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Hotspots of the sensitivity of the land surface hydrological cycle to climate change

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Due to the shortage of the global observational data of the terrestrial hydrological variables, the understanding of how surface hydrological processes respond to climate change is still limited. In this study, the Community Land Model (CLM4.0) with high resolution atmospheric forcing data is selected to simulate the global surface hydrological quantities during the period 1948–2006 and to investigate the spatial features of these quantities in response to climate change at the regional scales. The sensitivities of evaporation and runoff with respect to the dominant climate change factors (e.g. temperature and precipitation) derived from the concept of climate elasticity are introduced. Results show that evaporation has a declining trend with a rate of 0.7 mm per decade, while runoff shows a weak increasing trend of 0.15 mm per decade over the global land surface. Analyses of the hotspots in the hydrological cycle indicate that the spatial distributions for evaporation and runoff are similar over many areas in central Asia, Australia, and southern South America, but differ largely in high latitudes. It is also found that, the evaporation hotspots in arid regions are mainly associated with the changes in precipitation. Our sensitive analysis suggests that the hydrological quantities show a rather complicated spatial dependency of response of the water cycle to the different climate factors (temperature and precipitation).

hydrological cycle, hotspots, climate sensitivity, climate change

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The earth's climate has been warming throughout the 20th century and there is strong evidence that this warming, particularly over the last half-century, is very likely due to the increasing anthropogenic greenhouse gas concentrations [1]. One of the most direct impacts of the global warming is an accelerated hydrological cycle due to the increase of atmospheric water content associated with the warming [2]. Climate change is believed to strongly alter the global hydrological cycle [3,4]. A number of changes in the water cycle have been documented based on the observational studies. For example, Labat et al. [5] pointed out the global river flow has increased significantly during the 20th century and Roderick and Farquhar [6] found that pan evaporation has decreased in many areas of the world. Climate models also project that the frequency and intensity of extreme precipitation events will continue to increase [1]. These changes have important implications for water-resource management, agriculture, flood/drought control and many other sectors and thus the research on the changes in the global and regional water cycle has caused wide public concern all over the world.

The sensitivities of the hydrological responses to climate changes have been studied recently [7–9]. By analyzing the hydroclimate changes in the Mississippi River, Qian et al.

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[10] concluded that the increasing evapotranspiration was dominated by the changes in precipitation, whereas the impact of temperature was minor [11]. Meanwhile, the land hydrological cycle can also produce important feedbacks on the climate. For example, as one of the key land hydrological variables, soil moisture shows significant impacts on both weather and climate by altering water and energy fluxes between the land surface and the atmosphere [12–14].

Previous studies have been focused on the regional hydrological cycle based on the observations from stations. However, it is relatively difficult to explore the spatial features of the hydrological processes, especially at the global scale. Due to the shortage of a long-term and large spatial scale observed data, the land surface models can be used as an alternative tool for understanding the hydrological processes. These models can simulate important physical processes, such as energy, water and momentum fluxes that are hard to obtain directly from the observations. Therefore, it is possible and beneficial to explore the potential mechanism of hydrological variations to climate changes using land surface models. As a state-of-the-art land surface model, the Community Land Model (CLM) has been widely calibrated and evaluated at different temporal and spatial scales (e.g. using flux tower sites [15], at regional to continental scales [10]), and have been showing good performances in representing land surface processes. Particularly, compared with its previous versions, the latest one (Community Land Model version 4.0, CLM4.0) has been improved significantly [16]. Therefore, using the atmospheric forcing data from 1948 to 2006 as the inputs of CLM4.0 has the potential to provide reasonable estimate of the global hydrological quantities (e.g. runoff and evaporation).

Spatial and temporal variations in the surface hydrological variables over different regions are difficult to be accurately quantified. Recently, Giorgi [17] developed a regional climate change index (RCCI) which is an alternative approach for revealing the regional climate response. The concept of climate change hotspots can be defined as a region where climate is especially responsive to global change, which can provide the key information to identify the regional processes of climate change [17]. Using this approach, Sheng et al. [18] has investigated the hotspots of surface energy processes to the historical climate change, and Xu et al. [19] found that sub-regional hotspots exhibited evidently different responses to 21st century global warming over East Asia.

In the present study, we perform the analysis of hotspots on the hydrological response to climate change based on the CLM4.0 simulations, with an emphasis on the sensitivities of hydrological response to the changes of key climate variables of temperature (T) and precipitation (P). The concept of climate elasticity is adopted to qualitatively evaluate the sensitivities of the hydrological quantities [20–22]. This paper starts with a brief description of the model and methods in section 1, followed by the analysis results in section 2 and the major conclusions in Section 3.

1 Methodology

1.1 Model and experiment

CLM4.0 is the latest land component within the Community Earth System Model (CESM). Compared with its previous versions, CLM4.0 incorporates significant improvements on both its physical parameterizations and model structures, including improved hydrology, snow scheme, soil dynamics and albedo parameters, together with an updated distribution scheme of various plant functional types [16]. The performance of CLM in hydrological cycle simulation has been extensively evaluated recently. Results suggest that the long-term-mean freshwater discharge into the global and individual oceans simulated by CLM is comparable to 921 river-based observational estimates [23]. Niu and Yang [24], and Niu et al. [25] evaluated the improvements of CLM3.5 in runoff treatments. Oleson et al. [26] assessed the performance of CLM3.5 and found compared results from a set of offline simulations to the observed runoff, river discharge and total water storage. More recently, Dai et al. [27] showed that the CLM3-simulated streamflow generally agrees with the observed on both the interannual and multidecadal time scales; Lawrence et al. [16] compared the global river discharge simulations with the observations [28]; Li et al. [29] used CLM4.0 to examine the runoff simulations at watershed scales. All those studies suggest that CLM has the capability to reproduce the main features of the terrestrial hydrological cycle.

The global near-surface meteorological forcing data from 1948 to 2006, which was developed by the Land Surface Hydrology Research Group at Princeton University [30], was used as the model inputs to drive CLM4.0 for our offline experiments. The forcing data was constructed by combining observations with reanalysis datasets with a temporal resolution of three hours and a horizontal resolution of 1°×1°. The meteorological variables include humidity, longwave radiation, precipitation, shortwave radiation, surface air temperature, surface pressure and surface winds. Firstly, the model was spun up for 18 years using the forcing data of 1948 repeatedly to ensure that the deep soil moisture could reach its long-term equilibrium. Following the spin up, the simulation during 1948–2006 was performed for our following analysis.

1.2 Definition of climate change and hydrological cycle hotspots

To recognize the climate change hotspots, Giorgi [17] has proposed the concept of regional climate change index (RCCI) based on the change in mean value and interannual variability of temperature and precipitation. RCCI can be used to reflect the regional climatic responses to the global warming over selected regions. Following the work of Giorgi [17], Sheng et al. [18] quantified the index for individual energy variables such as net radiation and latent heat flux. One objective of this study is to identify the key regions where significant changes in the land surface hydrological cycle have occurred. Here we apply the concept of hotspots to explore the significance of the hydrological variations to climate change by calculating the evaporation and runoff change indexes. The change indexes of a hydrological variable S is acquired by,

$$S_{\text{Index}} = \sum_{\text{season}} [n(\lambda S) + n(\sigma S)], \tag{1}$$

$$\lambda S = avg\left(\frac{|S_{i,j,k} - \bar{S}_{i,j}|}{\bar{S}_{i,j}}\right), \tag{2}$$

$$\sigma S = \frac{SD(S_{i,j,k})}{\bar{S}_{i,j}}, \tag{3}$$

where S is the hydrological quantity (runoff or evaporation); i and j denote the meridional and zonal grid-points, respectively; k is the year; $\bar{S}_{i,j}$ is the multi-year mean during the sample period for each grid box; λS is the multi-year mean differences between S and $\bar{S}_{i,j}$ (anomaly of S for each year), which quantifies the contribution of the S change to the index; σS is defined as the standard deviation after detrending the annual time series (normalized by the 59-year climatological mean), which reflects the interannual variability of S; n is a classification coefficient, which is set to 0, 1, 2, and 4 when λS or σS is 0–5%, 5–%10%, 10%–15%, and >15%, separately [17,18]. According to the definition, higher change indexes of the hydrological quantities denote the hotspots with significant changes of the corresponding hydrological variables.

1.3 Sensitivity index of hydrological variables to climate change

Given the linkage between the hydrological cycle and climate change, a general expression for the changes of the hydrological variables due to the variations of T and P can be expressed as follows,

$$\Delta S = \frac{\partial S}{\partial T} \cdot \Delta T + \frac{\partial S}{\partial P} \cdot \Delta P, \tag{4}$$

where ΔT and ΔP represent the changes in temperature and precipitation, respectively. Each hydrological variable S (runoff or evaporation) is assumed to be a function of T and P, and thus the changes in S depend only on the variations of T and P. $\partial S/\partial T$ and $\partial S/\partial P$ represent the contribution of changes in T and P to the hydrological variables, respectively.

Schaake [20] first proposed the concept of climate elasticity to evaluate the sensitivity of the streamflow to climate changes. Based on this concept, similar definitions have been widely applied for other climate variables [21,22]. In this study, the sensitivity of the hydrological variables to climate changes (e.g., T and P) is defined as,

$$\frac{\Delta S}{\bar{S}} = \alpha \cdot \frac{\Delta T}{\bar{T}} + \beta \cdot \frac{\Delta P}{\bar{P}}, \tag{5}$$

where α and β are the sensitivity factors of the changes in T and P, respectively. $\bar{S}$, $\bar{T}$ and $\bar{P}$ are the multi-year mean of variable S, T and P, respectively. In order to emphasize the effects of the temperature and precipitation, and to separate their roles on the hydrological cycle, here we apply the similar approach to estimate the sensitivity of the hydrological quantities to climate forcing variables [11], which can be approximated as

$$\alpha + \beta = 1. \tag{6}$$

By combining eq. (5) with eq. (6), α and β can be acquired by

$$\alpha = \frac{\Delta S / \bar{S} - \Delta P / \bar{P}}{\Delta T / \bar{T} - \Delta P / \bar{P}}, \tag{7a}$$

$$\beta = \frac{\Delta S / \bar{S} - \Delta T / \bar{T}}{\Delta P / \bar{P} - \Delta T / \bar{T}}. \tag{7b}$$

For large sample size case, nonparametric approach can be used to estimate α and β in eqs. (7a) and (7b),

$$\alpha = \text{median}\left(\frac{\Delta S / \bar{S} - \Delta P / \bar{P}}{\Delta T / \bar{T} - \Delta P / \bar{P}}\right), \tag{8a}$$

$$\beta = \text{median}\left(\frac{\Delta S / \bar{S} - \Delta T / \bar{T}}{\Delta P / \bar{P} - \Delta T / \bar{T}}\right) \tag{8b}$$

and this approach has been proved to be an efficient estimator of the climate elasticity [31].

2 Results

2.1 Long-term trends of global land climate and hydrological variables

Figure 1 shows the annual anomalies of global averaged surface air temperature and precipitation rate over land excluding Antarctica. Strong variability is observed for both variables, especially precipitation. The temperature increases at a rate of 0.166°C per decade from 1948 to 2006, which is within the range from 0.10 to 0.16°C per decade during 1956 to 2005 as reported by IPCC [1]. On the other hand, the precipitation exhibits a weak downward trend (about 0.73 mm per decade), which is consistent with the results from Chen et al. [32]. It is noted that the variations of

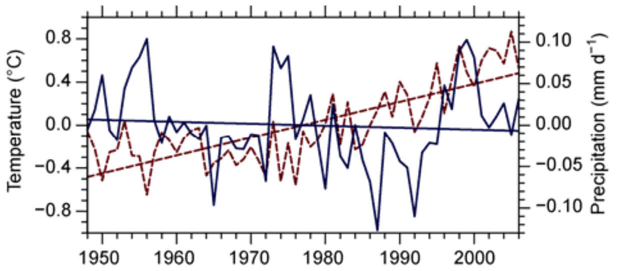

Figure 1 Anomalies of globally averaged air temperature and precipitation over land excluding Antarctica.

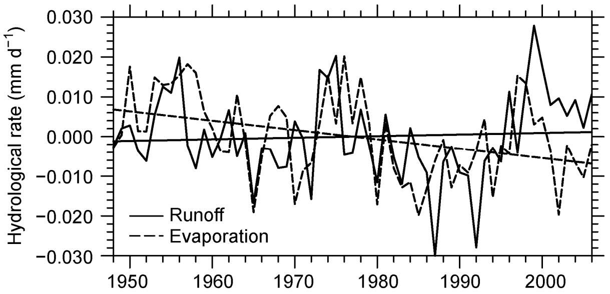

Figure 2 Anomalies for globally averaged evaporation and runoff (mm d^{-1}) over land excluding Antarctica.

Table 1 Correlations among globally averaged temperature, precipitation, evaporation and runoff during the period of 1948–2006[a]

	P	Evaporation	Runoff
T	0.051	**−0.278**	0.152
P		**0.552**	**0.934**
Evaporation			**0.313**

a) Values in bold are statistically significant at the 0.05 level.

evaporation obtained from the offline simulations from 1948 to 2006 correlated well (the correlation coefficient of 0.552) with that of *P* (Figure 2). Overall, the evaporation exhibits a declining trend with a rate of 0.7 mm per decade over the global land. In addition, the evaporation decreases before 1972 but increases after 1987. While the runoff shows a weak increasing trend (0.15 mm per decade) over the past 59 years. We calculated correlations among the globally averaged temperature, precipitation, evaporation and runoff during the period of 1948–2006 (Table 1). It is found that the evaporation bears a significant negative correlation with the temperature but a positive correlation with the precipitation, which indicate that the global land evaporation is mainly controlled by the precipitation. Figure 3 presents the geographic distribution of the correlation between evaporation and temperature/precipitation. Evaporation shows negative correlation with the temperature in most of the global areas, while significant positive correlations between evaporation and precipitation are mainly located in arid and semi- arid regions.

2.2 Hotspots in climate and hydrological cycle changes

The concept of hotspots is applied to quantify and identify the regions where significant changes in terrestrial water cycle have occurred. To explore the relationships between climate changes and the hydrological cycle, Figure 4 illustrates the spatial patterns of the change index of each variable as estimated by eq. (1), with regions with higher indexes represent the hotspots. Compared to the climate change indexes, hotspots of *T* (Figure 4(a)) and *P* (Figure 4(b)) are mainly located in the higher latitudes (e.g. North America, central Siberia and Greenland) and the low latitudes (e.g. northern and southern Africa, central Asia, and Australia), respectively, indicating that these regions have relative strong response to climate changes during the past 59 years. The *P* change indexes exhibit a similar spatial patterns to those in Sheng et al. [18], but with different magnitudes possibly due to differences in data processing methods and sample sizes (personal communication with Sheng). For the hydrological change indexes, their hotspots exhibit evidently different spatial patterns from the climate change hotspots. For example, the evaporation hotspots (Figure 4(c)) are located in central Asia, Australia and southern South America, while the runoff hotspots (Figure 4(d)) are located in central Asia, Australia, northern Africa and mid-latitude boundaries around 60 °N. Additionally, comparing the change indexes of precipitation (Figure 4(b)) against those of evaporation (Figure 4(c)), it is noted that

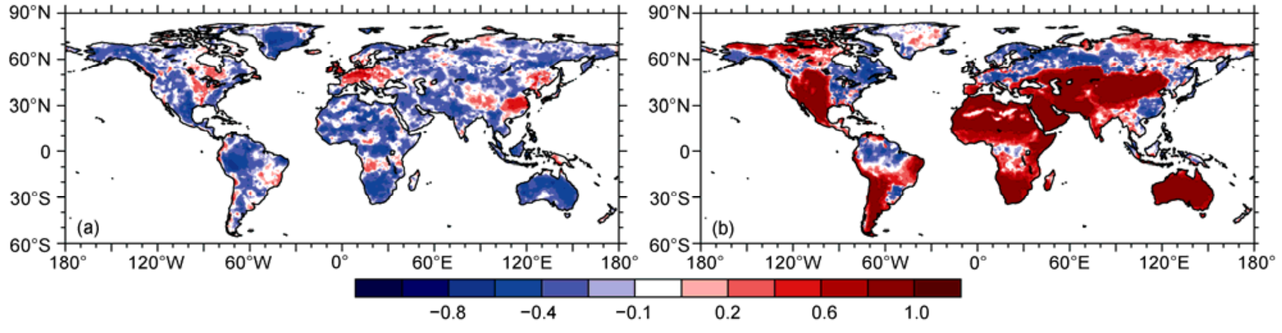

Figure 3 Spatial patterns of correlations between evaporation and (a) *T* and (b) *P*, respectively.

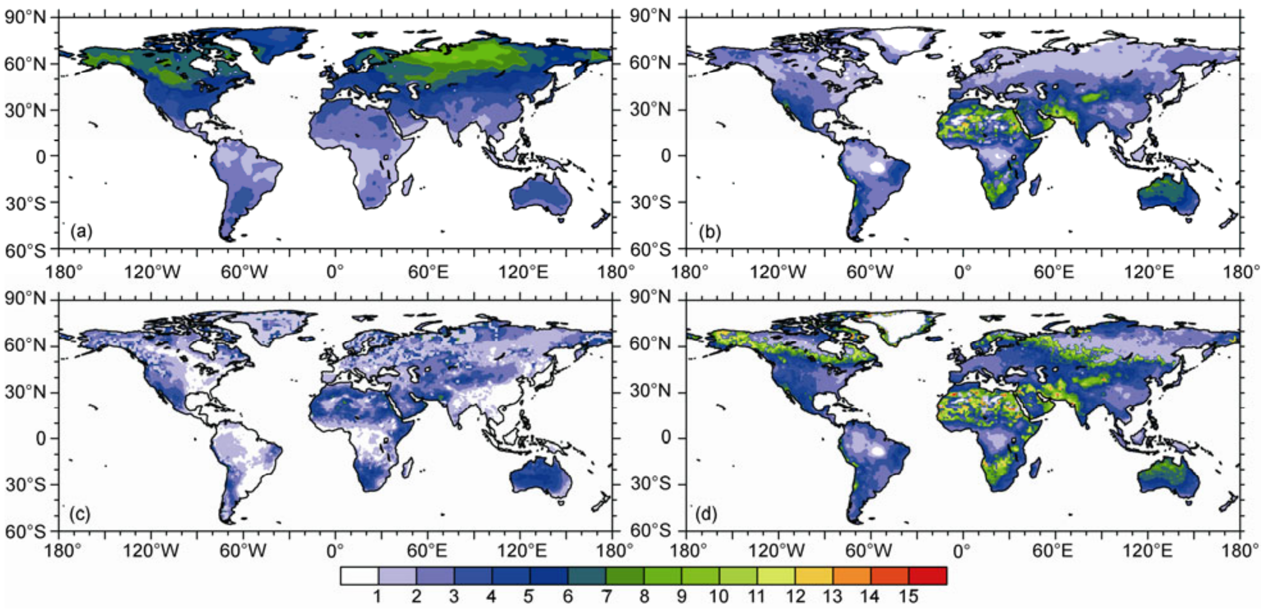

Figure 4 Regional change indexes for T (a), P (b), evaporation (c) and runoff over land (d). Regions with higher index values are defined as the hotspots.

the evaporation hotspots are not fully spatially associated with the P hotspot, implying a high complexity of land-atmosphere interactions. Moreover, it is noteworthy that the evaporation hotspots are mainly located in arid regions, which suggests that the evaporation changes are closely associated with the changes in precipitation over these regions.

2.3 Sensitivity of the hydrological cycle to climate change

The previous analysis in Section 2 indicates that the sensitivity of the hydrological cycle to climate change is strongly region-dependent, implying different responses at different locations. For the case of offline simulations, climate variables provide the forcing for the land surface model, and no land-atmosphere feedbacks are included. In particular, T and P are the most important climate forcing inputs. Given the close relationship between the changes in the water cycle and climate, next we investigate the regional scale sensitivities of hydrological quantities with respect to T and P using the hydrological sensitivities parameters (α and β) derived from the concept of climate elasticity.

Figure 5 presents the sensitivities of evaporation and runoff to T and P at each grid box excluding Greenland and Antarctica. Basically, our results inferred from the elasticity analysis are consistent with previous studies at both regional and global scales [33,34]. The evaporation elasticity to T is positive on the whole, ranging from 0.7 to 1.5 over most land areas (Figure 5(a) and (b)). Its higher values are mainly located in North America, North Europe, Russia, and the northern part of South America, implying that T plays a vital role in controlling the evaporation variation over these regions. However, the evaporation elasticity to P exhibits evidently spatial differences with a value between −1.2 and 1.5. Its high positive values (> 0.5) is mainly observed in North Europe, eastern North America and Amazon basin indicating that precipitation has a closer connection to the variation of evaporation than temperature.

The elasticity of runoff to the change in P is positive over most land areas, with the higher runoff elasticity values in the South America and the tropical Africa (Figure 5(d)), while the elasticity of runoff to T change is mainly negative in the low latitudes but positive in the mid- and high-latitudes. Basically, higher temperatures tend to enhance evaporation, resulting in less runoff. It is also possible that the warming in the high latitudes (Figure 5(b)) has melted permafrost and reduced the seasonal snow cover, both of which could have further accelerated the water cycle. On the other hand, higher temperatures tend to increase the frequency and intensity of extreme precipitation [35], which in turn results in larger runoff.

3 Conclusions and discussion

Owing to the lack of the global comprehensive observations of the hydrological variables, our current understanding on the terrestrial hydrological responses to climate change is still very limited. In this study, the spatial features of the global land evaporation and runoff together with their sensitivities to climate changes during the period of 1948– 2006 are investigated based on the long-term offline simulations by CLM4.0. In order to quantify such features effectively, the concepts of hotspot and climate elasticity are introduced. Generally, the changes in climate forcing can result in evident changes in the water budgets, and the response of the hydrological cycle to individual climate variables (i.e.,

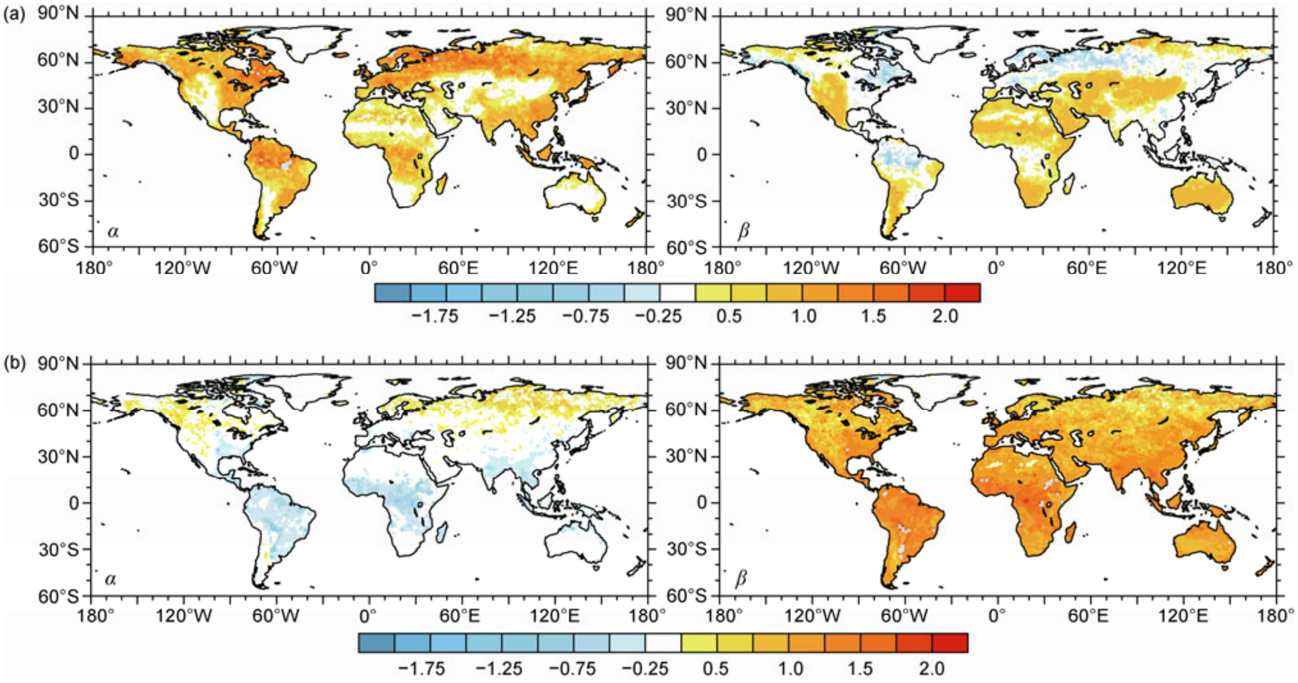

Figure 5 Contributions of T (α) and P (β) to the hydrological quantities of (a) evaporation and (b) runoff over land excluding Greenland and Antarctica.

temperature and precipitation) is region-dependent and nonlinear.

The global mean evaporation over land shows a decreasing trend with a rate of 0.7 mm per decade, while a weak increasing trend (0.15 mm per decade) is seen in runoff. Hotspots of both climate variables (temperature and precipitation) and hydrological quantities (evaporation and runoff) exhibit significant spatial variations. Basically, the regions with higher change indexes represent the hotspots, and the hydrological cycle over the hotspots is more sensitive to the climate change. For evaporation, most hotspots are located in central Asia, Australia and southern South America. The evaporative process in wet regions is generally controlled dominantly by the net radiative energy rather than by the availability of soil moisture, while the opposite is true in arid regions. Therefore, the evaporation hotspots in arid regions are mainly associated with the changes in P, and the runoff hotspots are similar to those of evaporation over most regions except for the high latitude areas.

It is noted that there are still some limitations and uncertainties in this study. The sensitivity analysis conducted here focused solely on the relationship between the hydrological cycle and climate change (only T and P were considered). Nevertheless, other climate quantities, such as solar radiation, wind speed and humidity, can also affect the hydrological cycle to some extent [6]. In addition, soil moisture also plays an important role in influencing land surface-atmosphere interactions through exchanges of energy and water fluxes. This study draws attention that most of the hydrological hotspots are located in water-limited arid and semiarid regions, where the uncertainties of the hydrological responses to precipitation are much higher [12]. During the past several decades, the land surface exhibits evident warming trends, and the effects of local warming on the hydrological cycle can not be ignored. For example the warming effects on evaporation in the high latitudes are remarkable. For some arid regions over Africa and Asia, however, evaporation seems insensitive to the changes in P, which needs further investigation. Furthermore, our results reported here are based on the simulations from one land surface model, and thus the use of multi-land surface model simulations will help reduce the model uncertainties. Therefore, the potential sensitivity of the hydrological cycle to climate changes remains to be further addressed in the future.

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