Research Article

Hydrological Response of East China to the Variation of East Asian Summer Monsoon

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Received 16 May 2016; Revised 29 July 2016; Accepted 10 August 2016

Academic Editor: Min-Hui Lo

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The sensitivity of hydrologic variables in East China, that is, runoff, precipitation, evapotranspiration, and soil moisture to the fluctuation of East Asian summer monsoon (EASM), is evaluated by the Mann-Kendall correlation analysis on a spatial resolution of $1/4^\circ$ in the period of 1952–2012. The results indicate remarkable spatial disparities in the correlation between the hydrologic variables and EASM. The regions in East China susceptible to hydrological change due to EASM fluctuation are identified. When the standardized anomaly of intensity index of EASM (EASMI) is above 1.00, the runoff of Haihe basin has increased by 49% on average, especially in the suburb of Beijing and Hebei province where the runoff has increased up to 105%. In contrast, the runoff in the basins of Haihe and Yellow River has decreased by about 27% and 17%, respectively, when the standardized anomaly of EASMI is below -1.00 , which has brought severe drought to the areas since mid-1970s. The study can be beneficial for national or watershed agencies developing adaptive water management strategies in the face of global climate change.

1. Introduction

Typical continental monsoon climate prevails across large territory of China. Among others, East Asian summer monsoon (EASM) has significant impacts on the amount and distribution of summer rainfall in East China and thus influences the spatial-temporal variations of water resources in this region [1–4]. Much of the previous research has focused on the relationship between EASM and precipitation as well as temperature in East China [5–18]. Among others, Yang et al. [19] and Huang et al. [20] find that both the severe floods in the watersheds of Yangtze River and Huaihe and the prolonged droughts in North China since the late 1970s are attributed to the interannual and interdecadal variations of the EASM. Guo et al. [21] and Zhu et al. [6] show that there is a distinct 80-year oscillation of summer rainfall in East China, and heavy summer rainfall over North China and serious droughts over the middle and lower reaches of Yangtze River could be found during strong EASM periods. Similarly, Zhao and Zhou [22] also discover that

a heavy rainfall over the Yangtze River watershed usually is accompanied with a weak EASM, which may strengthen the convergence and ascending motions of water vapor along the front of Plum Rains. Besides the researches on the relationship between the EASM and precipitation, Lin et al. [23] find a positive correlation between the East Asian summer monsoon index (EASMI) and the index of summer surface air temperature (SAT) in eastern China during 2/3 of the period of 1880–2004. Furthermore, Liu and Wang [10] recognize the middle reaches of Yangtze River, the most susceptible to the change of SAT due to EASM fluctuation. The increase of SAT in summer enhances the ocean-land thermal contrast [24], which in turn increases the intensity of EASM [25]. In conclusion, previous studies have indicated an evident relationship between EASM and meteorological variables (e.g., precipitation and air temperature) in East China.

The impact of EASM on streamflow of East China has also been evaluated in previous researches. Comparing to the meteorological data, relatively long-term flow discharge has

TABLE 1: Characteristic of the eight watersheds in the monsoon region of east China.

Basins	Drainage area		Average elevation (m)	Annual rainfall (mm)
	(10 ⁴ km ²)	% of total area of East China		
The yellow River	75.24	14.80	1918.51	459.60
The Yangtze River	180.00	35.54	1606.14	1126.70
The Liaohe River	29.69	5.86	423.62	638.20
The Pearl River	45.36	8.96	537.94	1579.00
The Huaihe River	27.47	5.42	86.36	814.80
The Haihe River	31.82	6.28	576.85	548.00
The Songhua River	95.22	18.80	453.31	534.90
The Southeast Rivers	21.59	4.26	478.86	1526.60

been recorded for a few large rivers in China. For example, Zhang et al. [26] find that the annual maximum discharge of the upper and lower Yangtze River, based on a 135-year record, is mainly influenced by Indian summer monsoon and EASM. Xu and Ma [27] and Xu [28] find a strong relationship between the 5-year moving averages of EASMI and discharge difference between Hekouzhen and Longmen gauges of the Yellow River in the period of 1919–2000. They argue that, during weak EASM events, less water vapor transport by the EASM decreases runoff at watershed scales. Wei et al. [29] examine the spatial variation of discharge oscillations of the Yangtze River and confirmed its strong correlation with EASM and El Nino Southern Oscillation (ENSO). All of these studies indicated a significant impact of EASM on the streamflow over East China.

Compared with numerous efforts directed at understanding the relationship between EASM and hydrometeorological variables (e.g., precipitation, air temperature), less researches have been done on the correlation between EASM and hydrogeological variables (e.g., soil moisture, runoff). As an important parameter denoting land surface condition, soil moisture within the depths of root systems is a critical factor that dominates crop yields from the perspective of agriculture [30]. Besides, soil moisture anomaly could modify the atmosphere circulation in seasonal to interannual time scales [31]. On the other hand, although rainfall and runoff are causally correlated in general, similar rainfall could generate distinct runoffs upon different land surfaces, especially for arid or semiarid lands. Runoff is an easily-accessible water resource and usually much more sensitive to climate change than precipitation does in East China, as discussed in the following sections. Besides, flow discharge recorded in hydrologic stations in large rivers such as the Yellow River or Yangtze River represents an average on a large spatial scale. Xu [28] found that EASM explains 72% variability in discharge difference between two consecutive gauges, Hekouzhen and Longmen, in the middle Yellow River. However, the drainage area between the two gauges is as large as 113,700 km² [28]; the above conclusion can hardly be applied to smaller spatial scales (e.g., croplands in the region) due to spatial variation in the Runoff-EASM relationship. The above concerns motivate the present study, which evaluates the response of runoff and

soil moisture as well as precipitation and evapotranspiration (ET) to the variation of EASM in the 1/4° spatial resolution.

During the past decades, East China has become one of the most rapidly developing regions in the world. Unfortunately, northern portion of the region has suffered from a prolonged drought and thus severe shortage of water resources since the 1970s due to weak EASM. There is a pressing need for hydrologists to identify the “critical zones” in which the local water resources are most susceptible to EASM fluctuation and estimate the variance amplitude of the water resources. The study aims at helping national or watershed agencies to develop adaptive water management strategies under the global climate change.

2. Study Area

The study area is the monsoon region in East China including eight watersheds, that is, the Songhuajiang, Liaohe, Haihe, Yellow River, Huaihe, Yangtze River, Southeastern Rivers, and Pearl River. Table 1 summarizes the drainage area, averaged elevation, and annual rainfall amounts of the eight watersheds. The 400 mm iso-hyetal line is usually used to separate the monsoon region from the arid and semiarid region of Western China. Figure 1 demonstrates the locations of the eight watersheds, ground elevation, and the iso-hyetal lines of 400 mm and 800 mm as well. The basins of Yangtze River (YRB), Pear River (PRB), and Southeastern Rivers (SRB) are located in South China and the other basins are located in North China. The vegetation types in the study area vary from temperate needle broad-leaved mixed forest to subtropical and tropical evergreen broad-leaved forest from north to south, in response to local climates. Most precipitation in the study area concentrates in the summer period from June to September; however, rainfall magnitude varies tremendously in space. In contrast to the frequent floods and waterlogging in Southern China, limited water resources often restrict the development of Northern China where large portions of the population and farmlands are located. For example, the population and GDP of the basins of the Yellow River, Huaihe, and Haihe accounted for about 34.7% and 32.1% of the whole country, whereas the region is supported by only 7.5% of the nation's water resources [32].

TABLE 2: Calibration and verification of VIC model by comparing with monthly streamflow in the monsoon region.

River basin	Calibration gauge	Calibration period	NS for calibration	Verification gauge	Verification period	NS for verification
SRB	Changjiangtun	1965–1984	0.82			
LRB	Liaoyang	1956–1975	0.83			
HHB	Luanxian	1958–1977	0.84	Luanxian	1981–2000	0.89
HHB	Guantai	1958–1977	0.77	Guantai	1981–2000	0.67
YRB	Tangnaihai	1958–1977	0.87	Tangnaihai	1981–2000	0.83
YRB	Lanzhou	1958–1977	0.85	Lanzhou	1981–2000	0.83
HRB	Lutai	1958–1977	0.75	Lutai	1981–2000	0.80
YZB	Shigu	1956–1975	0.89			
YZB	Wulong	1956–1975	0.82			
PRB	Boluo	1960–1979	0.82			
PRB	Wuzhou	1960–1979	0.96			

Note: YRB: Yellow River Basin; YZB: Yangtze River Basin; LRB: the Liaohe River Basin; PRB: Pearl River Basin; HRB: Huaihe River Basin; HHB: Haihe Basin; SRB: Songhua River Basin; SEB: Southeast Rivers Basin.

FIGURE 1: Watersheds in the monsoon region of East China. The 400 mm iso-hyetal line (pink curve) separates the monsoon region from the arid and semiarid region of Western China. Major croplands in China (gray areas) include A, the Sanjiang Plain, B, the Songnen Plain, C, the Hetao Plain, D, the North China Plain, E, the Taihu Plain, F, the Jiangnan Plain, H, the Dongtinghu Plain, I, the Poyanghu Plain, G, the Chengdu Plain.

Figure 1 also illustrates the locations of 10 major croplands including North China Plain. Four of them are located in North China.

3. Data Sources

The major dataset used in the present study includes (a) hydrologic data in the study area, including precipitation, runoff, ET, and soil moisture in spatial resolution of $1/4^\circ$ for the period of 1952–2011 and (b) EASMI data for the period of 1952–2011, indicating the intensity of the East Asian summer monsoon.

3.1. Hydrological Data. The hydrological data include precipitation, runoff, ET, and soil moisture, which indicate the natural water resources in the study area.

Since observed long-term, large-scale, and high-resolution runoff and soil moisture data in the study area are absent, this study utilized the Variable Infiltration Capacity (VIC) model to simulate hydrological variables. The calculated variables, which are available at <http://hydro.igsnrr.ac.cn/>, were provided with 3-hour time step and $1/4^\circ$ spatial resolution for the period of 1952–2011. For the detailed description of the computational procedure, refer to Zhang et al. [33] and a brief introduction of the model calibration/verification is given below. The VIC model is a mesoscale, grid-based water and energy balance model, which has been successfully applied in many large river basins with satisfactory results [34–36]. The VIC model was set up with three soil layers with varied soil depth for each layer [33]. Surface runoff is generated in the upper two layers by a variable infiltration curve, and soil moisture is produced by accumulating water content from all the three layers.

The input data of VIC model include meteorological data (precipitation, temperature, and wind), soil data, and land cover data. The meteorological data were obtained from 756 meteorological stations of China Meteorological Administration and interpolated to $1/4^\circ$ resolution. Soil parameters are based on the 5-arc-min Food and Agriculture Organization of the United Nations dataset [37] and specified following the method of Maurer et al. [38]. The vegetation classification is derived from the University of Maryland global land cover classifications [39].

The VIC model is calibrated and validated before using for the analysis. The information of observation gauges and periods of calibration and verification are addressed in Table 2. The Nash-Sutcliffe efficiency (NS) and the relative error (RE) are employed to assess the performance of model calibration and verification:

$$\begin{aligned}
 \text{NS} &= 1 - \frac{\sum (Q_{i,o} - Q_{i,s})^2}{\sum (Q_{i,o} - \bar{Q}_o)^2}, \\
 \text{RE} (\%) &= \left[\frac{(\bar{Q}_s - \bar{Q}_o)}{\bar{Q}_o} \right] \times 100\%,
 \end{aligned} \tag{1}$$

TABLE 3: The relative errors (%) of ET calibration in the eight watersheds (1984–2007).

River basin	ET_observation	ET_VIC	Relative errors (%)
The Yellow River	172.32	207.36	20.34
The Pearl River	453.61	466.38	2.82
The Huaihe River	318.33	376.31	18.21
The Haihe River	245.66	271.03	10.33
The Songhua River	261.32	219.00	−16.20
The Liaohe River	480.60	505.88	5.26
The Yangtze River	244.62	242.73	−0.77
The Southeast Rivers	332.64	334.85	0.67

where $Q_{i,o}$ and $Q_{i,s}$ are the observed and simulated data in month i and $\bar{Q}_o$ and $\bar{Q}_s$ are the observed and simulated mean annual data, respectively.

Table 2 shows the parameter calibration results at 11 streamflow gauges and verification results at 5 streamflow gauges distributed in major river basins of East China. Table 2 indicates VIC simulated streamflow agrees well with the observation at those gauges. All of the NS values for calibration are above 0.75, and NS values for verification are above 0.8 at 4 out of the 5 gauges. Table 3 compares the calculated 24-year-average ET with remote sensing data during the period of 1984–2007 [33]. The VIC simulated ET shows agreement with the observation data with the RE values below the 15.0% at 5 out of the 8 basins. The RE in the watersheds of the Yangtze River and the Pearl River show the minimum value as -0.77% and 0.67% , respectively. The maximum RE, that is, about 20%, occurs in the watershed of the Yellow River which is acceptable for ET calibration.

Besides streamflow and ET, the simulated surface radiation fluxes, soil moisture, and snow cover are also verified by the datasets from the Institute of Tibetan Plateau Research at Chinese Academy of Sciences [40], Princeton University global terrestrial water budget product [41], and National Snow and Ice Data Center [42], respectively (please see details in [33]). According to [33], substantial biases exist at some gauges in western China, while the seasonal cycle of the VIC-derived streamflow agrees well with the observations over the eight watersheds in East China.

3.2. Index of EASM. This study adopts the EASMI defined by [43]. Many indices have been proposed to quantify the EASM [8, 44–47]. Among these indices, the EASMI defined by [43] is based on the formative mechanism of the EASM and calculated as the difference in the monthly average air pressure in summer season (June, July, and August) at the sea level between the Asian Continent (110°E) and the Pacific Ocean (160°E) in the range of 10° – 50°N . For the procedures of EASMI calculation, refer to [43] or [28]. The data source is from NCEP/NCAR Global Reanalysis Products (<http://rda.ucar.edu/datasets/ds090.0/>). Figure 2 presents anomalies of EASMI and runoff in the Haihe basin

FIGURE 2: Temporal variation and categorization of standardized anomalies of EASMI and runoff in the Haihe River Basin.

over the period of 1952–2011. EASMI and runoff anomalies are calculated as follows:

$$P = \frac{E - \bar{E}}{\sigma}, \quad (2)$$

where P is the standardized anomaly; E denotes time series; $\bar{E}$ is the mean of time series; and σ is the standard deviation of the time series. Overall, EASMI has a distinct trend of decreasing after the 1960s. The prolonged drought in North China from the late 1970s has been attributed to the continuous decline of EASMI [19, 20]. It is worth mentioning that the EASMI trend line tends to rise again after 2000 which has brought relatively more rainfall to North China including the extraordinary rainstorm on July 21, 2012, in Beijing City and its suburb. As the typical basin in the North China, the Haihe River Basin shows the similar variation for the runoff as well as the EASMI.

4. Methods

The Mann-Kendall (MK) test [48, 49] has been widely applied to evaluate the long-term trends of time series [50–54]. Hirsch et al. successfully extended the MK function to examine the correlations between two time series [55, 56].

Although all the eight watersheds belong to monsoon-dominated region, the hydrologic variables in the study area are also impacted by many other oceanic-atmospheric factors such as ENSO [57, 58] and PDO [59, 60], which often results in statistical low correlation or even irrelevance between EASMI and the hydrologic variables when applying traditional regression equations. Besides, those impacting factors usually have various statistical distributions and interrelation between each other, which often invalidate or fail traditional regression methods.

To solve the above problem, the nonparametric method, that is, MK test, is employed in this study, which can present the correlation between two time series effectively. Since MK test is sensitive to the autocorrelation structure in the data [61], the lag-one ($k = 1$) autocorrelation coefficients (r_1) for EASMI and hydrometeorological variables in East China were calculated using

$$r_k = \frac{(1/(n-k)) \sum_{i=1}^{n-k} (x_i - \bar{x})(x_{i+k} - \bar{x})}{(1/n) \sum_{i=1}^n (x_i - \bar{x})^2}, \quad (3)$$

where $k = 1$; $n = 60$; x_i denotes time series; and $\bar{x}$ is the mean of time series.

Since r_1 values for EASMI and hydrometeorological variables data are not in the scope of $(-1 - 1.645\sqrt{n-2})/(n-2) \leq r_1 \leq (-1 + 1.645\sqrt{n-2})/(n-2)$, that is, independent test at 10% significance level, the data are considered to be serially correlated and prewhitening is required before applying the Mann-Kendall test. Based on the detailed calculating course of reference [61], the time series are recalculated to get the blended series which is applied to the MK test.

In the MK test, the null hypothesis H_0 states that there is no trend for the two time series varying in pairs. Equations (4) provide the statistical test:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n S_{gn}(x_j - x_k),$$

$$S_{gn}(x_j - x_k) = \begin{cases} +1 & (x_j - x_k) > 0 \\ 0 & (x_j - x_k) = 0 \\ -1 & (x_j - x_k) < 0, \end{cases}$$

$$\tau_{au} = \frac{2S}{n(n-1)}, \quad (4)$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & S < 0. \end{cases}$$

In the formulas, x_k and x_j are the independent samples; the statistic S with a mean of zero is approximately normally distributed; τ_{au} here is the MK correlation coefficient which indicates a significant correlation between the two time series of X and Y if X is other than time (τ_{au} is also called Kendall's τ coefficient identifying the significance of trend of the Y if X denotes time); the square root of $\text{Var}(S)$ is the variance of S which equals $n(n-1)(2n+5)/18$; n is the number of samples. The null hypothesis H_0 should be rejected when $|Z| \geq Z_{1-\alpha/2}$ at the α level of significance. This means that the correlation between the two time series is statistically significant at the significance level of α . The positive (+) and negative (−) signs of Z denote the positive and negative correlation between the two time series, respectively. $|Z| \geq 1.28, 1.64$, and 2.32 indicate the confidence level (the reciprocal of significance

level α) of the calculation is more than 90%, 95%, and 99%, respectively.

Student's t -test proposed by William Sealy Gosset [62] is also applied in Section 5.1 to examine if the mean value of selected sample is significantly different from the annual average, that is, the mean of the entire population in the period of 1952–2011. The statistical value of t -test is calculated as follows:

$$t = \frac{\bar{x} - \mu_0}{S_d / \sqrt{n}}, \quad (5)$$

where $\bar{x}$ and μ_0 are the means for selected sample and entire population, respectively. S_d is the sample standard deviation and n is the sample size. $S_d / \sqrt{n}$ denotes the standard error, and the t score represents the difference between sample means divided by the standard error. Student's t -test is selected herein since it is capable of dealing with problems associated with small sample sizes [63], which is suitable in the present study.

5. Results

5.1. Regions Susceptible to EASM Fluctuation. Figure 3 identifies the regions susceptible to the changes of runoff and ET due to EASM fluctuation, respectively. The white curves in Figure 3 enclose the regions with strong correlation between the hydrologic variables and EASM above the 95% confidence level.

Strong summer monsoon carries large quantity of water vapor from the southeastern coast and goes far into inland, which brings heavy rainfall precipitation to the north and central China. Figure 3(a) shows that runoff is positively correlated to EASM in the watershed of Yellow River, the plains of North China, Songnen and Chengdu, and the peninsulas of Liaodong and Shandong. $\tau_{au} > 0.3$ with 95% confidence level occurs in the plains of North China and Chengdu as well as the middle-lower Yellow River Basin, which indicates that the runoff in these regions is more sensitive to EASM variation compared to other areas of the north China. Xu [28] also studied the impacts of EASM on the runoff in the middle Yellow river based on the runoff observations from 1919 to 2010 provided by the Yellow River Conservancy Commission, and he argued that EASM explains 72% variability in runoff in this region and reconstructed the time series of runoff from 1873 to 1918 based on the significant correlation with EASMI.

In contrast, weak summer monsoon is usually accompanied with stagnation of water-vapor transfer, which brings droughts to the north and floods to the south. Figure 3(a) also indicates a negative correlation between runoff and EASM over most areas of south China, especially in the lower Yangtze River and the upper reach of Pear River at the higher 95% confidence level.

It is worth mentioning that Figure 3(a) indicates opposite relationships of EASM runoff in the upper and lower Yangtze River. Zhang et al. [26] state that different climatic systems, that is, the Indian summer monsoon and EASM, control the upper and lower Yangtze River, respectively. We also find a significant negative correlation between runoff and the

FIGURE 3: Correlations between EASM and runoff (a) as well as ET (b). The green curves draw the outline of region with 95% confidence level in MK test.

Indian summer monsoon in upper Yangtze River, especially in the basin of Jialing River (one of primary tributaries of the Yangtze River) (figures and calculation are not presented in this paper). There is a weak negative correlation between the Indian summer monsoon and runoff in the lower Yangtze River; however, the τ_{au} calculation does not pass the 95% confidence test. Our research is consistent with the findings of Zhang et al.'s [26].

As a significant water loss from drainage watersheds, ET is also an important component of the terrestrial water cycle. Figure 3(b) indicates a much larger area with significantly positive correlation between EASM and evapotranspiration including the upper Pear River Basin and coastal region in the east. Negative correlation between EASM and ET is limited to the upper and lower Yangtze River Basins and the statistics fail the 95% confidence test. The strong positive EASM-ET relationship in the study area is not surprising since increased monsoon winds accelerate evaporation rates. Besides, the formation mechanism of EASM indicates an in-phase variation of EASM and the summer air temperatures, which also tends to increase the ET. The spatial patterns of correlation between EASM and precipitation as well as soil moisture are similar to those between EASM and runoff in Figure 3(a); therefore they are not demonstrated in the present study.

The values of runoff and ET are usually much higher in South China, although they show stronger correlation with EASM in North China. To ensure the sensitivity of hydrologic variables in northern and southern China to EASM change, different EASM scenarios are considered to explore the change of hydrologic variables in East China.

5.2. Sensitivity of Hydrologic Variables to EASM Fluctuation in Basins. Besides identifying the regions susceptible to

hydrologic change after EASM fluctuates, water resources agencies are also interested in quantifying the variation of hydrologic variables in terms of EASM fluctuation. In this study, we divide the standardized anomalies of EASMI in the period of 1952–2011 (see (2)) into 5 categories, that is, $-2.00 \sim -1.00$, $-1.00 \sim -0.34$, $-0.34 \sim 0.34$, $0.34 \sim 1.00$, and $1.00 \sim 2.00$ (Figure 2). Out of the entire population of 60, the sample sizes of the 5 categories are 10, 19, 13, 6, and 9, respectively. The three samples with the standardized anomalies larger than 2.00 are excluded from statistics since their sampling pool is too small for statistical analysis. The hydrologic variables at each computational grid, that is, precipitation, ET, runoff, and soil moisture during the 5 categories, are arithmetically averaged and compared to the 60-year mean with Student's t -test. Table 4 summarizes the percentage change of the hydrologic variables in the eight watersheds as well as major croplands for all the categories except the category of $-0.34 \sim 0.34$ in which the changes of hydrological variables are insignificant.

Figures 4 and 5 further show the fluctuation percentages of the hydrologic variables when EASMI standardized anomalies are above 1.00 and below -1.00 , respectively. Fluctuation percentage (%) of a variable is calculated as follows:

$$FP = 100 * \frac{(e - \bar{e})}{\bar{e}}, \quad (6)$$

where FP is the fluctuation percentage of a variable; e denotes the variable; and $\bar{e}$ is the mean of variable during the period of 1952–2011. Student's t -test is applied in Figures 4 and 5 to examine if e is significantly or insignificantly different from $\bar{e}$ (with the significance level of 0.05). The two categories are selected herein since several recent studies have reported that climatic extremes are likely to become more severe in future due to climate change [64]. Besides, their sampling sizes (i.e.,

TABLE 4: Calculated anomalies of hydrological variables (%) under various monsoon scenarios.

Area	EASMI (0.34~1.00)				EASMI (1.00~2.00)				EASMI (-2.00~-1.00)				EASMI (-1.00~-0.34)			
	SM	R	ET	P	SM	R	ET	P	SM	R	ET	P	SM	R	ET	P
YRB	-1.0	-11.5	-7.1	-8.2	3.1	18.6	6.8	8.6	-2.3	-16.8	-4.8	-9.3	-0.4	1.2	0.2	0.9
YZB	-0.5	-5.3	-2.3	-3.5	3.1	7.0	3.5	3.0	0.2	1.6	-0.5	1.6	-1.2	-1.0	-0.9	-0.6
LRB	-1.7	-13.4	-3.0	-6.7	4.1	32.1	10.7	16.7	-1.2	-11.0	-4.3	-5.3	-1.1	-6.9	-3.0	-4.8
PRB	0.9	-5.0	-0.2	-2.1	0.2	-0.0	2.1	0.5	0.8	5.0	-0.4	3.0	-0.1	-0.2	-0.6	-0.4
HRB	-0.7	-12.7	-0.8	-7.1	5.4	17.4	5.6	9.1	0.1	2.0	-2.0	-4.1	-2.5	0.1	-1.9	1.1
HHB	-0.7	-12.9	-4.8	-5.8	9.1	49.0	11.4	18.5	-5.0	-26.7	-7.2	-14.0	-2.9	-9.5	-2.3	-3.8
SRB	-0.2	-3.4	0.8	-0.6	1.8	9.0	5.3	7.0	-1.4	-8.2	-5.7	-7.5	-1.1	-3.1	-1.6	-1.4
SEB	2.7	10.6	2.0	9.4	3.1	4.7	1.3	-0.4	-3.4	-7.2	-0.7	-2.3	-1.4	2.3	-0.5	0.9
CDP	2.7	9.5	3.1	7.0	5.0	13.3	9.1	11.4	-2.4	-7.9	-4.8	-7.8	-2.2	-7.1	-2.7	-4.6
SJP	1.1	9.0	3.0	5.3	3.3	19.0	7.3	11.3	-1.7	-13.9	-4.9	-10.7	-2.2	-8.6	-3.6	-4.4
NCP	-1.4	-14.1	-3.2	-7.4	7.0	32.9	8.2	13.0	-2.0	-13.8	-4.8	-10.2	-2.6	-4.3	-2.1	-0.9

Note: YRB: Yellow River Basin; YZB: Yangtze River Basin; LRB: Liaohe River Basin; PRB: Pearl River Basin; HRB: Huaihe River Basin; HHB: Haihe Basin; SRB: Songhua River Basin; SEB: Southeast Rivers Basin; CDP: Chengdu Plain; SJP: Sanjiang Plain; NCP: North China Plain.

$n = 10$ and 9, resp.) satisfy the requirement of Student's t -test [63]. Therefore, the following discussion will focus on the two extreme categories of EASMI.

5.2.1. When EASMI Standardized Anomaly Is above 1.00. Figure 4 indicates that the runoff increases significantly over northern China, especially in the suburb of Beijing and Hebei province where shortage of water resources is the severest in China [65]. Figure 4 presents a 50%~105% increment of runoff in the suburb of Beijing and Hebei province when the EASMI standardized anomaly is above 1.00. In contrast, no obvious change of runoff is observed in the southern China, where the fluctuation is generally in the range of -10%~10%. Comparing to the variation of runoff, both the precipitation and ET in East China vary in-phase and have the similar spatial pattern, but only with about a half fluctuating rate. Similar to runoff, the areas with the most increments of precipitation and ET are located in the Haihe and Liaohe River Basins. The precipitation and ET in the basins of Liaohe and Haihe increase by about 17~18% and 11% when the EASMI standardized anomaly is above 1.00, respectively. Based on Figure 4, runoff is more sensitive to the change of EASMI than precipitation or ET does; therefore runoff could serve as an effective index to climate change in the northern China, especially in the Haihe River Basin.

Comparing to other hydrologic variables, soil moisture usually shows a lag and damping response to the fluctuation of EASM. Figure 4 indicates that the soil moisture in Haihe basin varies significantly with 5~10% increment (10~20.9% in the suburb of Beijing), when the EASMI standardized anomaly is above 1.00. Besides, different from precipitation and runoff, there is much more area in the South China with notable increment in soil moisture (Student's t -test shows above 95% of confidence level). Based on the study, there is no evidence for severe soil moisture droughts in the South China during strong EASM years. It is different from the drought analysis based on the precipitation indices [6, 66], suggesting that agricultural drought and meteorological drought may respond differently to monsoon.

5.2.2. When EASMI Standardized Anomaly Is below -1.00. The Figure 5 shows that the most runoff decrement (with a calculated 30% dropping) occurs in the southern regions of the Haihe River Basin as well as some areas of the middle Yellow river, although it does not exceed the 95% confidence level of Student's t -test. Other hydrologic variables indicate the similar spatial variation patterns in the area, although the variations are gentle compared to the runoff. Figure 5 further indicates that all the hydrologic variables in the middle and lower Yangtze River Basin significantly increase when EASMI standardized anomaly is below -1.00. As discussed before, the hydrologic variables respond oppositely to EASM fluctuation in the upper Yangtze River Basin, which results in an inconspicuous change of the average hydrologic variables throughout the entire basin, as shown in Table 4. The biggest increment of runoff occurs in the lower Yangtze River, which reaches 30~50% increase. The spatial pattern of rainfall change is similar to runoff except the fluctuation rates are much smaller and the peak increment of rainfall occurs a bit upstream.

It is interesting that both ET and soil moisture significantly increase (5~10%) in the mountain area to the southeast of Chongqing City of Sichuan province when EASMI standardized anomaly is below -1.00, whereas the peak increase of rainfall occurs in the faraway downstream. The lack of synchronization between soil moisture and precipitation or runoff might be due to the hysteretic nature of cumulative soil moisture. Soil moisture usually shows a lag and damping response to climate change [35].

The FP of hydrologic variables in other categories of EASM fluctuation, that is, 0.34~1.00 and -1.00~-0.34 in the eight watersheds, is summarized in Table 4. Based on Table 4, the Liaohe and Haihe are the most sensitive basins responding to EASMI increase. The hydrologic variables in the two basins vary dramatically as the EASMI standardized anomaly is above 1.00; for example, the runoffs increase by 32% and 49% in the basins of Liaohe and Haihe, respectively. In contrast, the basins of Haihe and Yellow River are ranked the top 2 whose hydrologic variables are the most sensitive

FIGURE 4: Variation of precipitation (a), ET (b), runoff (c), and soil moisture (d) when EASMI standardized anomaly is within 1.00~2.00. The colors present the percentages of variation of variables from their annual means. The green curves draw the outline of regions with 95% confidence level in Student's t -test.

to when EASMI standardized anomaly is below -1.00 , which brings severe drought to these regions. The runoffs in the watersheds of Haihe and Yellow River decrease by about 27% and 17%.

5.3. Sensitivity of Hydrologic Variables to EASM Fluctuation in Croplands. Besides the FP of hydrologic variables to EASM fluctuation in the eight watersheds, Table 4 also shows their FP in three main croplands of China, that is, plains of Chengdu Plain (CDP), Sanjiang Plain (SJP), and North China Plain (NCP). Figure 1 shows the locations of ten croplands, that is, Sanjiang, Songnen, Hetao, North China (including Jianghuai), Taihu, Jiangnan, Dongtinghu, Poyanghu, and Chengdu. Since available water resources such as runoff

and soil moisture mainly restrict the grain production of croplands in the north and west; Table 4 selects the three main croplands as examples and summarizes the variations of their hydrologic variables with EASM. The Chengdu and Sanjiang Plains represent the government commodity grain bases in the west and north, respectively. North China Plain is the largest alluvial plain of eastern Asia and main area of sorghum, millet, maize, and cotton production in China. Wheat, sesame seed, and peanuts are also grown here.

Figure 3(a) indicates the runoffs in the three croplands are positively and highly correlated to EASM in general, although Table 4 suggests an exceptional case; that is, antiphase variations of hydrologic variables are observed in the North China Plain when the EASMI standardized anomaly is in

FIGURE 5: Variation of precipitation (a), ET (b), runoff (c), and soil moisture (d) when EASMI standardized anomaly is within $-2.00 \sim 1.00$. The colors present the percentages of variation of variables from their annual means. The green curves draw the outline of regions with 95% confidence level in Student's t -test.

the category of $0.34 \sim 1.00$. The abnormal example might be induced by the interannual relation between EASM and hydrological variable which is more complex than their interdecadal relation. The category of $0.34 \sim 1.00$ includes the years 1952, 1965, 1966, 1972, 1973, and 1975. Among them, El Niño, the most outstanding interannual variability in the ocean, has occurred in the years of 1965, 1966, 1972, and 1973. In the El Niño developing summers, warm Sea Surface Temperature (SST) anomalies could enhance convection in the tropical central Pacific and trigger an anomalous cyclone in the lower troposphere over the western North Pacific via the Gill-Matsuno mechanism [67, 68], which in turn causes the anomalous rainfall in China [69]. During El Niño

mature phase, the negative precipitation anomalies in the north China are statistically significant [70].

6. Conclusions and Discussions

This study identifies the watershed and crop regions in East China where hydrologic variables, that is, rainfall precipitation, ET, runoff, and soil moisture, are significantly correlated to EASM fluctuation. The MK nonparametric analyses indicate that the most significant positive correlation between runoff and EASM is located in the North China Plain and middle-lower Yellow River watershed, while the most

significant negative correlation exists in the upper reach of Pear River.

This study also examines the sensitivity of the hydrologic variables to the fluctuation of EASMI. Spatial analyses indicate the watersheds of Liaohe, Haihe, and the middle and lower Yellow River are the most sensitive regions susceptible to hydrological change when EASMI standardized anomaly is above 1.00. In contrast, the runoffs in the watersheds of Haihe and Yellow River decrease the most significantly when EASMI standardized anomaly is below -1.00, leading to severe droughts in the regions. Since runoff is double sensitive to the EASM fluctuation compared to precipitation over East China, it might serve as an efficient index to reflect the future droughts and floods due to climate change in the region.

This study also suffers from several shortcomings. First of all, the variation of the hydrologic variables in terms of the fluctuation ranges of EASMI is quantified based on limited historical data. The VIC hydrologic models need to be calibrated and verified by flow records at gauge stations (unimpaired to natural discharge) in major rivers and most of them are built after the year of 1949. More robust conclusions are expected in future after more data are collected. Secondly, implicit stationarity hypothesis has been applied in the study that assumes the change of climate, land cover, or other anthropogenic influences have not altered the main characterizes of hydrologic variables, for example, frequency. Recent studies have evidenced many flood series exhibit a nonstationarity, which challenges the conventional assumption in prediction [71]. To consider the nonstationary influence, a statistic of time-varying approach could be applied in the future study.

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

The financial support from the National Major Basic Research Program of China (2010CB428404) and the “Hundred Talents Program” of Chinese Academy of Sciences is gratefully acknowledged.

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