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Effects of surface wind speed decline on modeled hydrological conditions in China

X. Liu[1], X.-J. Zhang[1,2], Q. Tang[1], and X.-Z. Zhang[1]

[1]Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China

Correspondence to: Q. Tang (tangqh@igsnrr.ac.cn)

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Abstract. Surface wind speed decline in China has been widely reported, but its effects on hydrology have not been fully evaluated to date. In this study, the effects of wind speed change on modeled hydrological conditions are investigated using the Variable Infiltration Capacity (VIC) hydrological model for China during the 1966–2011 period. Two model experiments, i.e., VIC simulations with the observed (EXP1) and detrended wind speed (EXP2), are performed over the major river basins in China. The differences between the two experiments are analyzed to assess the effects of wind speed decline. Results show that wind speed has decreased by 29 % in China. The wind speed decline would have resulted in a decrease in evapotranspiration of 1–3 % of mean annual evapotranspiration and an increase in runoff of 1–6 % of mean annual runoff at most basins in China. The sensitivities of evapotranspiration and runoff changes to wind speed change are larger in humid areas than dry areas, while the sensitivity of soil moisture change to wind speed change is situation dependent. The wind speed decline would have offset the expansion of the drought area in China. It has contributed to reducing drought areas by 8.8 % of the mean drought area (i.e., approximate 106×10^3 km^2 out of 1.2×10^6 km^2) over China. The reductions of soil moisture drought induced by wind speed decline are large (more than 5 % of the mean drought area) in most basins, except in the Southwest and Pearl River basins.

1 Introduction

Drying trends have been detected in several regions of China during the past decades (Dai et al., 2004; Zou et al., 2005; Sheffield et al., 2012b). Soil moisture simulations derived from land surface models are widely used to assess hydrological drought conditions (Sheffield and Wood, 2008; Wu et al., 2011; Li and Ma, 2012). Soil moisture drought in China shows roughly the similar increasing trend in the last several decades as other drought indices (Wang et al., 2011). The reduction of precipitation and increase of temperature may have contributed to the drying trend in China (Ma et al., 2000; Ma and Fu, 2006; Xin et al., 2006; Tang et al., 2008b; Dai, 2011). However, few studies have addressed the effects of surface wind speed decline (i.e., atmospheric stilling) which may alleviate the drying of soil moisture by reducing atmospheric evaporative demand (McVicar et al., 2012b). Wind speed decline has been observed in the last several decades over many countries worldwide (Pryor et al., 2009; Vautard et al., 2010; Wan et al., 2010). The wind speed has declined as well over most areas in China (Xu et al., 2006; Jiang et al., 2010; Guo et al., 2011), including remote areas such as the Tibetan Plateau (Lin et al., 2013; Yang et al., 2014). The change in wind speed may have affected the surface hydrological cycle.

The hydrological consequence of wind speed decline has attracted great interest in recent years. The previous studies have tried to assess the effects of the wind speed decline on evaporation and suggested that the wind speed decline was a major or even the primary factor contributing to the decrease of evaporative demand (McVicar et al., 2012a). For example, Rayner (2007) and Roderick et al. (2007) suggested that wind speed change was the dominant factor causing the decreasing trends in pan evaporation in Australia. Wind speed decline was identified as the main factor that caused the decrease in pan evaporation in the Hai River basin (Zheng et al., 2009; Tang et al., 2011) and the dominant factor responsible for the decrease in pan evaporation from 1960 to the early 1990s in the northern and central regions of China (Liu et al., 2011). McVicar et al. (2012b) suggested that the impact of wind speed decline on actual evapotranspiration and streamflow was situation dependent. Wind speed decline tends to result in the decline of actual evapotranspiration and complementary increase of streamflow in wet river basins but has little impacts in dry basins. In the studies assessing the impacts of changes in meteorological variables on runoff in China, wind speed declines are often identified as being important. For instance, wind speed decline was the second greatest contributing factor, just after precipitation, to runoff changes at the Futuo River basin in northern China (Yang and Yang, 2011). The climate elasticity analyses suggested that runoff would increase 1–8 % when wind speed decreased 10 % at the catchments of the Hai River and the Yellow River basins of China (Yang and Yang, 2011). Increase in runoff induced by wind speed decline may have favored the recent recovery of natural runoff in the Yellow River basin (Tang et al., 2013).

Although the hydrological responses to widespread decline in wind speed have been reported at some basins in China, there are few studies in the literature assessing the hydrological impacts of wind speed decline across the major basins in China. While detecting the impacts of wind speed decline from observations is still difficult due to large variability of the hydrological variables, a model's approach could furnish a preliminary quantitative assessment. In this paper, a macroscale hydrological model is used to assess the effects of wind speed decline on the modeled hydrological conditions. The objective of this study is to quantify the potential contributions of wind speed change to changes in actual evapotranspiration, runoff, soil moisture and drought over the major river basins in China.

2 Method

The Variable Infiltration Capacity (VIC) hydrological model (Liang et al. 1994) is used to simulate the hydrologic conditions in the major rivers of China. The VIC model can enclose both water and surface energy within each model grid cell and it can statistically capture subgrid variability in land surface vegetation classes and soil moisture storage capacity. The key characteristics of VIC are the representation of vegetation heterogeneity, multiple soil layers (three soil layers are used in this study) with variable infiltration, and nonlinear base flow (Gao et al., 2010). Actual evapotranspiration in the VIC model consists of transpiration, canopy evaporation, and bare soil evaporation (Liang et al., 1994; Gao et al., 2010; Tang et al., 2012). Transpiration is estimated based on the potential evaporation calculated using the Penman–Monteith equation (Shuttleworth, 1993) and the architectural, aerodynamic and canopy resistances. Canopy evaporation is estimated from the intercepted water in canopy storage and potential evaporation. Bare soil evaporation is equal to potential evaporation at the saturated area and is below the potential rate at the unsaturated area. The evapotranspiration estimation in the VIC model is detailed in Liang et al. (1994) and Gao et al. (2010). The VIC model has been widely used for hydrological simulations in China (e.g., Xie et al., 2007; Wang et al., 2012) and throughout the world (Tang and Lettenmaier, 2010; Gao et al., 2010; Sheffield et al., 2012a). The routinely observed daily meteorological data (maximum and minimum temperature, precipitation, and surface wind speed measured at 10 m above ground) during the 1952–2011 period are obtained from the China Meteorological Administration (CMA). The meteorological data from 741 gauging stations are used in this study (Fig. 1). There are only a few stations available in the Tibetan Plateau and Northwest China. The analysis and results in these regions should be treated with considerable caution. The station data are interpolated to 0.25° grids using the synergraphic mapping system (SYMAP) (Shepard 1984) as implemented in the VIC model applications (Maurer et al., 2002; Tang et al., 2009). The SYMAP method uses an inverse distance squared weighting of observations at stations within a prescribed distance from a grid point to estimate the value at the grid. During the interpolation process, temperatures are lapsed by a rate of 6.5 °C km^{-1} to account for elevation differences between the target grid and the stations used in the interpolation (Maurer et al., 2002). No elevation adjustment is made for precipitation and wind interpolation. The model is run at a daily time step forced by the gridded meteorological data, and is calibrated following Shi et al. (2008) against the observed monthly streamflow data at 15 hydrological stations in the major basins of China (Fig. 1). The VIC model parameters are calibrated using an optimization of the multi-objective complex evolution (MOCOM-UA) method (Yapo et al., 1998) as detailed in Zhang et al. (2013, 2014). Surface radiations in the VIC model are derived from precipitation, mean temperature and diurnal temperature range using the built-in MTCLIM (Mountain Climate Simulator) algorithm (Kimball et al., 1997; Thornton and Running, 1999), the performance of which has been globally evaluated (Bohn et al., 2013). The radiation estimates in the VIC model were evaluated in Zhang et al. (2013, 2014) by comparing them with a radiation data set incorporating the available ground

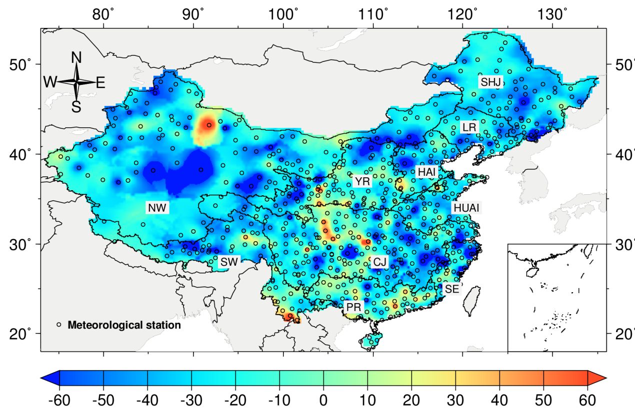

Figure 1. Relative change magnitude (%) of annual surface wind speed during the 1966–2011 period in China. The major river basins (NW: Northwest, YR: Yellow River, HAI: Hai River, LR: Liao River, SHJ: Songhuajiang, SW: Southwest, CJ: Yangtze River, HUAI: Huai River, PR: Pearl River, SE: Southeast) in China are shown.

radiation observations in China (Yang et al., 2010; Chen et al., 2011). The VIC model showed generally good performance in reproducing streamflow and surface radiations in China.

The VIC model is run with a long model spin-up period from 1952, producing an initial model state from which the experiments start. Two VIC experiments are performed over China for the period of 1966–2011. One experiment is forced with the observed wind speed (EXP1), and the other experiment is forced with the detrended wind speed (EXP2). The linear trends in annual wind speed over the study period are removed at each grid cell, and the mean of the detrended time series of wind speed is fixed to the mean of the first decade (1966–1975) in EXP2 (Tang et al., 2008b). Using the detrending method, the original time series of annual wind speed is adjusted to a time series without linear trend. The daily wind speed of each year is then adjusted using the proportion of the detrended annual value to the original annual value.

Three hydrological variables, evapotranspiration, runoff and total soil moisture of the three soil layers produced by the VIC model are used for analyses. The time series of differences in the annual means of the three hydrological variables between EXP1 and EXP2 are calculated to assess the wind speed decline effects. The change trends of the time series are calculated using the linear least-squares regression. The statistical significance of trend is evaluated by Student's t test at the 95 % confidence level (Santer et al., 2000). The change magnitude during the study period is computed as the slope of the linear regression times the length of the study period. The relative change magnitude is then calculated as the percentage of change magnitude relative to the mean value (Tang et al., 2008a).

Monthly soil moisture is transformed to percentiles by fitting it with an empirical cumulative probability distribution (Weibull distribution) for each grid cell and each month (Andreadis et al., 2005). The transformed soil moisture index is used in the soil moisture comparisons between EXP1 and EXP2. Drought is identified if the monthly soil moisture index is less than 20 % in a grid cell. The area sum of the drought grid cells is calculated for each month. The annual mean drought area is computed in the major river basins in China (Fig. 1). The Northwest, Yellow River, Hai River, Liao River and Songhuajiang River basins are referred as the northern basins and the rest are referred as the southern basins according to their geographic locations.

3 Results

The relative change magnitude of wind speed during the 1966–2011 period in China is shown in Fig. 1. Annual wind speed decreased by more than 20 % during the study period in most areas of China. Wind speed decreased up to 80 % in some regions in the Northwest, Songhuajiang, Yangtze River and Southeast River basins. Several previous studies have proposed different mechanisms to explain the wind speed decline, including upper-air wind change (Lin et al., 2013), temperature contrasts between land and ocean (Jiang et al., 2010), lower-troposphere pressure-gradient force and urban effects (Guo et al., 2011), air pollution (Xu et al., 2006), and surface roughness change (Vautard et al., 2010). All these studies have found widespread wind speed declines from urban to remote areas and across different climate regions. Some stations (located in the middle Yangtze River, Pearl River and Northwest basins) show wind speed increase, which is the opposite change direction of all neighboring stations. The wind speed change at these stations might be affected by local changes surrounding the stations. The opposite changes were also reported in the previous studies (e.g., Xu et al., 2006 and Guo et al., 2011). We examined the altitude differences between the station with opposite change and its four nearest stations and did not find a systematic altitude difference. Thus the opposite changes are unlikely caused by the altitude difference between the stations (Luo et al., 2008). Although the causes of opposite change are unclear, the opposite change likely has little influence on our impact assessment because the number of stations showing wind speed increase is quite small, accounting for less than 3 % of the stations investigated.

Figure 2 shows the areal annual wind speed before and after removing the tendencies of the major river basins in China. The observed wind speed shows a significant decreasing trend for all the basins. The trend is generally linear in China during the study period although the decreasing rate seems more rapid in the 1970s and 1980s than other periods in some river basins such as the Northwest Basin. This is in line with the previous studies (Jiang et al., 2010; Guo

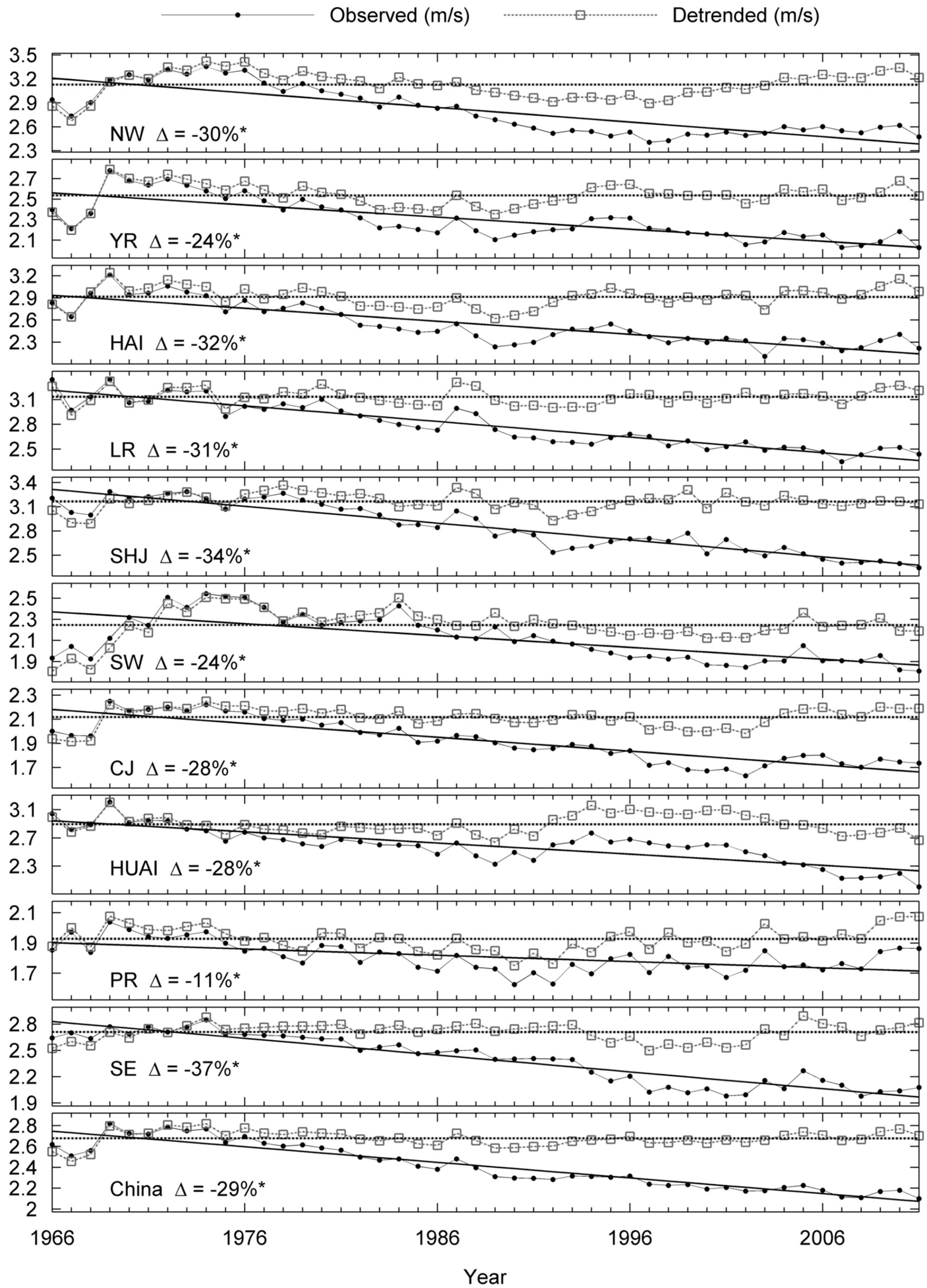

Figure 2. The observed and detrended time series of annual wind speed at the major river basins in China. The straight solid and dashed lines are trends for EXP1 and EXP2, respectively. Relative change magnitudes (Δ) of the observed annual wind speed during the study period are shown. The "*" symbol indicates the observed trend is significant.

et al., 2011) which found that surface wind speed in China stayed at a relatively high level in the 1960s and significantly declined after the 1970s. There is a step change in surface wind speed around the late 1960s. The step change might be spurious. While some previous studies suggested that the step change was caused by changes to the observation instrument (Xu et al., 2006; Fu et al., 2011; Chen et al., 2013), a recent study argued that step change was likely real (not instrumental) because the observed ground–air temperature gradient showed a similar step change during the same period (Lin et al., 2013). The cross-validation results in the recent study (Lin et al., 2013) suggested that the trends of

Table 1. Relative change magnitude (%) of annual evapotranspiration and runoff and change magnitude of soil moisture index for the major river basins during the 1966–2011 period. E1 and E2 are evapotranspiration from EXP1 and EXP2, respectively; likewise, R1 and R2 are for runoff, and S1 and S2 are for soil moisture index. Bold number indicate the trend is statistically significant.

Basin	E1	E2	R1	R2	S1	S2
NW	6.9	**8.0**	**20.5**	14.9	**−14.6**	**−16.3**
YR	−5.2	−4.4	−14.3	−16.4	**−18.1**	**−19.4**
HAI	−8.6	−8.0	−25.5	−27.6	**−20.3**	**−22.0**
LR	**−10.4**	−8.8	−4.0	−7.4	−6.1	−7.8
SHJ	−6.2	−3.6	7.8	1.5	−6.8	**−9.9**
SW	0.4	1.7	−5.7	−6.9	**−15.7**	**−15.8**
CJ	−2.3	−1.2	−2.2	−3.4	**−12.6**	**−13.3**
HUAI	0.4	1.7	13.5	11.8	10.9	8.2
PR	−3.7	−3.2	−3.8	−4.2	−7.3	−7.5
SE	0.3	1.6	7.7	6.4	0.1	−1.3
China	−3.0	−1.8	0.0	−1.5	**−9.1**	**−10.5**

the CMA surface wind speed data were quantitatively reliable although the changes to the instrument and station location might have contaminated the wind speed observation to some degree (Cao and Yan, 2012). The nonlinearity of the change is not considered and the linear trend is adopted as a first step to assess the effect of surface wind speed decline on the hydrologic cycle. The largest and smallest decreasing magnitudes are found in the Southeast (−37%) and Pearl River basins (−11%), respectively. In China, the wind speed decreased by about 29 % during the study period.

Table 1 shows the relative change magnitudes in evapotranspiration and runoff and change magnitude in soil moisture from EXP1 and EXP2 during the study period for the major river basins. The hydrological variables from EXP1 show a decreasing trend for most basins, but the trends in evapotranspiration and runoff are seldom significant. The relative change magnitude in evapotranspiration from EXP1 is smaller than that from EXP2 at all the river basins, indicating that wind speed decline would have caused a decrease in evapotranspiration. Consequently, the relative change magnitude in runoff from EXP1 is greater than that from EXP2, suggesting that more runoff would have been generated due to the wind speed decline. Although the effect of wind speed decline is relatively small compared to the runoff change caused by other climatic factors, it may be important for the northern dry river basins such as the Northwest, Yellow River, and Hai River where small changes in hydrology and water resources would have significant implications for water management. Soil moisture has decreased in most of the river basins, with significant decreases in the Northwest, Yellow River, Hai River, Southwest and Yangtze River basins. The decreasing soil moisture in the Northwest river basins is interesting, especially in the context of increases in evapotranspiration and runoff. It implies a general increase in soil moisture drought in the arid and semiarid areas. The change magnitude in soil moisture from EXP1 is greater than that from EXP2 at all the river basins, suggesting that wind speed decline would have alleviated the soil moisture drought although it could not reverse the general drying trend. Figure 3 shows the EXP1 and EXP2 differences (EXP1 minus EXP2) of annual evapotranspiration, runoff, and soil moisture index from 1966 to 2011. The differences are generally small in the 1960s because the wind speed in EXP2 is set to the 1960s' conditions in EXP1. The differences become large at present (i.e., the end of the study period) when the wind speed difference becomes large. The relative change magnitude of the difference provides an assessment of the effect of wind speed decline to the modeled hydrological conditions. Note that the trends of the differences between EXP1 and EXP2 are significant because of the significant decline in wind speed, but the trend of the individual hydrologic variable is seldom significant (Table 1) due to its large natural variability. At all the river basins, wind speed decline would result in decrease in evapotranspiration and increase in runoff and soil moisture. The annual evapotranspiration in the 2000s would be more than 5 mm higher in most basins in eastern and southern China and about 2 mm higher in the northern dry basins if the wind speed stayed at a relatively high level in the 1966–1975 period. The wind speed decline would have resulted in a decrease in evapotranspiration of 1–3 % of mean annual evapotranspiration and an increase in runoff of 1–6 % of mean annual runoff at most basins. The relative change magnitude of runoff associated with wind speed decline is generally large (3–6%) in the northern basins and small (1–2%) in the southern basins. The simulated soil moisture index in the 2000s is higher than the soil moisture index simulations in which the wind speed was assumed to stay at a relatively high level in the 1966–1975 period. The relative change magnitude of the soil moisture index is about 3 % in China, and is generally large in the northern basins (3–6%) and small in the southern basins (mostly less than 3 %). It suggests that wind speed decline may play a role in regulating soil moisture drought. The variability of the differences seems to increase with time in Fig. 3. There is little difference in wind speed between EXP1 and EXP2 during the 1966–1975 period when the annual means of wind speed are the same for the two experiments. The variability increases when wind speed differences become large after the 1970s (see Fig. 2). The large variability is likely due to the nonlinear hydrological responses to wind speed change.

Figure 4 shows the relative change magnitude of the differences (EXP1 minus EXP2) of annual evapotranspiration, runoff and soil moisture index from 1966 to 2011 at the model grid cells. The relative change magnitude of evapotranspiration difference (Fig. 4a) is negative in most areas of China with great changes (less than −4 %) in parts of the southern basins and the Songhuajiang and Northwest basins. The positive differences are scattered in the middle Yangtze River, Pearl River and Northwest basins, corresponding to

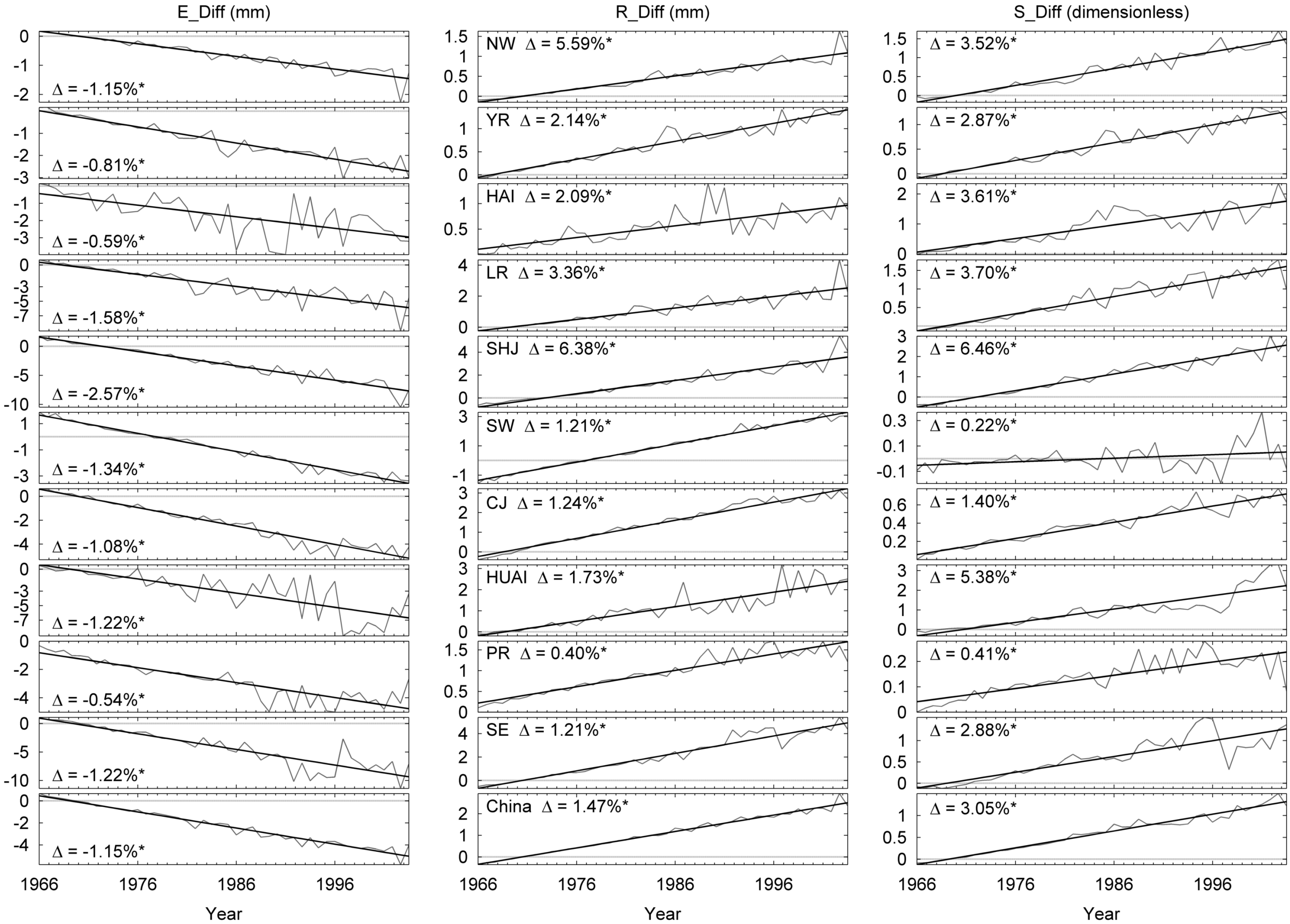

Figure 3. Differences of annual evapotranspiration (E_{Diff}), runoff (R_{Diff}) and soil moisture index (S_{Diff}) between EXP1 and EXP2 for major river basins and the whole of China. Δ is the relative change magnitude. The "*" symbol indicates the trend is significant.

the stations with increased wind speed (see Fig. 1). The estimated runoff and soil moisture from EXP1 are generally more positive than those from EXP2. The relative change magnitude of runoff difference (Fig. 4b) is positive in most areas of China and negative at some scattered locations, corresponding to the stations with increased wind speed. The relative change magnitude of the runoff difference is large (2–10 %) in northeastern and northwestern China, while it is small (less than 2 %) in southern China. It should be noted that the change magnitude in the southern China is comparable to that in the northern China because the mean annual runoff is larger in southern China. The relative change magnitude of the soil moisture index difference (Fig. 4c) is large in the north of northwestern China and eastern China where the wind speed decline is large. This suggests that wind speed decline may have alleviated the soil moisture drought over these areas. Again, the relative changes of the soil moisture difference are negative at some scattered locations in the Southwest, Pearl River and Northwest basins, corresponding to the stations with increased wind speed. It should be noted that the results in the Southwest and Northwest basins may be of high uncertainty because of the low density meteorological stations.

The modeled sensitivities of changes in the hydrological variables to wind speed change are shown in Fig. 5. The sensitivity of annual evapotranspiration change (Fig. 5a) is positive across China, with large sensitivity in the humid regions including the southern basins and parts of the Songhuajiang and Northwest basins. The sensitivity of evapotranspiration change is small (less than 8 mm change in annual evapotranspiration associated with $1\,\mathrm{m\,s^{-1}}$ decline in wind speed) in the dry regions including large parts of the Northwest, Yellow River, Hai River and Liao River basins. The sensitivity of annual runoff (Fig. 5b) to wind speed change is negative across China with small sensitivity in the dry regions and high sensitivity in the humid regions. It is likely because actual evapotranspiration is more closely related to precipitation so wind speed change has little impact on streamflow in the arid environments (McVicar et al., 2012b). The sensitivity of the soil moisture index (Fig. 5c) is generally

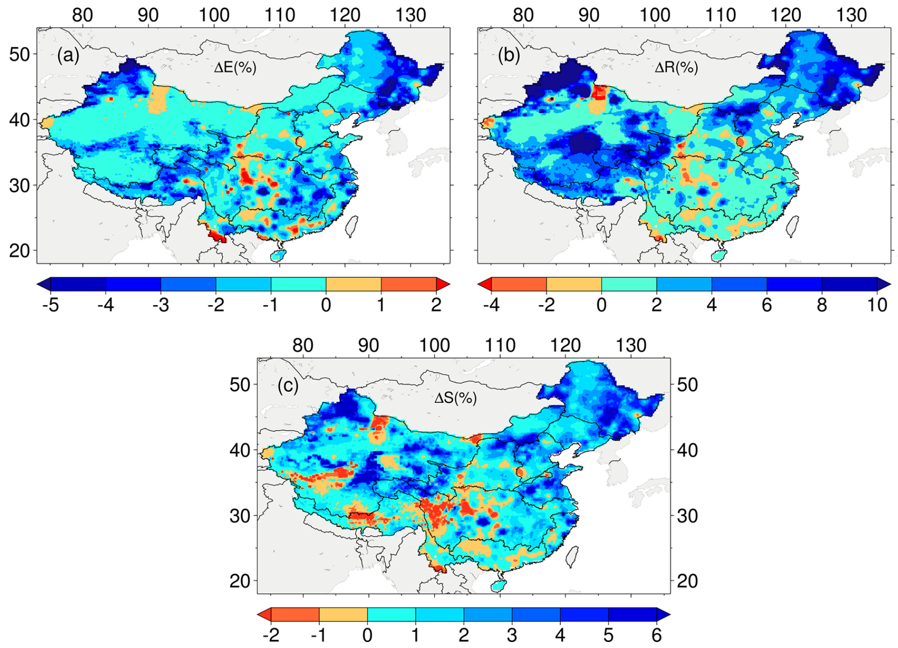

Figure 4. Relative change magnitude of the differences in evapotranspiration **(a)**, runoff **(b)** and soil moisture index **(c)** between EXP1 and EXP2 in 1966–2011.

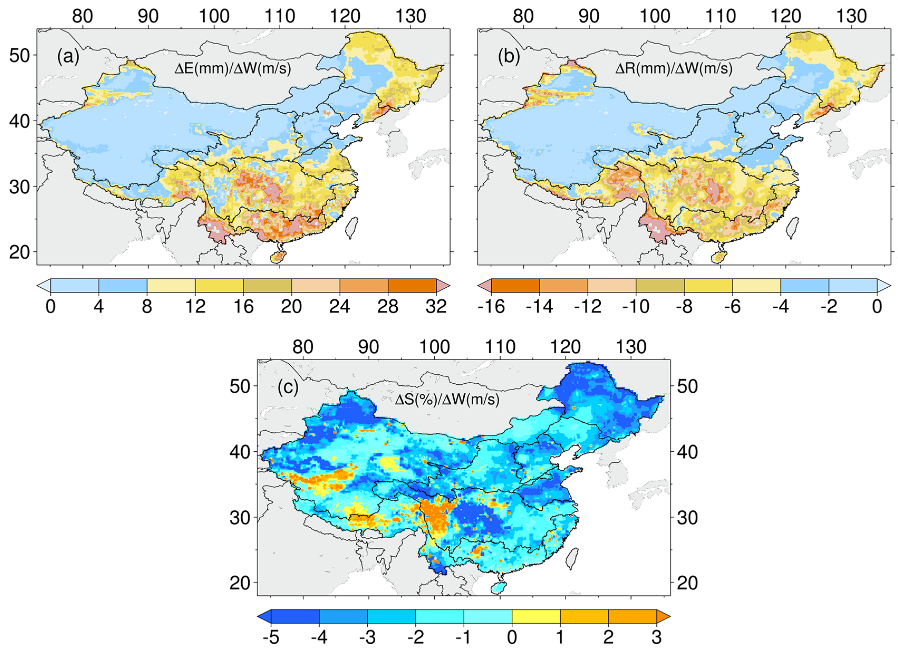

Figure 5. The modeled sensitivities of annual evapotranspiration **(a)**, runoff **(b)** and soil moisture index **(c)** to wind speed change. Sensitivity is calculated as the change magnitude of the differences of the hydrological variables between EXP1 and EXP2 divided by the change magnitude of wind speed in 1966–2011.

negative across China, suggesting that wind speed decline would generally suppress evapotranspiration and leave more moisture in the soil layer. However, in a small part of the Tibetan Plateau, wind speed decline seems to result in the increase in ground temperature and might lead to the increase in evapotranspiration and decrease in soil moisture (Yang et al., 2014).

Figure 6 shows the drought area and the effect of wind speed decline on the drought area change during the study period. The estimated mean drought area is about

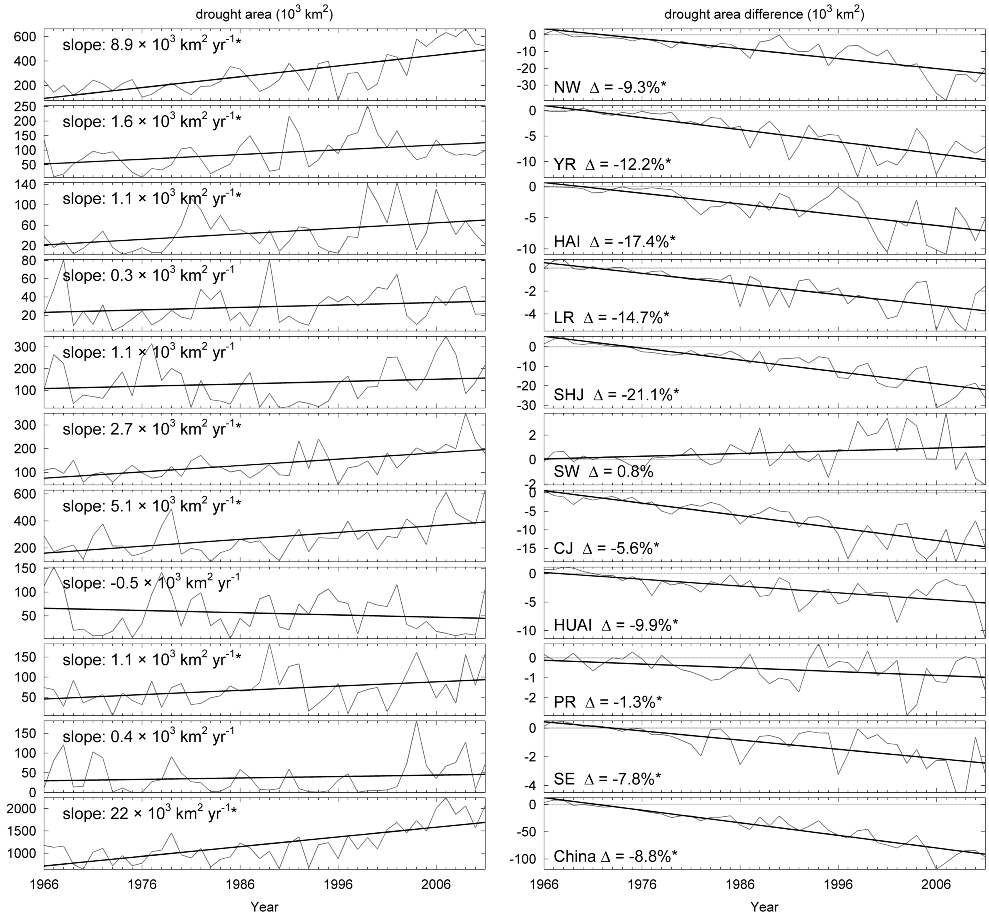

Figure 6. Annual drought area from EXP1 (left) and the drought area differences (EXP1 minus EXP2) (right). Δ is the relative change magnitude. The "*" symbol indicates the trend is significant.

1.2×10^6 km^2 across China. The drought area in China has increased at a rate of 22×10^3 km^2 yr^{-1} during the study period. Significant increases in drought area are found in six river basins, namely the Northwest, Yellow River, Hai River, Southwest, Yangtze River and Pearl River basins. The Northwest Basin shows the largest increasing trend in drought area (8900 km^2 yr^{-1}) followed by the Yangtze River basin (5100 km^2 yr^{-1}). The Liao River, Songhuajiang River, and Southeast basins show a nonsignificant increasing trend, while the Huai River basin shows a nonsignificant decreasing trend in the drought area. Wu et al. (2011) used the VIC model to estimate soil moisture drought in the nine regions of China during the 1951–2009 period. Wang et al. (2011) used the ensemble of soil moisture from four land surface models to estimate soil moisture drought in China during the 1950–2006 period. They have also reported a general increasing trend of drought area in most parts of China.

Although the modeled drought area increased, wind speed decline shows the effect of reducing the modeled drought area. The estimated drought area with the observed wind speed is generally smaller than the estimates that assume the wind speed stayed at a relatively high level in the 1960s. Wind speed decline has contributed to reducing the drought area by 21.1, 17.4, 14.7 and 12.2 % of the mean drought area in the Songhuajiang River, Hai River, Liao River and Yellow River basins, respectively. The effect of wind speed change on drought area is small at the Southwest and Pearl River basins where wind speed decline and its effect on soil moisture are relatively small. Over China, wind speed decline has contributed to reducing drought areas by 8.8 % of the mean drought area by the end of the study period. In other words, the drought area implied by the simulation at present could be 106×10^3 km^2 larger if the wind speed at present stayed at a relatively high level as in the 1960s.

4 Conclusion and discussion

Effects of surface wind speed decline (atmospheric stilling) on modeled hydrological conditions in China during the 1966–2011 period are investigated using the VIC model. Two VIC experiments, one using the observed (EXP1) and the other using the detrended wind speed (EXP2), are implemented. The differences in hydrological variables and soil moisture drought between the two experiments are compared to assess the wind speed decline effects. Results show that wind speed decline has somewhat offset the land surface drying trend in China.

Surface wind speed in China has decreased by 29 % of its mean during the study period. The decline of wind speed has resulted in a reduction in evapotranspiration and an increment in runoff and soil moisture in all the river basins. This suggests that wind speed decline would offset the drying trend and favor a wet condition. The results show that land surface would be even dryer without wind speed decline. The wind speed decline has resulted in an increase in runoff of 1–6 % of mean annual runoff at most basins. The effect of wind speed on runoff and soil moisture is large in the northern basins and relatively smaller in the southern basins. The sensitivity of evapotranspiration change to wind speed change is positive across China with larger sensitivity in humid areas than dry areas. The sensitivity of runoff change to wind speed change is negative, with great sensitivity in humid areas and little sensitivity in dry areas. The sensitivity of soil moisture change to wind speed change is situation dependent and is generally negative.

The area of soil moisture drought has significantly increased in most basins, and has increased at a rate of $22 \times 10^3\,\mathrm{km^2\,yr^{-1}}$ in China during the study period. Although the drought area has increased rapidly, the increasing rate could be even larger without wind speed decline. Our results show that wind speed decline has contributed to reducing drought areas by 8.8 % of the mean drought area over China. Wind speed decline has alleviated the soil moisture drought over a $106 \times 10^3\,\mathrm{km^2}$ area comparing with the experiments in which wind speed is assumed to be at the high condition in the 1960s. The effect of wind speed decline on soil moisture drought is large in most basins in China except for the Southwest and Pearl River basins.

The assessment presented here is based on the observations at the meteorological stations and the simulations of the VIC model. The results in western China (e.g., the Southwest and Northwest basins) may have large uncertainty because of the sparse stations. The wind speed observations may be affected by the local environments. There are a few suspicious stations showing opposite change direction of wind speed from all neighboring stations. The interpolated wind speed data are imperfect with these suspicious stations. Furthermore, the parameterization of land surface processes in the model may affect the results and the assessment might be model dependent. Decline in surface wind speed may be accompanied with changes in cloud, radiation, and other meteorological parameters due to the complex interactions in the climate system. The coupled changes and their effects on hydrological conditions are not considered in this paper. In spite of these deficiencies, the model-based assessment can provide useful information concerning the effects of wind speed decline on the hydrological conditions in China. The signs of the modeled sensitivities of evapotranspiration and runoff agree well with the observations reported in the previous studies and are expected according to the evapotranspiration theory (McVicar et al., 2012a). The modeled evapotranspiration and runoff sensitivities are greater in humid areas than dry areas, which is also in line with the previous findings (McVicar et al., 2012b).

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