EVALUATION OF CLIMATE CHANGE IMPACTS ON HYDROLOGICAL PROCESSES IN THE YANGTZE RIVER DELTA REGION, CHINA

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(Received 28th Oct 2016; accepted 28th Feb 2017)

Abstract. Water resources in the Yangtze River Delta region have been suffering significant impacts of increasing extreme hydrological events associated with climate change. In the present work, the Taihu Basin was selected as the study area to quantify the effects of climate change on hydrological processes using an integrated modeling system, coupling the distributed hydrological model VIC (Variable Infiltration Capacity) with the regional climate model PRECIS (Providing Regional Climate for Impact Studies) generating future climate scenarios. The results indicate that the mean annual runoff under different future climate scenarios will increase, especially during flood seasons, which is consistent with the changes in precipitation and evapotranspiration for both spatial and temporal distribution, implying more frequent occurrence of extreme floods in the future. These results are significant to future water resources management and sustainable development in the Yangtze River Delta region.
Keywords: *water cycle, distributed hydrological model, downscaling, flood, water resources, extreme events*

Introduction

Taihu Basin, located in the Yangtze River Delta, east China, is a typical area in China with high vulnerability to natural disasters for its rapid development of economics and society. In recent years, frequent occurrence of extreme flood events in the basin has received significant attention from both local and central government in China, especially two major flood events in 1991 and 1999 with water levels that exceeded historical records and induced severe damage to local people's property and safety. Increasing extreme precipitation events associated with great spatio-temporal variation induced by climate change are expected to lead to more frequent occurrence of extreme flood events (Jiang et al., 2005; Su et al., 2006; He, 2007). For the special natural topography and great anthropogenic activities in the Taihu Basin which is a typical complex river network region mainly characterized by dense river networks, polders and hydraulic structures, it is of great importance for officials to understand and prepare to deal with the effects of climate change. Some hydrological models have been applied to investigate the impact of climate change on runoff and water resources in the Taihu Basin. The distributed hydrological model L-THIA, and the conceptual hydrological models LASCAM, STREAM and HEC-HMS (Wu et al., 2006; Zhang et al., 2006; Li et al., 2007; Wan et al., 2007) have been applied to investigate the impact of climate change on runoff and water resources in the Taihu Basin, mostly focusing on runoff simulation and the impact of LUCC on streamflow. Wang et al. (2000) analyzed the flood generating process in the Taihu Basin according to a numerical model of river network unstable flow; Gao (2002) discussed the flood

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1503_10251040

response to land use change in the Taihu Basin and indicated that the increase of land use for construction purposes would result in serious damage. However, acceleration of the hydrological cycle induced by climate change and intensive urbanization will result in more frequent occurrence of extreme events, which could not be effectively reflected in previous studies.

In this study, VIC-3L (Variable Infiltration Capacity-Three Layer) model, the latest version of VIC, was coupled with PRECIS (Providing Regional Climate For Impacts Studies) regional climate model to assess the impact of climate change on runoff and evapotranspiration in the Taihu Basin at a spatial resolution of 5 km × 5 km, and the Xitiaoxi catchment located at the southwest of the basin was selected to calibrate VIC model parameters. Results of this study could be used to provide a technical support for water resources management in the Yangtze River Delta region, especially under future global climate change scenarios.

Methodology

Study area description

Taihu Basin, with an area of 36895 km^2, is located on the southern side of the Yangtze River Delta region, which incorporates three provinces (Shanghai, Jiangsu and Zhejiang) currently hosting 13% of China's GDP. Due to its remarkable vulnerability to flooding and more and more significant impact of climate change, the area is now facing sever challenge for water resources management.

Area of the lakes is more than 2000 km^2 in the basin, including the large Taihu Lake, from where the basin derives its name. Floodplain covered with dense river networks counts for about 67% of the total area in the basin, while others are comprised of hills or mountains. Average annual precipitation ranges from 1010 to 1400 mm in the basin, and most precipitation occurs between June and August in a year. Meteorological stations within or around the Taihu Basin is shown in *Fig. 1*.

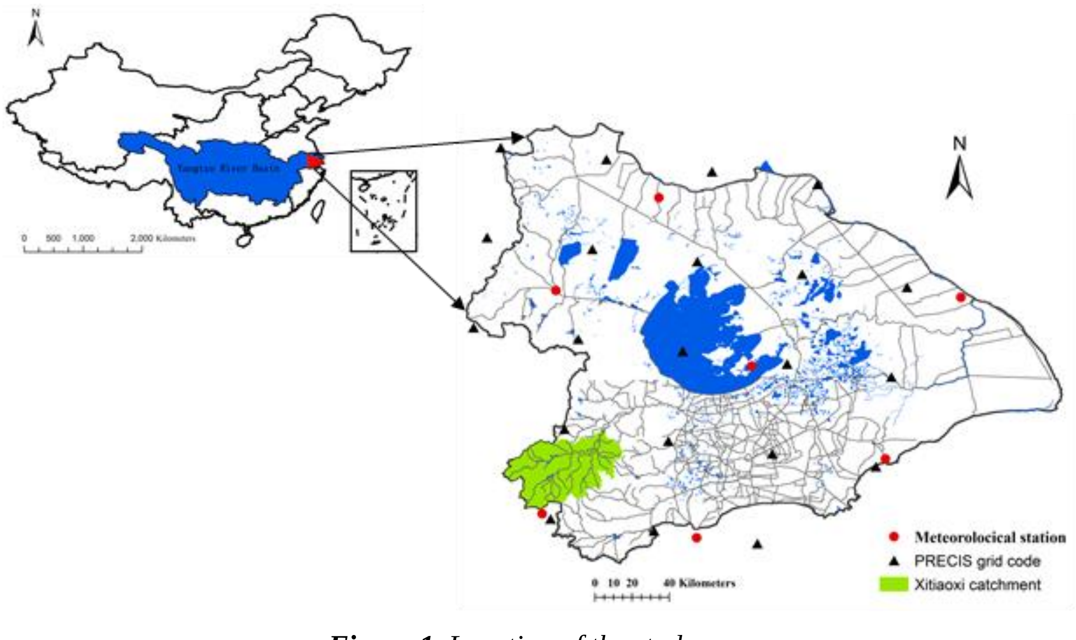

Figure 1. *Location of the study area*

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DOI: http://dx.doi.org/10.15666/aeer/1503_10251040

VIC model

The VIC macro-scale hydrological model was selected to evaluate hydrological responses to climate change in the Taihu Basin, which could be characterized as: (1) with both water balance and energy balance parameterization (Liu, 2015); (2) with two kinds of runoff generation mechanism-saturation excess runoff and infiltration excess runoff (Xie et al., 2003); (3) with the consideration of sub-grid scale soil heterogeneity (Liang and Xie, 2001); and (4) the sub-grid spatial variability of precipitation (Liang et al., 1996).

Calibration and validation of the VIC model have already been conducted by Liu and Xu (2015) in the Xitiaoxi catchment, which demonstrates that it is feasible to transfer parameters calibrated in the Xitiaoxi catchment to the entire basin for the impact assessment of climate change. In this study, the calibrated VIC model by Liu and Xu (2015) would be coupled with the regional climate model to evaluate climate change impacts on hydrological processes in the Taihu Basin.

Regional climate model

Details of PRECIS could be found in Jones et al. (2004). PRECIS outputs have already been successfully used to generate climate change scenarios in China for the period from 2000 to 2100, indicating spatio-temporal distributions of precipitation, maximum and minimum air temperatures in China could be simulated well by PRECIS (Xu et al., 2005; Xu and Jones, 2004). To validate the adaptability of PRECIS in the Taihu Basin, in the current study, daily precipitation, daily maximum and minimum air temperature over the Taihu Basin for baseline (Bs) during the period from 1961 to 1990 and 2030s during the period from 2021 to 2050 were simulated by running PRECIS at a 50 km×50 km resolution. A2 and B2 scenarios in terms of IPCC (Intergovernmental Panel on Climate Change) Special Report on Emissions Scenarios (SRES) were adopted. Observed data for the period 1961-1990 from the meteorological stations over the Taihu Basin were selected to validate the simulation capacity of PRECIS, the distribution of meteorological stations and PRECIS grids were shown in *Fig. 1*.

Results

PRECIS validation

Precipitation

In this study, precipitation intensity was graded to seven types according to meteorology observation regulation: grade 1: 0.0-0.1 mm/d, grade 2: 0.1-10.0 mm/d, grade 3: 10.0-25.0 mm/d, grade 4: 25.0~-50.0 mm/d, grade 5: 50.0-100.0 mm/d, grade 6: 100.0-250.0 mm/d, grade 7: >=250.0 mm/d. Frequencies and percentiles of wet day precipitation from PRECIS and gauging stations were calculated according to these grades.

Observed precipitation data for the period 1961-1990 from 9 meteorology stations over the basin were analysed to derive extreme value statistics of 10-90 day precipitation totals. Using the Pearson-III distribution curve, extreme rainfall corresponding to the 50, 100, 200 and 500 year return period events were estimated for 10, 30, 60, 90 day duration and for each station respectively. Results were shown in *Table 1*.

APPLIED ECOLOGY AND ENVIRONMENTAL RESEARCH 15(3): 1025-1040.
http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
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Table 1. *Extreme precipitation for each return period and each duration (based on observation of 1961-1990, Unit: mm)*

station	duration	long return period				
		1000a	**500a**	**200a**	**100a**	**50a**
58238 Nanjing	10d	593.51	552.15	496.71	454.02	410.62
	30d	754.78	713.53	657.19	614.32	566.86
	60d	950.36	905.12	842.93	793.78	742.15
	90d	1115.76	1066.72	999.23	945.63	889.08
58343 Changzhou	10d	455.83	430.72	396.51	369.72	341.99
	30d	638.04	607.67	565.92	532.92	498.26
	60d	848.28	809.96	757.24	715.43	671.36
	90d	1054.99	1011.23	950.99	903.04	852.40
58345 Liyang	10d	503.45	472.74	431.23	399.03	365.89
	30d	658.47	625.82	581.15	546.77	509.35
	60d	900.25	858.48	801.04	755.55	707.70
	90d	1103.07	1057.31	994.33	944.20	891.24
58358 Wuxiandongshan	10d	401.09	378.45	347.85	324.05	299.49
	30d	619.49	588.30	545.69	513.36	477.36
	60d	805.79	771.36	723.98	686.30	646.52
	90d	990.79	950.69	895.45	851.45	804.97
58367 Longhua	10d	409.36	388.91	360.91	338.79	315.58
	30d	639.07	607.39	564.03	530.67	494.35
	60d	809.35	774.77	727.17	689.33	649.38
	90d	1053.73	1008.71	946.74	897.46	845.45
58436 Ningguo	10d	666.65	614.49	545.09	492.25	439.09
	30d	933.23	870.60	786.77	722.32	656.90
	60d	1127.79	1064.94	979.99	914.12	846.32
	90d	1591.68	1495.22	1365.52	1265.48	1163.54
58445 Tianmushan	10d	494.02	470.02	437.16	411.20	383.97
	30d	756.64	726.28	684.39	650.98	615.66
	60d	1092.17	1051.23	994.70	949.53	901.59
	90d	1364.65	1317.41	1251.74	1199.15	1143.40
58457 Hangzhou	10d	440.99	418.55	387.84	364.01	338.45
	30d	684.16	653.25	610.73	577.00	541.46
	60d	863.05	829.60	783.25	746.39	707.29
	90d	1107.78	1064.31	1004.51	957.14	907.28
58464 Pinghu	10d	666.68	612.48	540.65	486.03	431.16
	30d	681.61	646.90	599.41	561.89	522.55
	60d	809.91	775.31	727.68	689.80	649.82
	90d	957.17	919.13	866.77	825.21	781.37

Based on the daily gridded data from PRECIS and observed data from nine gauging stations (as shown in *Table 1*), seasonal and annual mean precipitation for the Taihu Basin were obtained by spatial interpolation, from which frequency-intensity curves of

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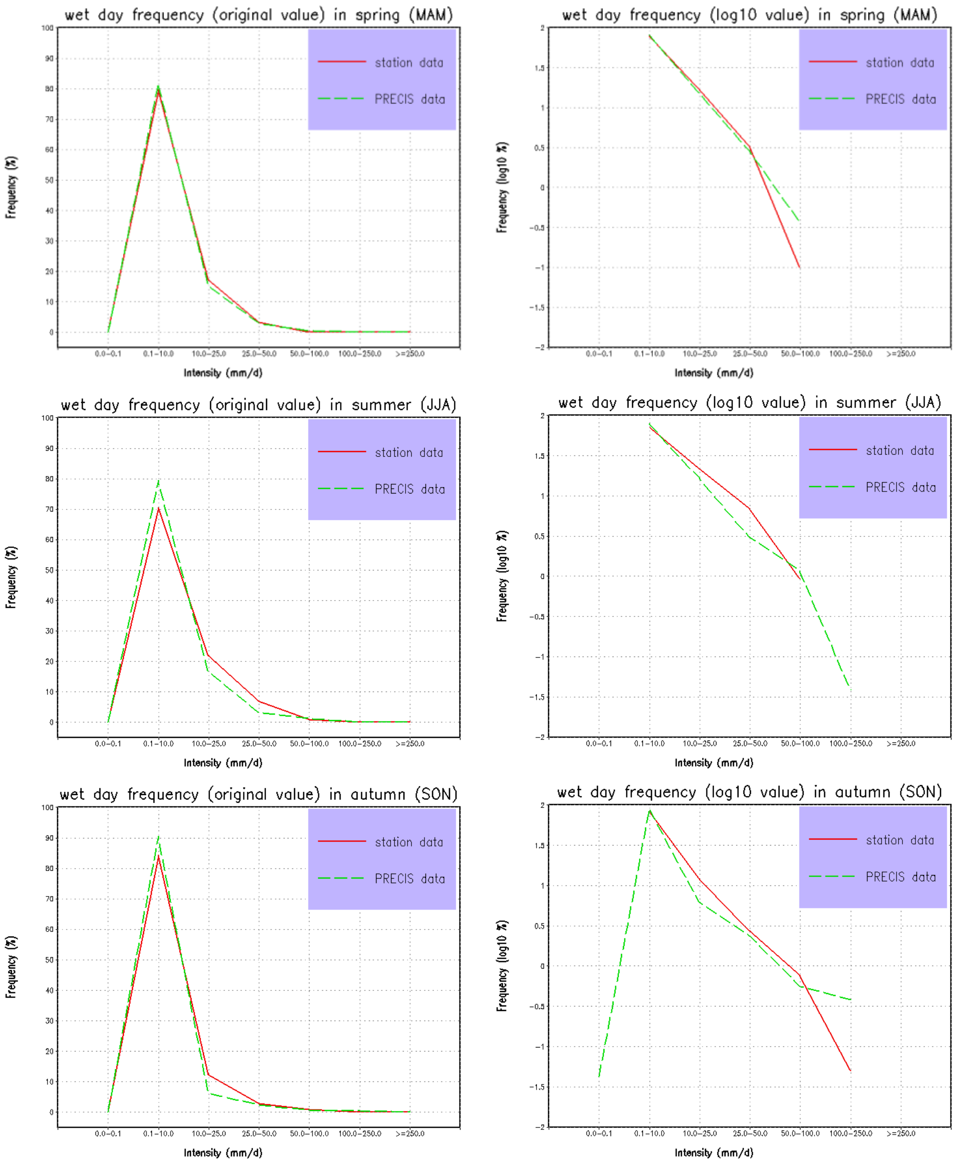
precipitation were drawn. As shown in *Fig. 2*, most part of frequency-intensity curves of PRECIS and observation fit well, implying a satisfied simulation capacity of PRECIS in the Taihu Basin. However, frequencies of grade 2 (0.1-10.0 mm) simulated by PRECIS are higher than those from gauging stations in all calculated time-scales, especially in summer, while frequencies of grade 4 (25.0-50.0 mm) from PRECIS are smaller than those calculated by observed data, where most difference also occurs in summer.



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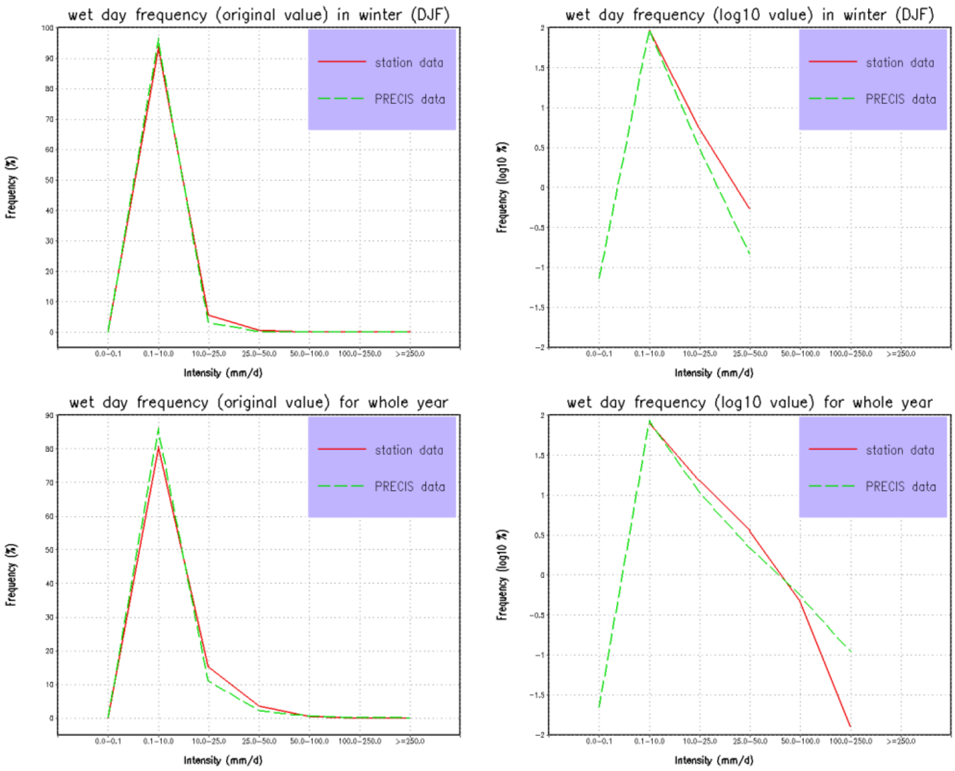

Figure 2. *Frequency-intensity curve (left) and log10 curve (right) of precipitation of region average for each season and whole year data*
X,Y-coordinate represent intensity (unit: mm/d) and frequency (unit: %) respectively

The mean annual frequency-intensity curves of wet day precipitation for nine gauging stations and the whole basin were used to assess the simulation effect of spatial patterns. For PRECIS data, the curve was drawn based on the data from the grid-box containing the corresponding station. As shown in *Fig. 3*, gridded simulations from PRECIS fit quite well with observations from nine gauging stations, while there is a slight difference after interpolating to the whole basin.

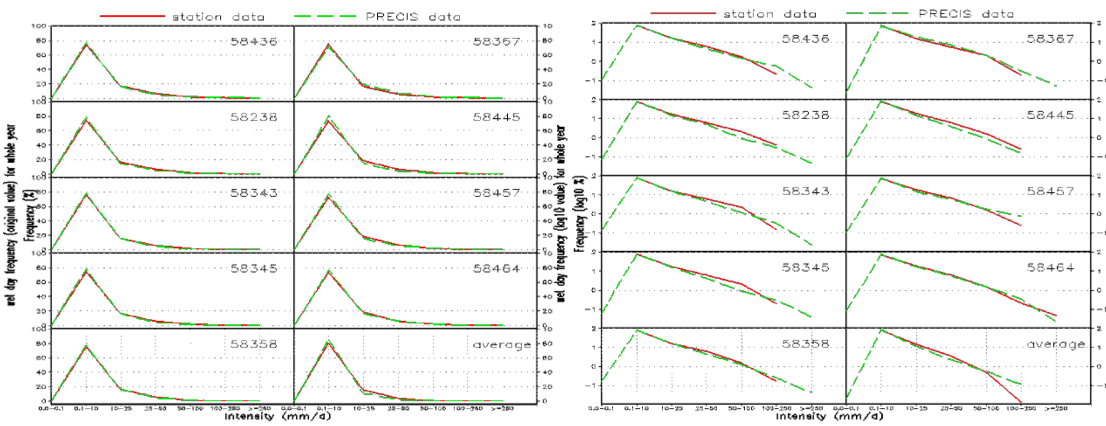

Figure 3. *Frequency-intensity curve (left) and log10 curve (right) of precipitation for each station and region average (bottom right in each map) for whole year data*
X,Y-coordinate represent intensity (unit: mm/d) and frequency (unit: %) respectively

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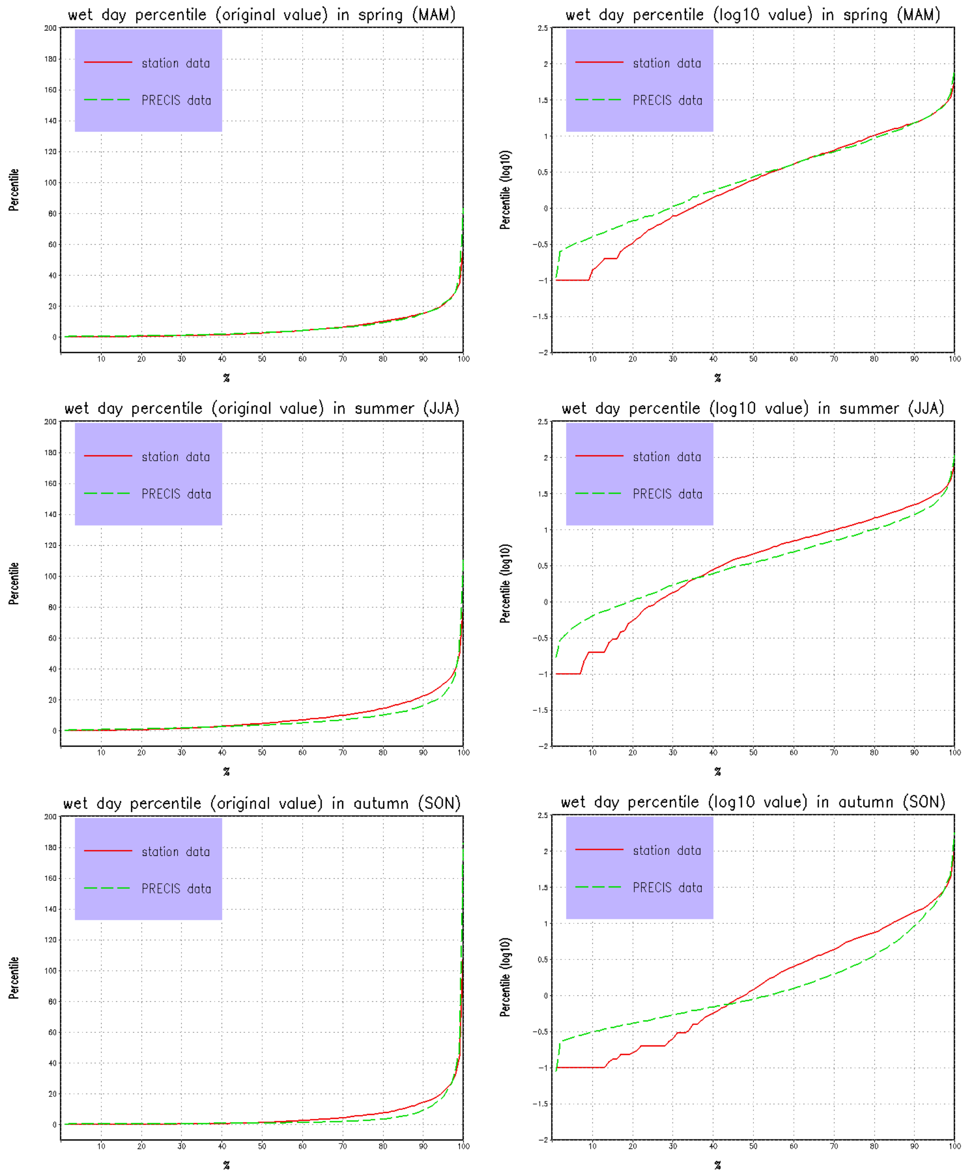
Figs. 4 and *5* are the wet day precipitation percentile curves of PRECIS data and observed data. Both the original value and log10 value are showed for details of extreme value (frequency or percentile). Because some value (frequency or percentile) is zero, the corresponding log10 value is undefined. Apparently, distributions of percentiles of PRECIS data are quite close to those of observed data, which are consistent with results obtained from frequency-intensity curves aboved.



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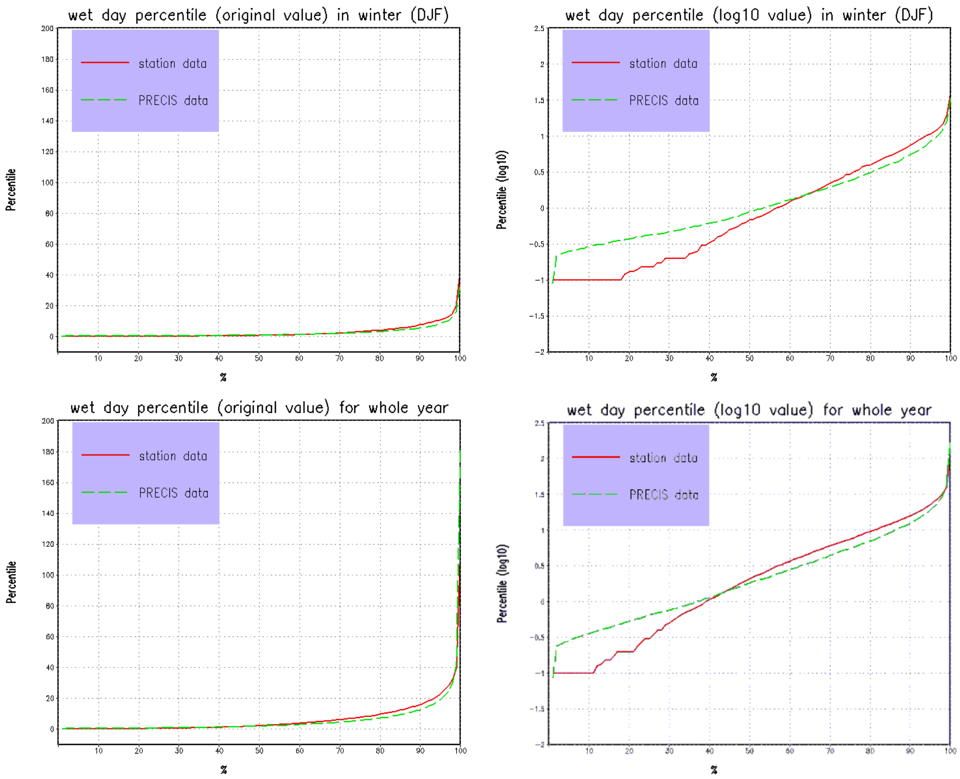

Figure 4. *Percentiles curve (left) and log10 curve (right) of precipitation of region average for each season and whole year data*
X,Y-coordinate represent frequency (unit: %) and percentiles (unit: mm/d) respectively

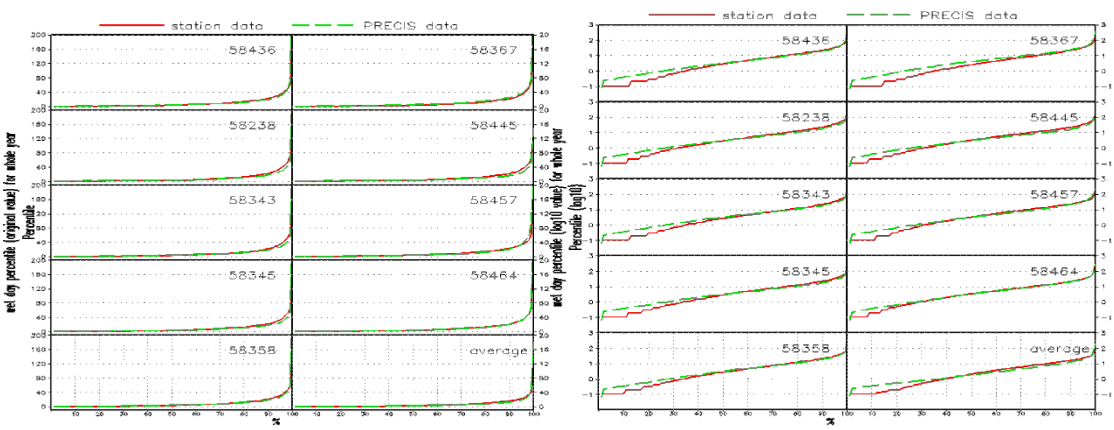

Figure 5. *Percentiles curve (left) and log10 curve (right) of precipitation for each station and region average (bottom right in each map) for whole year data*
X,Y-coordinate represent frequency (unit: %) and percentiles (unit: mm/d) respectively

Maximum/minimum temperature

In order to drive VIC model, daily maximum and minimum temperature data are also needed. Similar with precipitation validation, frequency-intensity curves were used to assess the simulation capacity of PREICS. Time series of temperature from PRECIS

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and gauging stations were all corrected to sea level to eliminate bias induced by different elevations from PRECIS grids and gauging stations. As shown in *Figs. 6* and *7*, outputs of PRECIS fit well with observations. However, for the maximum temperature, the frequency of extreme high value of PRECIS is higher than that of observations, and for the minimum temperature, the frequency of extreme low/high temperature of PRECIS is also higher than that of observations from most of stations.

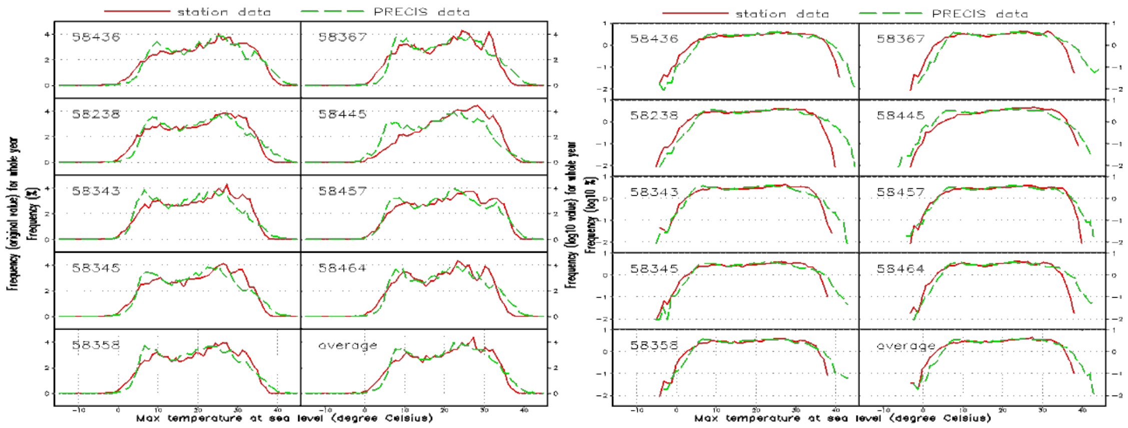

Figure 6. *Frequency curve (left) and log10 curve (right) of observation and PRECIS maximum temperature of 1961-1990 for each station and region average (bottom right) X,Y-coordinate represent temperature (unit: °C) and frequency (unit: %) respectively*

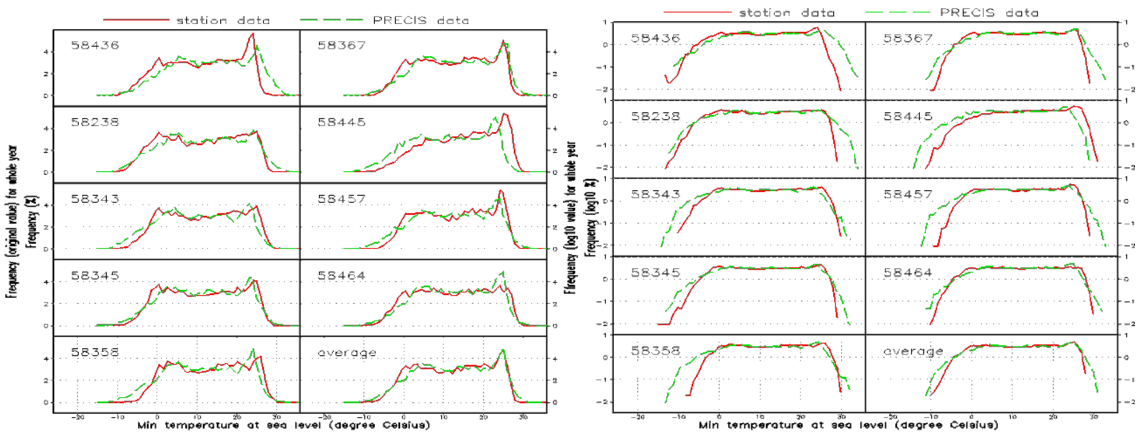

Figure 7. *Frequency curve (left) and log10 curve (right) of observation and PRECIS minmum temperature of 1961-1990 for each station and region average (bottom right) X,Y-coordinate represent temperature (unit: °C) and frequency (unit: %) respectively*

Impact assessment

The calibrated VIC model (Liu and Xu, 2015) was driven using the PRECIS outputs of daily precipitation, daily maximum and minimum temperatures for the baseline and 2030s to generate runoff and evapotranspiration in 1452 grids that covering the entire Taihu Basin at a resolution of 5 km × 5 km.

As shown in *Table 2*, mean annual precipitation and runoff in the Taihu Basin under A2 and B2 scenarios during 2021-2050 compared with that during 1961-1990 exhibit increasing trends, ranging from 5.97%-3.54% and 10.63%-12.13%, respectively. While

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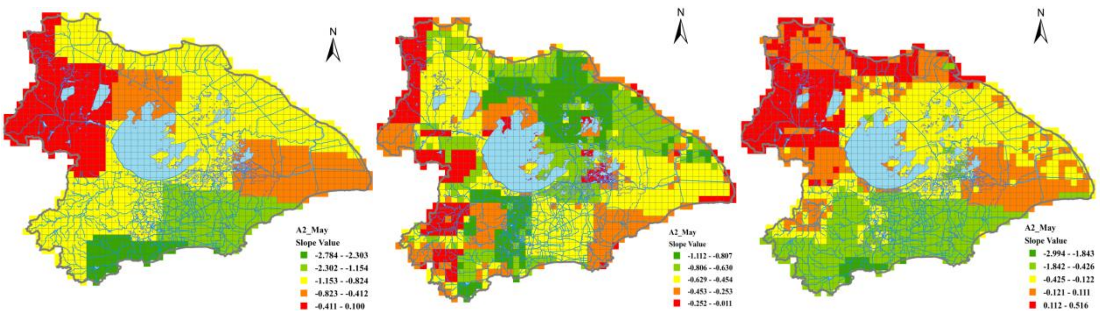
mean annual evapotranspiration tends to decrease by -1.96% under B2 scenario and increase only by 2.73%, which could be ignored compared to the significant increasing of temperature in the Taihu Basin, seemingly opposite of the general expectation which is global warming will lead to an increase in evapotranspiration. Similar changing characteristics in the Yangtze River Basin have already been found (Wang et al., 2007; Xu et al., 2006a; 2006b), implying both potential evapotranspiration and crop reference evapotranspiration have declined over recent decades in a globally warming climate. By comparing 148 regional studies on trends in evapotranspiration over the world, McVicar et al. (2012) advocates that in addition to considering air temperature trends, trends in wind speed, atmospheric humidity and the radiative balance must also be considered to fully understand trends of evapotranspiration in a changing climate. More sophisticated exploitation on spatio-temporal characteristics of evapotranspiration in the Taihu Basin should be studied in the future.

Table 2. *Mean annual statistics under different scenarios*

Variables	Baseline mm	A2 mm	B2 mm	A2-Change %	B2-Change %
Precipitation	1186.38	1257.15	1228.42	5.97	3.54
Runoff	444.52	491.75	498.45	10.63	12.13
Evapotranspiration	731.82	751.80	717.47	2.73	-1.96

Due to suffering frequent floods which cause huge losses of wealth and life, mostly occurring during the plume rain season from May to September, one of the most concerned problems in the Taihu Basin is flood management. Therefore, in this study, attention is mainly focused on the spatio-temporal characteristics of hydrological processes during the plume rain season under future climate change scenarios. The nonparametric Mann–Kendall test proposed by Mann (1945) and improved by Kendall (1975) was employed to test trends of precipitation, runoff and evapotranspiration owing to its capability of handling non-normality and seasonality (Gan, 1998). The Kendall slope, which is an unbiased estimator of trend magnitude, was adopted to estimate the magnitude of the trend. Based on the precipitation, runoff and evapotranspiration in each grid during May to September from 2021 to 2050, which were extracted from outputs simulated by coupled VIC model and PRECIS, the Kendall slope in each grid was calculated at the confidence level of 95% and shown in *Figs. 8* and *9*.



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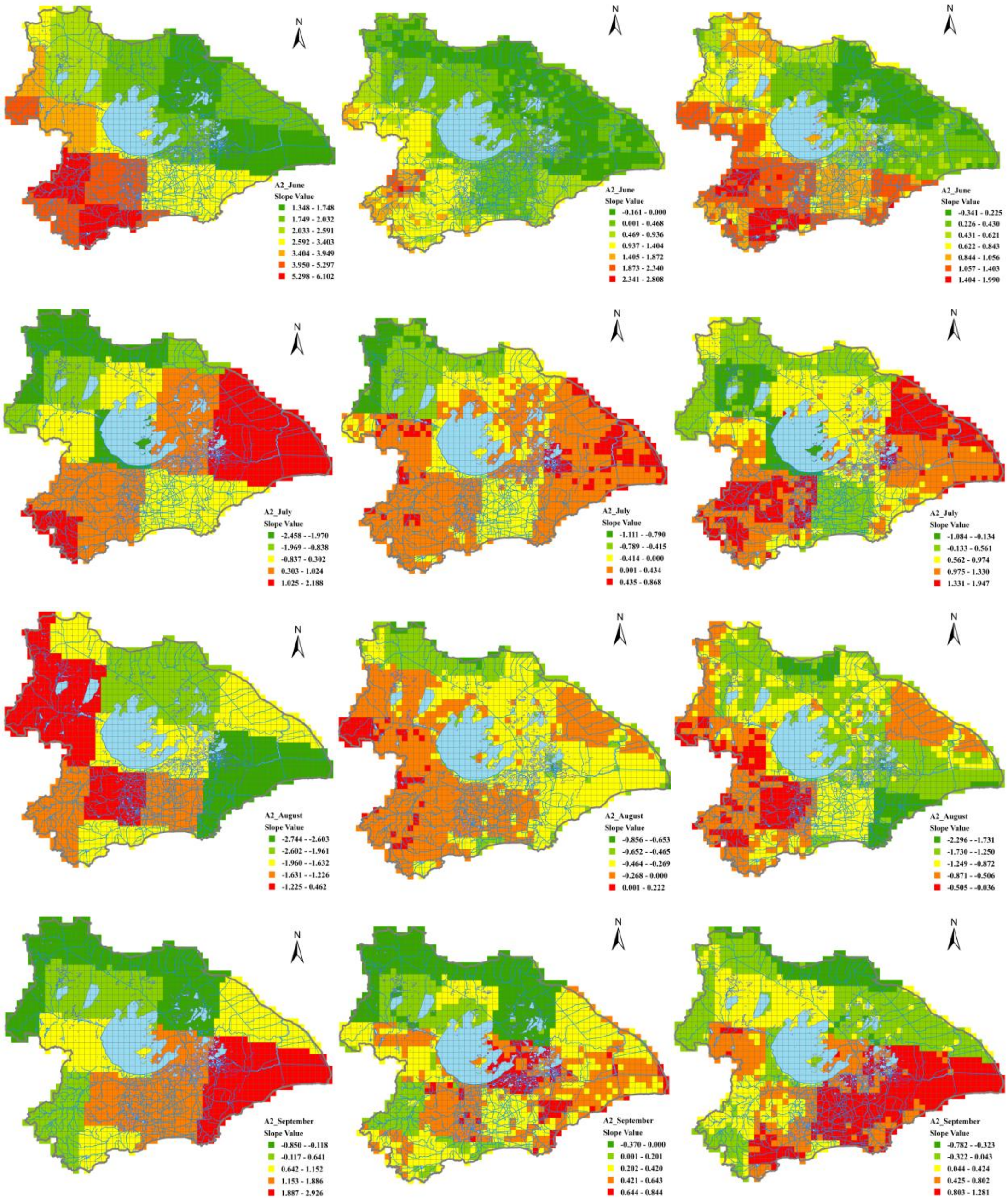
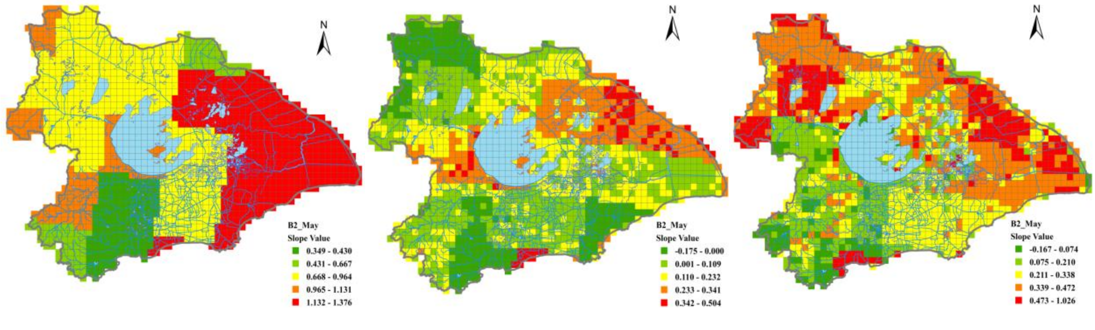


Figure 8. *Kendall slopes of monthly precipitation, runoff depth and evapotranspiration during plume rain season from 2021-2050 under A2 scenario (Left column is precipitation, middle column is runoff depth, and right column is evapotranspiration)*



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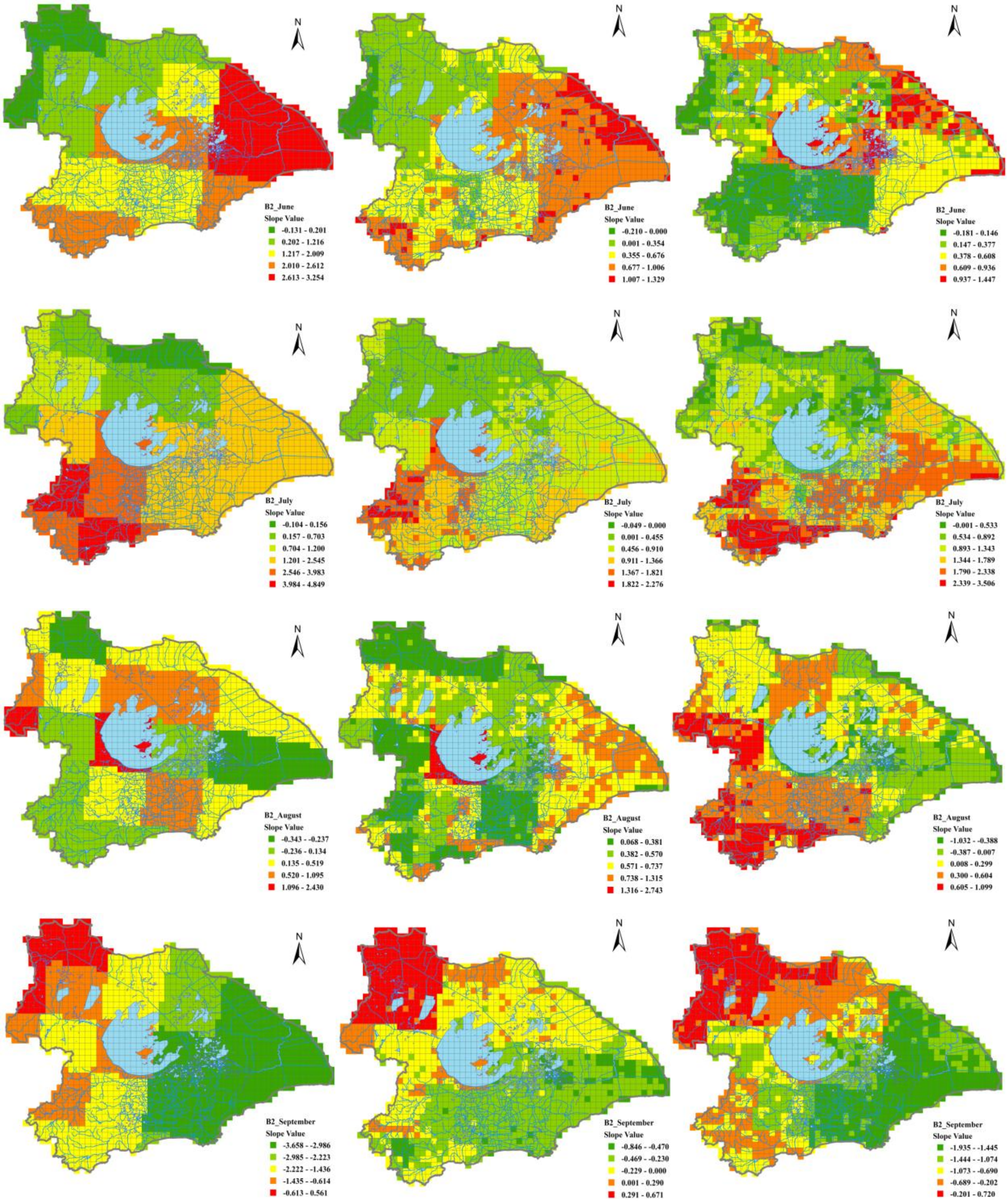

Figure 9. *Kendall slopes of monthly precipitation, runoff depth and evapotranspiration during flood season from 2021-2050 under B2 scenario (Left column is precipitation, middle column is runoff depth, and right column is evapotranspiration)*

As *Fig. 8* shows, runoff depth in May under A2 scenario during 2021-2050 exhibits a decreasing trend in the whole basin, with Kendall slopes ranging from -11.12 - -0.11 mm/(10 years), and higher decreasing magnitudes occur in north compared with that in south. Precipitation in May shows a similar decreasing trend with larger Kendall slopes compared with runoff depth in most parts of the Taihu Basin, while a slight increasing trend was detected in the northeastern part with a Kendall slope of 1.00 mm/(10 years). The reason increasing of precipitation accompanied with decreasing of runoff in

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northeast could be explained by increasing of evapotranspiration as shown in the right column of *Fig. 8*, which is consistent with results obtained by Bao and Feng (2016), Guan et al. (2014), and Zhang et al. (2014). Furthermore, in other parts of the Taihu Basin, decreasing magnitude of runoff is less than that of precipitation in May, for the reason that there is a decreasing trend of evapotranspiration in the corresponding area, consistent with water balance principle. Similar hydrological responses in both spatial distribution and changing magnitude were found in August.

As to changing patterns in June, there are decreasing trends of runoff depth in the northern part of the basin and the Shanghai surrounding area with relative small magnitudes ranging from -1.61-0.00 mm/ (10 years), which are opposite of the increasing of precipitation due to increasing of evapotranspiration. Other parts of the basin exhibit increasing trends, especially in southeastern mountain region with Kendall slopes all over 9 mm/(10 years), similar consistent changing features of precipitation and evapotranspiration could also be found.

Compared with Kendall slopes of runoff depth in June, areas with decreasing trends shift from northeast to northwest and south in July, with larger 10-year decreasing rates of -11.11-0.00 mm, while the zone with increasing trends expands to east with relative smaller magnitudes ranging from 0.01-8.68 mm/(10 years).

In September, precipitation, runoff and evapotranspiration all exhibit increasing trends in most parts of the basin except the northern part. Although there is a significant increasing of precipitation in the eastern part with the highest 10-year rate of 29.26 mm, there is no corresponding highest increasing of runoff depth attributing to remarkable increasing of evapotranspiration in the east, implying that only considering precipitation traditionally recognized as the key factor of flood in the Taihu Basin is not sufficient to identify and quantify flood disasters. Similar results were also obtained by Lai et al. (2013), Lu et al. (2014), Ping et al. (2014).

Kendall slopes of precipitation, runoff and evapotranspiration during 2021-2050 under B2 scenario are shown in *Fig. 9*. Compared with decreasing trends of runoff over the whole basin in May under A2 scenario, runoff under B2 scenario in May shows an increasing trend in most parts, with Kendall slopes of 0.01-5.04 mm/(10 years), while a slight decreasing trend is situated in part of Zhexi and Huxi district with the 10-year decreasing rate of -1.75-0.00 mm. As to June, decreasing trend was only detected in the western part of Huxi district while other parts of the basin exhibit increasing trends, especially in the upstream of Zhexi district and northeastern part of the Taihu Basin with Kendall slopes all over 6.77 mm/(10 years).

Different from A2 scenario, there is a significant increasing trend of runoff in July under B2 scenario over the whole basin, especially in southeastern part with Kendall slopes all over 10.00 mm/(10 years). In August, an increasing trend of runoff over the whole basin was detected under B2 scenario with 10-year rate of 0.68-2.74 mm, which is opposite of the decreasing trend under A2 scenario. Trends of runoff in September under B2 and A2 scenarios are also opposite, which are increasing under B2 scenario and decreasing under A2 scenario. Similar with results obtained under A2 scenario, precipitation and evapotranspiration keep consistency in both spatial patterns and changing magnitudes in terms of water balance principle under B2 scenario.

Although there are differences of runoff during the plume rain season from 2021-2050 under A2 and B2 scenarios, it could be confirmed that there will be an increasing trend of runoff in south while the northern part will exhibit a decreasing trend in the future.

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Conclusions

In this study, the Taihu Basin was selected as the typical area of the Yangtze River Delta region to investigate the climate change impacts on hydrological processes. The VIC model was coupled with PRECIS regional climate model to assess the impact of climate change on hydrological conditions at a spatial resolution of 5 km × 5 km. Outputs including daily precipitation, maximum and minimum air temperature from PRECIS under three climate scenarios, i.e. baseline climate (1961-1990), future climate (2021-2050) under A2 and B2, were adopted to drive the VIC model to simulate the changes of runoff and evapotranspiration in the Taihu Basin.

The Taihu Basin was represented by 1452 cells with a spatial resolution of 5 km × 5 km for each cell to assess the hydrological response to climate change by VIC model. VIC model parameters calibrated in the Xitiaoxi catchment was transferred to the whole basin based on the assumption that the hydrological process and its related parameters are similar in a same climate zone. The runoff simulation showed an increasing trend from 2021 to 2050 based on the scenarios obtained by PRECIS, especially in the southern part of the basin.

Precipitation, with great spatial and temporal variability, is a great dominant factor in controlling floods in the Taihu Basin. However, to identify and quantify flood disasters precisely, combined qualitative analysis on spatial patterns of precipitation, runoff and evapotranspiration are necessary. Therefore, accurate simulation of precipitation, evapotranspiration and other related hydro-meteorological factors is of great importance to conduct cross-validation for the climate change impact assessment.

Acknowledgements. This work was jointly supported by the National Natural Science Foundation of China (51509247, 91425302). Assistance from colleagues in the Taihu Basin Authority and Chinese Academy of Agricultural Sciences who kindly provided valuable data and comments from reviewers that greatly improved the quality of the paper are gratefully acknowledged as well.

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