1419
Kogan FN (1995a) Droughts of the late 1980s in the United States as derived from NOAA polar-orbiting satellite data. Bull Am Meteorol Soc 76(5):655–668
Kogan FN (1995b) Application of vegetation index and brightness temperature for drought detection. Adv Space Res 11:91–100
Kogan FN (1997) Global drought watch from space. Bull Am Meteorol Soc 78:621–636
Kogan FN (2001) Operational space technology for global vegetation assessment. Bull Am Meteorol Soc 82:1949–1964
Lotsch A, Friedl M, Anderson BT, Tucker CJ (2003) Coupled vegetation-precipitation variability observed from satellite and climate records. Geophys Res Lett 30(14):1774. doi:10.1029/2003GL017506
Lotsch A, Friedl MA, Anderson BT, Tucker CJ (2005) Response of terrestrial ecosystems to recent Northern Hemispheric drought. Geophys Res Lett 32:L06705. doi:10.1029/2004GL022043
McKee TB, Doesken NJ, Kleist J (1993) The relationship of drought frequency and duration to time scales. Paper presented at 8th conference on applied climatology. American Meteorological Society, Anaheim, CA
McKee TB, Doesken NJ, Kleist J (1995) Drought monitoring with multiple time scales. Paper presented at 9th conference on applied climatology. American Meteorological Society, Dallas, Texas
Mishra AK, Singh VP (2010) A review of drought concepts. J Hydrol 391:202–216
Palmer WC (1965) Meteorologic Drought. US Department of Commerce, Weather Bureau, Research Paper No. 45, p 58
Qi S, Niu Z, Wang J (2006) Study on the spatio-temporal characteristics of drought in China with remote sensing during 1982–2005. Acta Pedol Sin 43(3):376–382
Quiring SM, Ganesh S (2010) Evaluating the utility of the Vegetation Condition Index (VCI) for monitoring meteorological drought in Texas. Agric For Meteorol 150:330–339
Shafer BA, Dezman LE (1982) Development of a Surface Water Supply Index (SWSI) to assess the severity of drought conditions in Snowpack Runoff Areas. In Preprints, Western Snow Conference Reno, NV, Colorado State University, pp 164–175
Singh RP, Roy S, Kogan F (2003) Vegetation and temperature condition indices from NOAA-AVHRR data for monitoring drought over India region. Int J Remote Sens 24(22):4393–4402
Tucker CJ (1979) Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens Environ 8:127–150
Tucker CJ, Choudhury BJ (1987) Satellite remote sensing of drought conditions. Remote Sens Environ 23:243–251
Van Rooy MP (1965) A rainfall anomaly index independent of time and space. Notos 14:43
Vicente-Serrano SM (2007) Evaluating the impact of drought using remote sensing in a Mediterranean, semi-arid region. Nat Hazards 40:173–208
Wang Y, Huangyao ZW (2008) Variation and tendency of surface aridity index from 1960–2005 in three provinces of northeast China. Adv Earth Sci 23(6):619–627
Wang J, Price KP, Rich PM (2001) Spatial patterns of NDVI in response to precipitation and temperature in the central Great Plains. Int J Remote Sens 22:3827–3844
Yin YH, Wu S, Chen G (2009) Regional difference of climate trend and abrupt climate change in china during 1961–2006. J Nat Resour 24(12):2147–2157
Zhai JQ, Liu B, Hartmann H, Su B, Jiang T, Fraedrich K (2010) Dryness/wetness variations in ten large river basins of China during the first 50 years of the 21st century. Quat Int 226:101–111
Zou X, Zhai P, Zhang Q (2005) Variations in droughts over China: 1951–2003. Geophys Res Lett 32:L04707. doi:10.1029/2004GL021853