

# Spatial variability of the trends in climatic variables across China during 1961–2010

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**Abstract** Distribution of meteorological stations is not uniform in many regions of the world, especially in developing countries like China. To eliminate the effect of uneven stations, this study produced a data set of areal average precipitation, air temperature, solar radiation, and wind speed from 736 meteorological station observations during 1961–2010 using an inverse-distance weighted technique. Based on the data set, this study detected the trends in climatic variables. Precipitation has a slight but no significant ( $p=0.78$ ) trend for the whole of China and has a significant increase trend in northwest China. Surface air temperature has a significant ( $p<0.001$ ) accelerating warming trend of  $0.032\text{ }^{\circ}\text{C/a}$  for the whole of China, and spatially larger in northern China than that in southern China. Solar radiation has a significant ( $p<0.001$ ) dimming trend of  $-0.14\text{ W}/(\text{m}^2\cdot\text{a})$  for the whole of China, and the largest dimming trend appears in eastern China, the possible cause for which is a high-aerosol concentration. Surface wind speed has a significant ( $p<0.001$ ) stilling trend of  $-0.012\text{ m}/(\text{s}\cdot\text{a})$  for the whole of China, the causes for which were speculated the changes in atmospheric circulation and surface roughness, as well as increases in aerosol concentration and the decrease in the south-north temperature gradient in China. In addition, three large-scale instrument replacements increase uncertainties of the trend analysis.

## 1 Introduction

In the past half century, a significant climate change has been widely reported (IPCC 2007). That change has been impacting hydrologic cycle, which will in turn impact ecological, social, and economic systems (Dibike and Coulibaly 2005).

Many researchers reported changes (or variability) in climatic variables, such as precipitation, air temperature, solar radiation, and wind speed. Dai (2006) reported a slight increase in precipitation based on the observed data from 15,000 meteorological stations across the world. Also, in China, precipitation changes were reported in many literatures. Liu et al. (2005) found that observed precipitation at 272 stations increased by 2 % during 1960–2000. Ren and Ren (2012) detected trends of 1.42 and 1.46 % per decade during 1961–2009 from two precipitation observational networks with 740 and 2,070 stations, respectively. Zhai et al. (2005) detected that there is little trend in annual total precipitation observed from 740 stations, but there is a distinctive regional patterns of trend. Regionally, annual precipitation has an increase in eastern and southern China, northeast China, and western China, while it has a decrease in North China (Ye et al. 2004; Ren et al. 2000; Ding et al. 2007). In the Yellow River basin, precipitation from 35 stations shows linear slopes ranging from  $-5.8$  to  $1.6\text{ mm/a}^2$  during 1961–2006 (Liu et al. 2008). In the upper reach of the Yangtze River basin, Xu et al. (2008) detected an increase from 7 stations and a decrease from 26 stations during 1961–2000. Meanwhile, global warming was widely observed (IPCC 2007). Like other regions in the world, China also has a remarkable warming trend. Yang and Yang (2012) detected a  $0.027\text{ }^{\circ}\text{C/a}$  air temperature increase from 54 stations across China during 1961–2001. Similarly, Cong et al. (2009) detected a warming trend of  $0.023\text{ }^{\circ}\text{C/a}$  for 317 stations during 1956–2005. Ren et al. (2005a) detected a  $0.025\text{ }^{\circ}\text{C/a}$  warming trend from 740 stations during 1956–2004. Ren et al. (2012) detected a  $0.025\text{ }^{\circ}\text{C/a}$  warming trend from 730 stations during

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1951–2007. Regarding solar radiation, a decline was widely reported across the world, termed as global dimming (Stanhill and Cohen 2001; Wild et al. 2005). Similar to other parts of the world, a decrease in sunshine hours or solar radiation was documented in most parts of China, such as North China (Yang et al. 2009), eastern China (Zhang et al. 2004), and Southwest China (Li et al. 2012). Over past several decades, a decline in surface wind speed has been observed in many regions of the world (McVicar et al. 2012; Vautard et al. 2010), and it is termed wind stilling. Similarly, there are many literatures on wind stilling in China. Yang and Yang (2012) detected a 0.01 m/(s·a) decrease trend in wind speed from 54 stations during 1961–2001. Yin et al. (2010) documented a 0.009 m/(s·a) decrease from 652 stations during 1961–2008. Ren et al. (2005b) reported a 0.0121 m/(s·a) decrease during 1956–2002, and a similar decrease during 1956–2004 was detected by Jiang et al. (2010). Furthermore, a spatial pattern in wind stilling was also revealed, and weakening trends ranging from 0.007 to 0.029 m/(s·a) were reported for different regions in previous literatures (McVicar and Roderick 2010; Mahowald et al. 2007; Song et al. 2010; Yang and Yang 2011; Zheng et al. 2009; Fan and Thomas 2013).

In previous researches, to detect the change rate of climatic variables over China, areal average was estimated by using an arithmetic mean method from meteorological station observations (Shi et al. 2008; Cong et al. 2009; Yang and Yang 2012; Tang et al. 2011). Theoretically, that method is appropriate for dense networks with uniform station locations. However, meteorological stations are dense in eastern China and sparse in western China. Therefore, it is necessary to assign different weights for different stations when evaluating climate change for China as a whole. To accurately detect the change rate, some studies firstly divided China into longitude and latitude grids (one grid is generally larger than  $2^\circ \times 2^\circ$ , approximately  $40,000 \text{ km}^2$ ), then calculated the grid average as the arithmetic mean of all stations in the grid, and afterward, used the grid average to compute the national average by taking the size of grids as weights (Liu et al. 2005; Zhai et al. 2005; Ren et al. 2005a, b). Nonetheless, in a grid, stations are generally unevenly distributed, especially in western China.

China has a vast territory, which ranges from the tropical zone to the cold temperate zone. Consequently, climate changes or variability shows a regional pattern. In addition, it is a hot spot to evaluate hydrologic response to climate change at a catchment scale (Yang and Yang 2011; Wang and Hejazi 2011; Roderick and Farquhar 2011), and the response can be estimated based on the change in climatic variables at a catchment scale, such as precipitation, temperature, radiation, and wind speed (Yang and Yang 2011). Therefore, this study aims to (1) produce a grid data set of climatic variables by interpolating into areal values from meteorological station observations, and (2) detect trends in climatic variables at catchment scales by dividing China into 210 catchments, in

order to understand the regional variability of climate change and further evaluate its impacts on hydrological cycle in China.

## 2 Data and method

### 2.1 Climatic variables and the 10-km grid data set

Daily meteorological data, namely, precipitation, surface air temperature, sunshine hours, and wind speed (at 10 m above ground surface), were collected from 736 stations during 1961–2010 from the China Meteorological Administration (CMA). The data was released as the data set (SURF\_CLI\_CHN\_MUL\_DAY) after quality control in the Web site <http://cdc.cma.gov.cn>. In addition, daily solar radiation was collected from 118 stations during 1961–2002. There are three large-scale instrument replacements in the Chinese meteorological observation networks. The first is the instrument replacement for wind speed during 1967–1970 (Liu 2000). The second is the instrument replacement for solar radiation around the early 1990s (Tang et al. 2011). The third is manual observation being replaced by automatic weather stations during 2001–2005 (Wang et al. 2007).

To obtain a daily 10-km grid data set of daily climatic variables, the procedure was designed as follows: (a) a 10-km grid data set covering the study area was interpolated from the meteorological station observations, and then (b) the catchment average (or national average) values were calculated. Therein, air temperature was interpolated using an inverse-distance weighted technique that considers the effect of elevation. Other variables were interpolated using an inverse-distance weighted technique (Yang et al. 2004). Based on the daily areal values for each catchment, we further calculated annual areal average. Since only 118 meteorological stations directly measure solar radiation, we estimated it using the Angstrom equation (Allen et al. 1998):

$$R_s = \left( a_s + b_s \cdot \frac{n}{N} \right) R_a \quad (1)$$

where  $n$  is actual sunshine hour,  $N$  is maximum possible sunshine hour,  $R_a$  is the extraterrestrial radiation, and  $a_s$  and  $b_s$  are parameters. In this study, the parameters ( $a_s$  and  $b_s$ ) were calibrated using the observed data for each month at the 118 stations with solar radiation observations, and their values for each grid were obtained from the nearest station (Yang et al. 2006).

### 2.2 Catchment average of climatic variables

Catchment information data set was from the Ministry of Water Resources (MWR) of the People's Republic of China

(Water Resources and Hydropower Planning and Design General Institute 2011). In the data set, the first-level basins are the 10 large river basins in China (see Fig. 1 for the map), such as the Yangtze River basin and the Yellow River basin; the second-level basins are tributary basins of the 10 large ones; the third-level basins are tributary basins of the second-level basins. Catchment extent was determined according to the third-order basins in China. Hereby, China was divided into 210 catchments, whose areas range from 3,100 to 682,700 km<sup>2</sup> (Yang et al. 2014). Therein, 18 catchments belong to the Songhua River basin (SRB), 12 belong to the Liao River basin (LRB), 15 belong to the Hai River basin (HaRB), 29 belong to the Yellow River basin (YeRB), 15 belong to the Huai River basin (HuRB), 45 belong to the Yangtze River basin (YaRB), 10 belong to the southeast rivers basin (SERB), 19 belong to the Pearl River basin (PRB), 14 belong to the southwest rivers basin (SWRB), and 33 belong to the northwest rivers basin (NWRB). In the 210 catchments, the Taiwan Island was the one that we could not collect observation data from; therefore, it was excluded from the study region. According to the daily 10-km grid data set, areal average of climatic variables for each catchment was calculated.

### 2.3 Trend analysis

The Mann-Kendall (MK) nonparametric test is an appropriate statistical tool to detect trends of meteorological and hydrological variables in a time series (Maidment 1993). A precondition before using the MK test is that sample data are serially independent. In fact, climatic and hydrologic series may generally display serial correlation. To

eliminate the effect of a serial correlation on the MK test, Kulkarni and von Storch (1995) proposed to pre-whiten a series prior to applying the MK test. Furthermore, Yue and Wang (2002) proposed a modified pre-whitening procedure named trend-free pre-whitening (TFPW).

First, we used TFPW to eliminate the effect of serial correlation, and then detected the trends in climatic factors, together with their significance. The slope of the trends was estimated as follows (Burn and Elnur 2002; Gan 1998):

$$\beta = \text{Median} \left[ \frac{(x_j - x_i)}{(j - i)} \right], \quad \text{for all } i < j \quad (2)$$

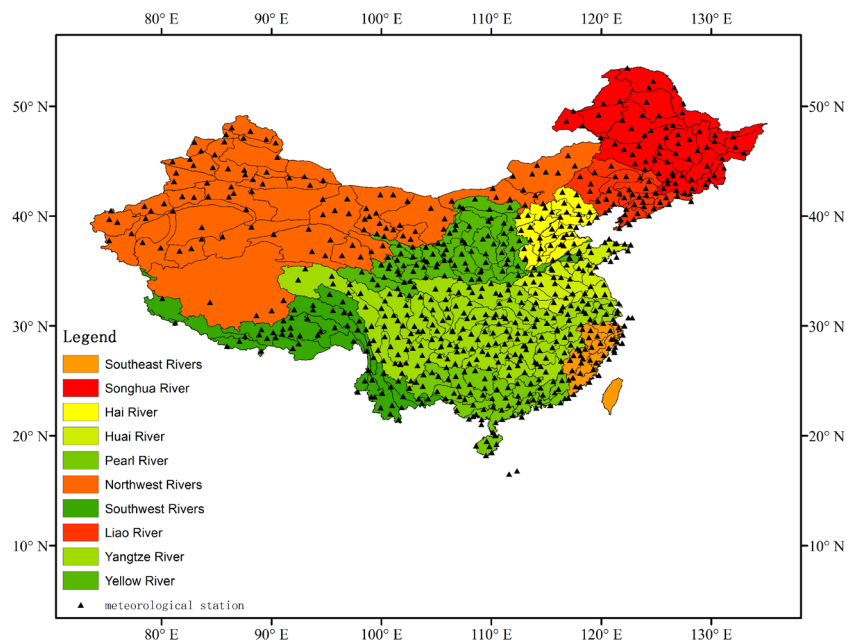
where  $\beta$  is the trend magnitude, and  $x_i$  and  $x_j$  are the  $i$ th and  $j$ th observations, respectively. A positive value of  $\beta$  indicates an increasing trend and a negative value of  $\beta$  indicates a decreasing trend.

## 3 Results

### 3.1 Climatic variables for China as a whole

Mean annual areal average of the climatic variables are given in Table 1, namely, precipitation, 590 mm/a; air temperature, 8.07 °C; solar radiation, 173.3 W/m<sup>2</sup>; and wind speed, 2.48 m/s.

**Fig. 1** Maps of the 10 large basins, the 210 catchments, and the spatial distribution of CMA stations

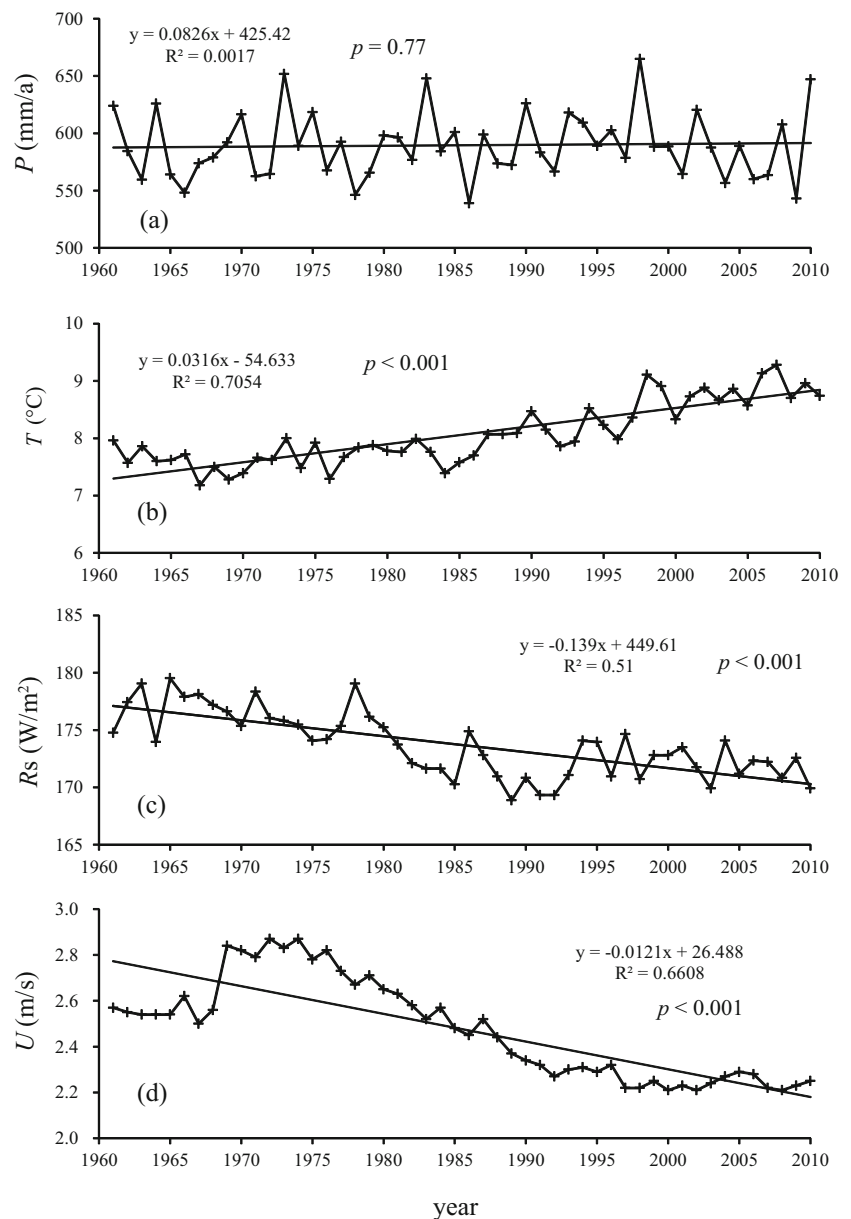


**Table 1** Mean annual values of climatic variables for the whole of China

Period	$P$ (mm/a)	$T$ (°C)	$R_s$ (W/m <sup>2</sup> )	$U$ (m/s)
1961–1970	587	7.57	177.0	2.61
1971–1980	586	7.71	176.0	2.77
1981–1990	592	7.89	171.8	2.49
1991–2000	599	8.34	172.0	2.27
2001–2010	584	8.85	171.8	2.24
1961–2010	590	8.07	173.3	2.48

Precipitation has a slight but not significant ( $p=0.78$ ) increase during 1961–2010, with a linear trend of  $0.08 \text{ mm/a}^2$ , as shown in Fig. 2a. Furthermore, its inter-decade variation is shown in Table 1, the peak (up to 599 mm/a) occurring in the

**Fig. 2** Changes in climatic variables for the whole of China during 1961–2010: **a** precipitation, **b** surface air temperature, **c** solar radiation, and **d** wind speed at 10 m



1990s and the minimum (584 mm/a) occurring in the 2000s. In particular, there is a large decline from the 1990s to the 2000s, by  $1.5 \text{ mm/a}^2$ .

Air temperature has a significant ( $p < 0.001$ ) increase during 1961–2010, with a linear trend of  $0.032 \text{ °C/a}$ , as shown in Fig. 2b. Therein, there is no trend during 1961–1978, and then there is a  $0.046 \text{ °C/a}$  warming trend in the following period (1979–2010). Regarding its inter-decade variation, Table 1 shows a monotonous accelerating increase, and the decade of 2001–2010 is the hottest one since 1960. The increment is only  $0.14 \text{ °C}$  from the 1960s to the 1970s, but that is  $0.51 \text{ °C}$  from the 1990s to the 2000s.

Solar radiation has a significant ( $p < 0.001$ ) decline, with a linear trend of  $-0.14 \text{ W/(m}^2\cdot\text{a)}$ , as shown in Fig. 2c. Therein, a dimming trend lasts since 1961 until the early 1990s.

Afterward, there is a transient increase in the 1990s and a decrease (with a linear trend of  $-0.12 \text{ W}/(\text{m}^2 \cdot \text{a})$ ) during 1994–2010. Table 1 shows an inter-decade variability that monotonously decreases from the 1960s to the 1980s and remains steady from the 1990s to the 2000s.

Wind speed at 10 m has a significant ( $p < 0.001$ ) decline, with a linear trend of  $-0.012 \text{ m}/(\text{s} \cdot \text{a})$ , as shown in Fig. 2d. Therein, there is a platform from 1961 to 1968, afterward a decrease until 1996, and then nearly a platform. The largest change rate occurred in the period of 1969–1996 of up to  $0.025 \text{ m}/(\text{s} \cdot \text{a})$ . Regarding the inter-decade variation of wind speed, it strengthens from the 1960s to the 1970s, has a peak up to  $2.77 \text{ m/s}$  in the 1970s, and then weakens from the 1970s to the 2000s.

### 3.2 Trend in climatic variables at catchment scales

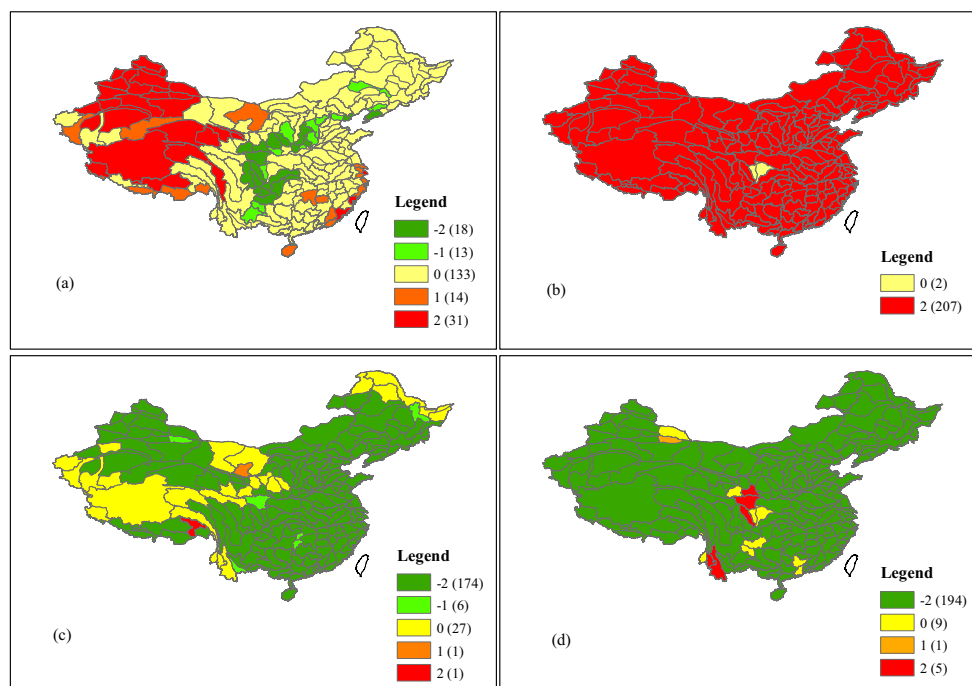
Figure 3a shows that annual precipitation (1) significantly ( $p < 0.05$ ) increased at 31 catchments, mainly located in NWRB and SWRB; (2) has no significant ( $p < 0.10$ ) trend at 133 catchments; (3) significantly ( $p < 0.05$ ) decreased at 18 catchments, mainly located in the upper reach of YaRB and the middle reach of YeRB; (4) significantly ( $p < 0.10$ ) increased at 14 catchments except the 31 catchments belonging to (1); and (5) significantly ( $p < 0.10$ ) decreased at 13 catchments except the 18 catchments belonging to (2). Furthermore, the change rate of precipitation is shown in Fig. 4a. It has a relatively large increase rate by  $3.0\text{--}5.1 \text{ mm}/\text{a}^2$  at several catchments in eastern China; an increase rate by  $0.0\text{--}3.0 \text{ mm}/\text{a}^2$  mainly located in NWRB, SWRB, SERB, the lower reach of YaRB, and part of HuRB; a relatively slight

decrease rate by  $-1.0$  to  $0.0 \text{ mm}/\text{a}^2$  mainly in SRB, LRB, HuRB, and PRB; a decrease rate by  $-3.0$  to  $-1.0 \text{ mm}/\text{a}^2$  mainly in most of HRB, YeRB, the upper reach of YaRB, and the southern part of SWRB; and a large decrease rate by  $-6.5$  to  $-3.0 \text{ mm}/\text{a}^2$  at three catchments located in the upper reach of YaRB. Therein, increasing precipitation mainly occurs in western China and the lower reach of YaRB, while decreasing precipitation mainly occurs in eastern China (except in the lower reach of YaRB).

Figure 3b shows that annual air temperature has a significant ( $p < 0.05$ ) increase at almost all of the 209 catchments (207 catchments) and has no significant trend only at 2 catchments. Regarding the change rate as shown in Fig. 4b, the warming rate is by  $0.015\text{--}0.030 \text{ }^\circ\text{C}/\text{a}$  in most regions of southern China, as well as HaRB and LRB, and that is by  $0.030\text{--}0.045 \text{ }^\circ\text{C}/\text{a}$  in most regions of northern China.

Figure 3c shows that most catchments (174) have a significant ( $p < 0.05$ ) decrease in solar radiation. In addition, 27 catchments have no significant ( $p < 0.10$ ) trend, mainly located in NWRB and SRB. Figure 4c shows the change rate of annual solar radiation, and that is by (1)  $0.00\text{--}0.21 \text{ W}/(\text{m}^2 \cdot \text{a})$  at four catchments in the northern part of SRB and the SWRB; (2)  $-0.15$  to  $0.00 \text{ W}/(\text{m}^2 \cdot \text{a})$  mainly in SRB, the southern part of NWRB, SWRB, the upper reach of YaRB, and the upper reach of YeRB; (3)  $-0.30$  to  $-0.15 \text{ W}/(\text{m}^2 \cdot \text{a})$  mainly in the western and eastern parts of NWRB, LRB, the upper and middle reaches of YaRB, and PRB; (4)  $-0.45$  to  $-0.30 \text{ W}/(\text{m}^2 \cdot \text{a})$  mainly in HaRB, HuRB, and the lower reach of YaRB; and (5) up to  $-0.51$  to  $-0.45 \text{ W}/(\text{m}^2 \cdot \text{a})$  in part of HaRB and HuRB. In brief, almost all catchments have a decline in solar radiation, and therein, eastern China has the largest decline.

**Fig. 3** Significance of climatic variables change during 1961–2010: **a** precipitation, **b** air temperature, **c** solar radiation, and **d** wind speed. In the legends, 2 and 1 indicate a significant increase at a significance level of 0.05 and 0.10, respectively; 0 indicates no significant change at a significance level of 0.10; and -2 and -1 indicate a significant decrease at a significance level of 0.05 and 0.10, respectively. The number in parentheses is the frequency



**Fig 4** Changes of rate of **a** precipitation ( $\text{mm}/\text{a}^2$ ), **b** air temperature ( $^{\circ}\text{C}/\text{a}$ ), **c** solar radiation ( $\text{W}/(\text{m}^2\cdot\text{a})$ ), and **d** wind speed ( $\text{m}/(\text{s}\cdot\text{a})$ ) during 1961–2010

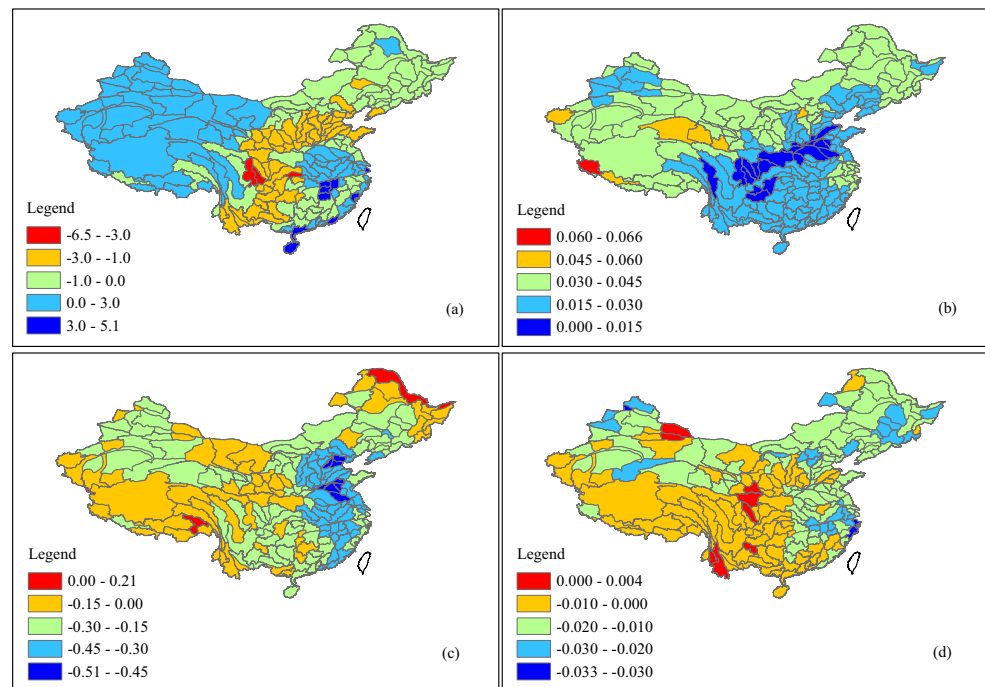


Figure 3d shows that almost all catchments (194) have a significant ( $p < 0.05$ ) decrease in wind speed, and 9 catchments have no significant ( $p < 0.10$ ) trend. In addition, five catchments have a significant ( $p < 0.05$ ) increase. Figure 4d shows the change rate of wind speed. Therein, only several catchments have a strengthened wind speed at a rate of 0.000–0.004  $\text{m}/(\text{s}\cdot\text{a})$ . Besides, there is a  $-0.010$  to  $0.000$   $\text{m}/(\text{s}\cdot\text{a})$  weaken trend mainly in part of NWRB, SWRB, the middle and upper reaches of YeRB, and the middle and upper reaches of YaRB, and PRB; there is a  $-0.020$  to  $-0.010$   $\text{m}/(\text{s}\cdot\text{a})$  weaken trend mainly in the northern part of NWRB, SRB, LRB, HaRB, HuRB, and the lower reach of YaRB; there is a  $-0.030$  to  $-0.020$   $\text{m}/(\text{s}\cdot\text{a})$  weaken trend mainly in part of NWRB, part of SRB, part of HaRB, and the lower reach of YaRB. Overall, almost all of China has weakening wind; herein, eastern China and the northwest China have relatively larger decline.

## 4 Discussion

### 4.1 Precipitation

Annual precipitation has no significant trend, but there is a distinctive regional pattern of trend during 1961–2010. This is similar to the characteristics during 1951–2000, which was detected by Liu et al. (2005) and Zhai et al. (2005) from 740 stations. Regarding the regional pattern, this study detects a decrease in HaRB and an increase in the lower reach of YaBR, and it may be caused by weakening of Asian summer

monsoon wind (Xu et al. 2006; Luo et al. 2013). In addition, increasing urban and industrial air pollution leads to a high-aerosol concentration in eastern China (Zhao et al. 2006), and weakening wind also increases the concentration (Zhu et al. 2012). The increasing aerosol concentration has a negative impact on the formation of precipitation (Rosenfeld 2000), which possibly further leads to a decline in precipitation. Remarkably, the instrument replacement during 2001–2005 leads to an inconsistency in observed annual precipitation series, and the relative error is beyond 8 % at less than 30 % stations, which are mainly located in Xinjiang province and the Qinghai-Tibet Plateau (Wang et al. 2007).

### 4.2 Air temperature

In this study, we detected a  $0.032$   $^{\circ}\text{C}/\text{a}$  warming trend during 1961–2009 (Table 2), which has a good agreement with the trend ( $0.031$   $^{\circ}\text{C}/\text{a}$ ) proposed by CARCCC (2011) based on the observations from up to 2,200 stations across mainland China. In China, meteorological data from the 736 stations were released in the Web site <http://cdc.cma.gov.cn/> for scientific researches. However, it is very difficult to collect the data set covering the 2,200 stations. Furthermore, to compare with previous studies, we detected trends in air temperature during different periods, as shown in Table 2. Therein, during 1979–2010, there is a larger warming trend ( $0.046$   $^{\circ}\text{C}/\text{a}$ ), compared to a  $0.035$   $^{\circ}\text{C}/\text{a}$  warming trend in the Northern Hemisphere (Jones et al. 2012) and a  $0.025$   $^{\circ}\text{C}/\text{a}$  for the average of earth land surface (Rohde et al. 2013). The difference is possibly caused by fast urbanization in China. Ren et al. (2012) proposed that urbanization has an at least

**Table 2** Comparison of surface air temperature trend across China between previous reports and present study

Author	Number of stations	Estimation method for average	Period	Trend (°C/a)
CARCCC (2011)	2200	Arithmetic mean <sup>a</sup>	1961–2009	0.031
Present	736	Inverse-distance weighted <sup>b</sup>		0.032
Cong et al. (2009)	317	Arithmetic mean	1961–2005	0.024
Present	736	Inverse-distance weighted		0.029
Yang and Yang (2012)	54	Arithmetic mean	1961–2001	0.027
Present	736	Inverse-distance weighted		0.026
Ren et al. (2005a)	740	Grid weight <sup>c</sup>	1961–2004	0.030
Present	736	Inverse-distance weighted		0.029
Present	736	Inverse-distance weighted	1979–2010	0.046

<sup>a</sup> Estimation of areal average using an arithmetic mean technique from meteorological stations

<sup>b</sup> Estimation of areal average using an inverse-distance weighted technique from meteorological stations that consider the effect of elevation

<sup>c</sup> Estimation of areal average using a method that first divides China into several grids of  $2.5^{\circ} \times 2.5^{\circ}$ ; second, calculates the grid average as the arithmetic mean of all stations in the grid; and third, uses the grid average estimate the national average by taking the areas of grid as weights

27 % contribution to warming trend for China as the whole during 1960–2004. Regionally, in eastern China, Duan et al. (2012) reported an 18 % contribution of urbanization to warming trend during 1957–2005; Wu and Yang (2013) detected an 11.4 % contribution during 1979–2008; Yang et al. (2011) revealed a 24.2 % contribution to regional warming trend during 1981–2007. In the northwest, Fang et al. (2007) reported a 0.02 °C contribution from urbanization effect to warming trend during 1961–2000, which is much less than that in eastern China because of a lower density of cities. In addition, the instrument replacement during 2001–2005 caused an inconsistency of air temperature observation. The error of annual air temperature was not larger than  $\pm 0.1$  °C at 76.5 % of stations, and the stations with errors larger than  $\pm 0.2$  °C are mainly located in Qianghai, Sichuan, Jiangxi, Hunan, and Shanxi provinces (Wang et al. 2007).

There is a larger warming trend in northern China than in southern China, which declines the south-north temperature gradient. That may be partly responsible for wind stilling (Xu et al. 2006; Yang 2008).

#### 4.3 Solar radiation

Regarding solar radiation, several previous literatures reported a decrease ranging from  $-0.41$  to  $-0.52$  W/(m<sup>2</sup>·a) during 1961–2000 (Liang and Xia 2005; Che et al. 2005; Shi et al. 2008) and  $-0.45$  W/(m<sup>2</sup>·a) during 1961–2001 (Yang and Yang 2012), as shown in Table 3. Nonetheless, Tang et al. (2011) documented the results in those literatures that suffered from some shortcomings and uncertainties, i.e., the inconsistencies due to a large scale of new instruments retrofitted around the early 1990s and irregular calibration operations and some stations being moved from one place to another one. They furthermore estimated a  $-0.23$  W/(m<sup>2</sup>·a) trend from 716 stations by a physical model in the period of 1961–2000. For the

same period, we detected a dimming rate of  $0.18$  W/(m<sup>2</sup>·a), which is close to the trend estimated by Tang et al. (2011). However, it is worth noting that our result is a little smaller. The possible cause is that the western part has a smaller dimming trend than the eastern part, and on the other hand, the western part has more sparse stations than the eastern part. That leads to an overestimation of solar radiation dimming, since Tang et al. (2011) used an arithmetic mean method to estimate areal values. In addition, our results show only a transient brightening in the 1990s and a  $-0.14$  W/(m<sup>2</sup>·a) dimming linear trend ( $p=0.07$ ) during 1994–2010, which does not completely support the widespread brightening since the late 1980s proposed by Wild et al. (2005). There is only a slight but not significant ( $p=0.72$ ) brightening trend during 1990–2010.

The largest dimming trend occurs in eastern China, especially in HaRB and HuRB and the lower reach of YaRB, ranging from  $-0.45$  to  $-0.51$  W/(m<sup>2</sup>·a). This may be caused by high-aerosol concentration in those regions, since the contour of dimming rate (Fig. 4c) has a good agreement with that of aerosol concentration mapped by Zhao et al. (2006) according to MODIS data during summer from 2000 to 2005.

#### 4.4 Wind speed

Regarding wind speed, we detected a  $-0.012$  m/(s·a) ( $\sim 0.52$  %/a), which is close to the results reported by some previous researches, such as  $-0.020$  m/(s·a) by Xu et al. (2006) from 305 stations across China during 1969–2000,  $-0.018$  m/(s·a) by Guo et al. (2011) from 652 stations over China from 1969 to 2005,  $-0.013$  m/(s·a) by Ren et al. (2005b) from 740 stations across China during 1961–2002, and  $-0.0124$  m/(s·a) by Jiang et al. (2010) from 535 stations across China during 1956–2004. More widely, a  $0.17$ – $0.51$  %/a decrease from 822 stations over the northern midlatitudes

**Table 3** Comparison of solar radiation trend across China between previous reports and present study

Author	Number of stations	Estimation method for average	Period	Trend W/(m <sup>2</sup> ·a)
Che et al. (2005)	64	Arithmetic mean <sup>a</sup>	1961–2000	−0.45
Liang and Xia (2005)	42	Arithmetic mean		−0.52
Shi et al. (2008)	72	Arithmetic mean		−0.41
Tang et al. (2011)	459	Arithmetic mean		−0.23
Present	736	Inverse-distance weighted <sup>b</sup>		−0.18
Yang and Yang (2012)	54	Arithmetic mean	1961–2001	−0.45
Present	736	Inverse-distance weighted		−0.17
Present	736	Inverse-distance weighted	1994–2010	−0.14

<sup>a</sup> Estimation of areal average using an arithmetic mean technique from meteorological stations

<sup>b</sup> Estimation of areal average using an inverse-distance weighted technique from meteorological stations

during 1979–2008 was reported (Vautard et al. 2010), which is smaller than what was detected in this study,  $-0.015 \text{ m}/(\text{s}\cdot\text{a})$  ( $\sim 0.60 \text{ \%}/\text{a}$ ) in China during the same period (Table 4). The causes of wind stilling were the changes in atmospheric circulation and surface roughness (Vautard et al. 2010), especially urbanization and environmental changes around meteorological stations in China (Zhang et al. 2009), for example, urbanization contributes up to  $\sim 35 \text{ \%}$  of wind stilling in the Greater Beijing Metropolitan Area during 1961–2008 (Hou et al. 2013) and environmental changes contribute up to one third of wind stilling in Hebei province during 1975–2004 (Liu et al. 2009). Han et al. (2008) reported that the surface roughness around the Tianjin Meteorological station increased from 20–30 m in 1996 to 30–40 m in 2005. Also, agricultural irrigation was speculated as one cause for wind stilling (Han and Hu 2012; Han et al. 2012). In addition, the observed weakening in summer wind speeds is also caused by the increases in aerosols (Zhu et al. 2012; Bichet et al. 2012), and the decrease in the

south-north temperature gradient in China (Xu et al. 2006; Yang 2008).

A replacement of wind speed instrument occurred during 1967–1970 (Liu 2000), which possibly caused an inhomogeneity of wind speed series. The homogeneity test on annual wind speed series from 1951 to 1990 shows that the series from about 80 % of the stations is homogenous and that replacement has a remarkable inhomogeneity at a small number of stations located at high mountains, highlands, and hillsides. In addition, the instrument replacement during 2001–2005 caused a small inconsistency: 10-min average wind speed being less than 0.2 m/s at most stations (Wang et al. 2007).

## 5 Conclusion

In this study, we took notice of the fact that meteorological observation network is not uniform in China, i.e., dense in the

**Table 4** Comparison of surface wind speed trend across China between previous reports and present study

Author	Number of stations	Estimation method for average	Period	Trend m/(s·a)
Guo et al. (2011)	652	Arithmetic mean <sup>a</sup>	1969–2005	−0.018
Present	736	Inverse-distance weighted <sup>b</sup>		−0.021
Xu et al. (2006)	305	Thiessen polygon <sup>c</sup>	1969–2000	−0.022
Present	736	Inverse-distance weighted		−0.024
Yang and Yang (2012)	54	Arithmetic mean	1961–2001	−0.010
Present	736	Inverse-distance weighted		−0.013
Ren et al. (2005b)	740	Grid weight <sup>d</sup>	1961–2002	−0.013
Present	736	Inverse-distance weighted		−0.013
Present	736	Inverse-distance weighted	1979–2008	−0.015

<sup>a</sup> Estimation of areal average using an arithmetic mean method from meteorological stations

<sup>b</sup> Estimation of areal average using an inverse-distance weighted technique from meteorological stations

<sup>c</sup> Estimation of areal average using the Thiessen polygon method from meteorological stations

<sup>d</sup> Estimation of areal average using a method that first divides China into several grids of  $2.5^\circ \times 2.5^\circ$ ; second, calculates the grid average as the arithmetic mean of all stations in the grid; and third, uses the grid average estimate the national average by taking the areas of grid as weights



eastern part and sparse in the western part, and then estimated areal average of climatic variables based on the interpolation using an inverse-distance weighted technique from meteorological station observations. Furthermore, we divided China into 210 catchments to understand spatial characteristics of climatic variables changes.

During 1961–2010, the mean annual precipitation is 590 mm/a for the whole of China. There is a slight but no significant trend ( $p=0.78$ ), with a linear trend of  $0.08 \text{ mm/a}^2$ . Herein, the 1990s is the decade with the most precipitation of up to 599 mm/a. Precipitation change also shows a spatial pattern; therein, significant ( $p<0.05$ ) increase trends were detected in catchments in northwest China, with a linear trend ranging from 0.0 to  $3.0 \text{ mm/a}^2$ . In addition, a decrease in HaRB and an increase in the lower reach of YaBR were detected, and one of the possible causes is the weakening of Asian summer monsoon wind (Xu et al. 2006; Luo et al. 2013).

Mean annual surface air temperature is  $8.07 \text{ }^\circ\text{C}$ , and there is a significant ( $p<0.001$ ) warming trend ( $0.032 \text{ }^\circ\text{C/a}$ ) for the whole of China during 1961–2010. Also, the warming trend keeps accelerating, and the increment is  $0.51 \text{ }^\circ\text{C}$  from the 1990s to the 2000s. The warming trend is larger in China than in the Northern Hemisphere (Jones et al. 2012), and the difference is possibly due to the effect of rapid urbanization in China (Ren et al. 2012). Spatially, the warming trend is larger in northern China than in southern China.

Mean annual solar radiation is  $173.3 \text{ W/m}^2$ , together with a significant ( $p<0.001$ ) dimming trend ( $-0.14 \text{ W/(m}^2\cdot\text{a)}$ ) for the whole of China during 1961–2010. Different with the widespread brightening since the late 1980s proposed by Wild et al. (2005), our results show only a transient brightening in the 1990s and a  $-0.14 \text{ W/(m}^2\cdot\text{a)}$  dimming linear trend ( $p=0.07$ ) during 1994–2010. Spatially, the largest dimming trend appears in eastern China, especially in HaRB and HuRB and the lower reach of YaRB, ranging from  $-0.45$  to  $-0.51 \text{ W/(m}^2\cdot\text{a)}$ , and the possible cause is a high-aerosol concentration in those regions.

Mean annual wind speed at 10 m is  $2.48 \text{ m/s}$ , together with a significant ( $p<0.001$ ) stilling trend ( $-0.012 \text{ m/(s}\cdot\text{a)}$ ) for the whole of China during 1961–2010. Therein, it has a platform from 1961 to 1968 and afterward decreases until 1996, and then keeps steady. The causes of wind stilling were the changes in atmospheric circulation and surface roughness (Vautard et al. 2010), including urbanization (Hou et al. 2013) and an increase in agricultural irrigation (Han and Hu 2012; Han et al. 2012). In addition, the increases in aerosol concentration (Zhu et al. 2012) and the decrease in the south-north temperature gradient in China (Xu et al. 2006; Yang 2008) possibly contributed to wind stilling.

Remarkably, there are three large-scale instrument replacements, namely, wind speed instrument replacement during 1967–1970, solar radiation instrument replacement around the 1990s, and manual observations being replaced by

automatic weather stations during 2001–2005. Those lead to an inconsistency of observed climatic variable series, which may increase uncertainties of climate change analysis over China.

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