

Article

Shifts in Dry-Wet Climate Regions over China and Its Related Climate Factors between 1960–1989 and 1990–2019

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Abstract: The shifts in dry-wet climate regions are a natural response to climate change and have a profound impact on the regional agriculture and ecosystems. In this paper, we divided China into four dry-wet climate regions, i.e., arid, semi-arid, semi-humid, and humid regions, based on the humidity index (*HI*). A comparison of the two 30-year periods, i.e., 1960–1989 and 1990–2019, revealed that there was a shift in climate type in each dry-wet climate region, with six newly formed transitions, and the total area of the shifts to wetter conditions was more than two times larger than that of the shifts to drier conditions. Interestingly, the shifts to drier types were basically distributed in the monsoon region (east of 100° E) and especially concentrated in the North China Plain where agricultural development relies heavily on irrigation, which would increase the challenges in dealing with water shortage and food production security under a warming climate. The transitions to wetter types were mainly distributed in western China (west of 100° E), and most areas of the Junggar Basin have changed from arid to semi-arid region, which should benefit the local agricultural production and ecological environment to some extent. Based on a contribution analysis method, we further quantified the impacts of each climate factor on *HI* changes. Our results demonstrated that the dominant factor controlling *HI* changes in the six newly formed transition regions was *P*, followed by air temperature (*Ta*). In the non-transition zones of the arid and semi-arid regions, an increase in *P* dominated the increase of *HI*. However, in the non-transition zones of the semi-humid and humid region with a more humid background climate, the thermal factors (e.g., *Ta*, and net radiation (*Rn*)) contributed more than or equivalent to the contribution of *P* to *HI* change. These findings can provide scientific reference for water resources management and sustainable agricultural development in the context of climate change.

Keywords: dry-wet climate regions; humidity index; climate change; dominant factor



Citation: Xu, J.; Zhu, X.; Li, M.; Qiu, X.; Wang, D.; Xu, Z. Shifts in Dry-Wet Climate Regions over China and Its Related Climate Factors between 1960–1989 and 1990–2019.

Sustainability **2022**, *14*, 719. <https://doi.org/10.3390/su14020719>

Academic Editors: Baojie He, Ayyoob Sharifi, Chi Feng and Jun Yang

Received: 13 December 2021

Accepted: 5 January 2022

Published: 10 January 2022

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1. Introduction

Climate change is characterized by a higher global average temperature with the ability to alter the global and regional atmospheric water cycle [1–5]. It is expected to have a profound impact on the hydroclimate conditions, terrestrial water balance and water resources [6–11]. The variation of dry-wet climate regions is the embodiment of the changes in the atmospheric water cycle and is generally considered as an important aspect of climate change.

The classification of dry-wet climate regions depends on certain pre-determined indicators. The simplest classification approach is to identify dry-wet regions based solely on annual precipitation [12–14]. Nevertheless, such approach merely considers the input of water and ignores the expenditure of water, thus cannot fully characterize the water budget of a specific region. Moreover, intensification of global warming has modified the potential evaporation which in turn influenced the surface moisture status [15–17]. In this

sense, the abnormal precipitation cannot fully characterize the dry and wet changes of the surface. Currently, the most widely used classification of dry-wet climate regions is based on a comprehensive index coupled with precipitation and potential evapotranspiration. It can better reflect the dry and wet conditions of the actual climate from the atmospheric water balance perspective and has practical relevance for agricultural production. Many studies applied the humidity index, a ratio of annual precipitation (P) to annual potential evapotranspiration (PET), to divide drylands into hyper-arid, arid, semi-arid, and dry sub-humid regions [18–24]. They reported about the climate shift in various dry-wet regions around the world, and specifically on the significant expansion trend of semi-arid region.

The shift of dry and wet climate types usually occurs between adjacent hydroclimate regions [19,22,25]. It is the result of the cumulative effect of climate becoming wet or dry for many years. Changes in dry and wet conditions are controlled by two major driving factors, i.e., precipitation (P ; amount of water supply) and potential evapotranspiration (PET ; amount of moisture demand). Changes in other meteorological variables (e.g., air temperature, net radiation, wind speed, and relative humidity) can directly affect changes in PET , which will in turn affect the dry and wet changes. In recent years, numerous studies have explored the drivers of dry and wet changes using qualitative analysis method (e.g., correlation analysis method [26,27]), or quantitative methods (e.g., differential equation approach [15,18,28–30], sensitivity experiment method [31,32], and sensitivity coefficient analysis method [33,34]). Most studies have indicated that P has a greater impact on dry and wet changes than PET in most parts of the world [15,29,35]. Meanwhile, as the climate warms up, the contribution of air temperature to climate drying or drought is also increasing [35,36]. Previous studies on the influencing factors of changes in dry and wet conditions were mostly conducted in different hydroclimate types or in specific regions. Detailed investigation on the dominant factors of dry and wet changes in newly formed climate transition regions is limited. In the context of climate change, it is unclear what the key factors that lead to the shifts in each dry-wet region. Little is known whether these key factors also dominate the climate of various dry-wet regions to turn dry or wet, and how much warming has played a role in the transitions of dry-wet regions. These questions need to be further complemented.

In this paper, we divided China into four dry-wet climate regions based on the humidity index (HI), compared the changes in dry-wet climate regions over the past two 30-year periods and further explored its related climate factors affecting the changes. The objectives of our research are to (1) reveal the patterns of the shifts between different dry and wet climate regions in China; (2) quantify the role of main climate elements in dry-wet climate changes; (3) compare the differences in the dominant factors controlling the changes in dryness/wetness between dry-wet transition regions and non-transition regions. Our research can provide a reliable scientific basis for government departments (especially agriculture and water conservation departments) to better grasp the pattern of dry and wet changes under climate change. This would allow them to formulate more reasonable agricultural production plans and water management strategies.

2. Materials and Methods

2.1. Study Region and Data

China is one of the countries with the largest territorial area in the world, and its terrain is high in the west and low in the east, with a step-like distribution. The landform is complex, and the five basic landform types on land are all distributed in China. There are various climate types, i.e., arid, semi-arid, semi-humid and humid. Taking 100° E as the boundary, the east region is a typical East Asian monsoon region with a relatively humid climate, while the west region is characterized by a temperate continental climate and an alpine climate, with sparse precipitation and a relatively arid climate.

In this study, the meteorological observations for the period 1960–2019 were obtained from 635 meteorological stations of the China Meteorological Administration (CMA). These observations included monthly precipitation, air temperature (i.e., average, maximum,

and minimum), wind speed, relative humidity, and sunshine duration. To understand the transitions in dry-wet climate regions over the past 60 years, we divided the whole study period into two sub-periods: the first 30 years (from 1960 to 1989) and the recent 30 years (from 1990 to 2019). We performed quality control on all data sessions, i.e., the stations with observation data less than 11 months per year or less than 15 years total for the two sub-periods (1960–1989 and 1990–2019) were eliminated, and the missing values of other stations were filled by linear regression equations using the data of nearby stations. In addition, IDW (Inverse Distance Weighted) interpolation method was adopted to obtain the spatial distribution map.

2.2. Classification of Dry-Wet Climate Regions

In the process of classifying dry and wet climate regions, it should be consistent with the natural geographical environment in the study area, and also be comparable to the division of the world's dry-wet climate regions, because climate and environmental changes are global. The most common and reliable international standard for the classification of dry and wet climate regions is based on the humidity index (HI) [37]. According to this standard, drylands can be divided into hyper-arid ($HI < 0.05$), arid ($0.05 < HI < 0.2$), semi-arid ($0.2 < HI < 0.5$), and dry sub-humid ($0.5 < HI < 0.65$) regions [21–23]. By considering the distribution characteristics of the vegetation belt from east to west in China and the Qinling-Huaihe natural geographical boundary [38,39] adapted the original international classification standard of dry-wet regions, and divided China into arid region (AR, $HI < 0.2$), semi-arid region (SAR, $0.2 < HI < 0.5$), semi-humid region (SHR, $0.5 < HI < 1$), and humid region (HR, $HI > 1$). The spatial distributions of dry-wet climate regions (defined by HI from 1960 to 1989) in China are shown in Figure 1. From the southeast coast to the northwest inland, China is divided into HR, SHR, SAR and AR, with area proportions of 25.94%, 21.62%, 29.75%, and 22.69%, respectively.

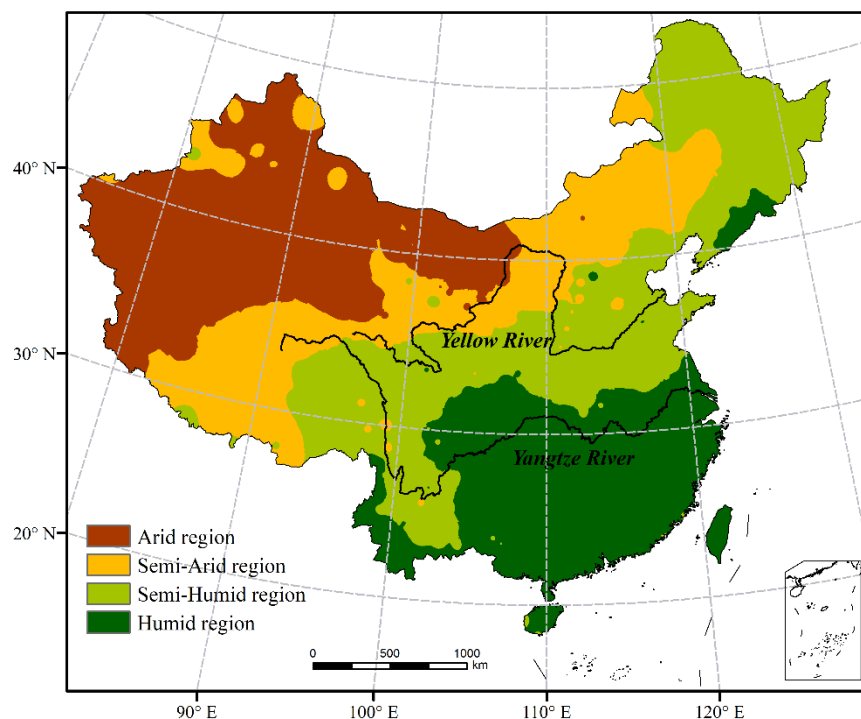


Figure 1. Spatial distribution of dry-wet climate regions derived from the humidity index (HI) calculated using meteorological observations during 1960–1989.

2.3. Contribution Analysis

To examine whether water input or water output contributes the most to the change of *HI*, we calculate the contributions of changes in *P* and *PET* on the *HI* changes using the derivative of *HI* with respect to year (*t*), as follows:

$$\frac{dHI}{dt} = \frac{d}{dt} \left(\frac{P}{PET} \right) = \frac{1}{PET} \frac{dP}{dt} + \left(-\frac{P}{PET^2} \right) \frac{dPET}{dt} \quad (1)$$

where $\frac{dHI}{dt}$ represents the trend in *HI*, $\frac{1}{PET} \frac{dP}{dt}$ and $\left(-\frac{P}{PET^2} \right) \frac{dPET}{dt}$ represents the annual contributions of *P* and *PET* to the variation of *HI*, respectively.

PET is calculated using the FAO Penman-Monteith model [40], i.e.,

$$PET = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2)$$

where Δ (kPa °C⁻¹) is the slope of the vapor pressure curve, *Rn* (MJ m⁻² day⁻¹) is the net radiation at crop surface, *G* (MJ m⁻² day⁻¹) is the soil heat flux density, γ (kPa °C⁻¹) is the psychrometric constant, *T* (°C) is the mean temperature at 2 m height, calculated as the average of monthly maximum and minimum temperature, *u*₂ (m s⁻¹) is the wind speed at 2 m height, *e*_s (kPa) is the saturation vapor pressure, and *e*_a (kPa) is the actual vapor pressure.

Based on the multilinear regression method [15,34,41–43], *PET* can be decomposed into several key climate factors, i.e., average air temperature (*Ta*), net radiation (*Rn*), wind speed (*WS*), and relative humidity (*RH*), given by,

$$PET = a_1 Ta + a_2 Rn + a_3 WS + a_4 RH + b \quad (3)$$

where *a*₁, *a*₂, *a*₃, and *a*₄ represents the regression coefficients of *Ta*, *Rn*, *WS*, and *RH*, respectively, and the constant *b* is the intercept.

By taking the derivative of both sides of Equation (3) with respect to year (*t*), we have,

$$\frac{dPET}{dt} = a_1 \frac{dT_a}{dt} + a_2 \frac{dR_n}{dt} + a_3 \frac{dW_S}{dt} + a_4 \frac{dR_H}{dt} \quad (4)$$

where $\frac{dPET}{dt}$ represents the changes in *PET*, and the terms on the right-hand side represent the contributions of changes in *Ta*, *Rn*, *WS*, and *RH* to the *PET* changes.

Then, Equation (1) can be rearranged as:

$$\begin{aligned} \frac{dHI}{dt} &= \frac{1}{PET} \frac{dP}{dt} + \left(-\frac{P}{PET^2} \right) \left(a_1 \frac{dT_a}{dt} + a_2 \frac{dR_n}{dt} + a_3 \frac{dW_S}{dt} + a_4 \frac{dR_H}{dt} \right) \\ &\approx \frac{1}{\overline{PET}} \frac{dP}{dt} + \left(-\frac{\overline{P}}{\overline{PET}^2} \right) \left(a_1 \frac{dT_a}{dt} + a_2 \frac{dR_n}{dt} + a_3 \frac{dW_S}{dt} + a_4 \frac{dR_H}{dt} \right) \end{aligned} \quad (5)$$

where the terms on the right-hand side represent the contributions of changes in *P*, *Ta*, *Rn*, *WS*, and *RH* to the *HI* changes. $\overline{P}$ and $\overline{PET}$ represent the multi-year average values of annual *P* and *PET* for the study period, respectively.

For each station in China, we calculate the sum of the contributions of *P* and *PET* (refer to Equation (1)) and the sum of the contributions of *P*, *Ta*, *Rn*, *WS* and *RH* (refer to Equation (5)). Our comparison shows that Equations (1) and (5) can accurately reproduce the actual change of *HI* in Figure 2a (*R*² = 1, RMSE = 0.0003) and Figure 2b (*R*² = 0.998, RMSE = 0.003), respectively. To understand whether Equations (1) and (5) can represent the spatial pattern of actual change in *HI*, we plot the spatial distributions of actual change in *HI* (Figure 3a), total contributions of *P* and *PET* to *HI* change (Figure 3b), and total contributions of *P*, *Ta*, *Rn*, *WS*, and *RH* to *HI* change (Figure 3c). These plots demonstrate that the spatial distributions of Figure 3a,b are almost identical. Despite the minor differences in the sporadic areas in the northeast and northwest of China, the spatial distributions of

Figure 3a,c are basically the same. In general, these results confirm that the contribution analysis method (above) is reliable.

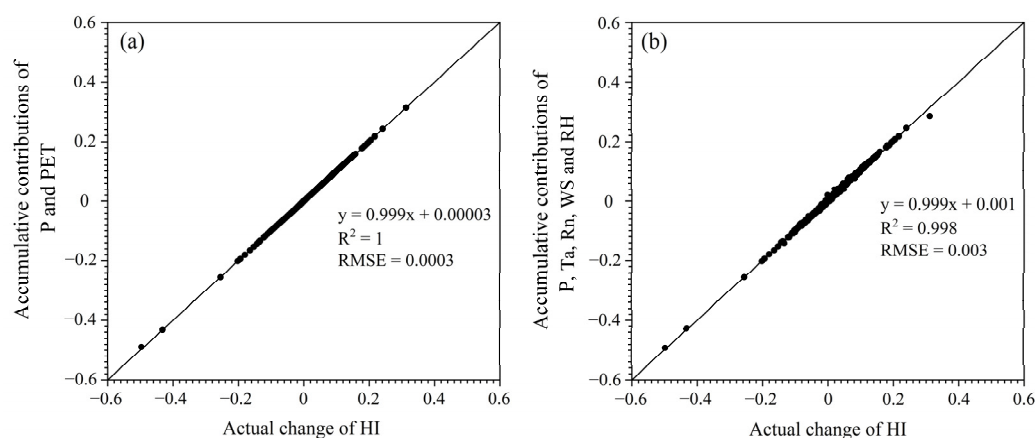


Figure 2. Scatter plots of the (a) sum of the contributions of P and PET , and (b) sum of the contributions of P , Ta , Rn , WS , and RH , against the actual change of HI based on meteorological observation stations.

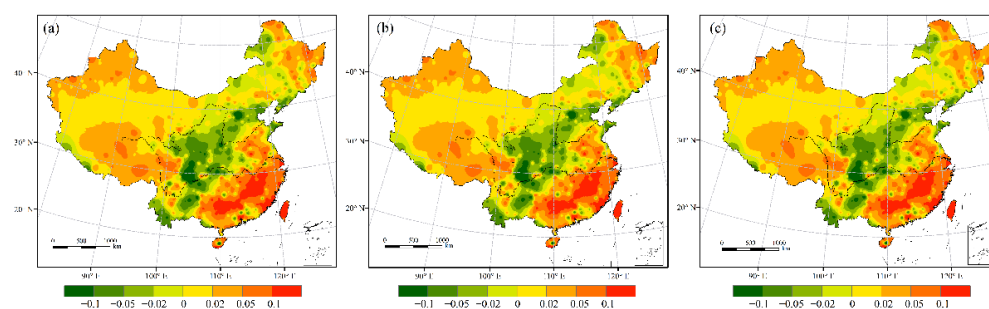


Figure 3. Spatial distributions of (a) actual change of HI , (b) the sum of contributions of P and PET to HI change, and (c) the sum of contributions of P , Ta , Rn , WS , and RH to HI change.

3. Results

3.1. Shifts in Dry-Wet Climate Regions

Figure 4 displays the time series of area of dry-wet climate regions in China derived from HI . The area of AR (SAR) decreased (increased) significantly at a rate of $4.9 \times 10^3 \text{ km}^2/\text{year}$ ($5.6 \times 10^3 \text{ km}^2/\text{year}$) during 1960–2019, but an upward (a downward) trend occurred after the late 2000s (Figure 3a,b). The areal changes in SHR and HR were insignificant during the past 60 years (Figure 4c,d), and the area of both for the recent 30 years (1990–2019) was comparable to that during 1960–1989 (Table 1). As shown in Table 1, the relative changes in the area of SHR and HR were -0.58% and -1.3% , respectively. Besides, the area of SAR during 1990–2019 was $0.4 \times 10^6 \text{ km}^2$ (or 19.43%) larger than that during 1960–1989. Relative to 1960–1989, the area of AR has decreased by $0.35 \times 10^6 \text{ km}^2$ (or 14.39%) in 1990–2019.

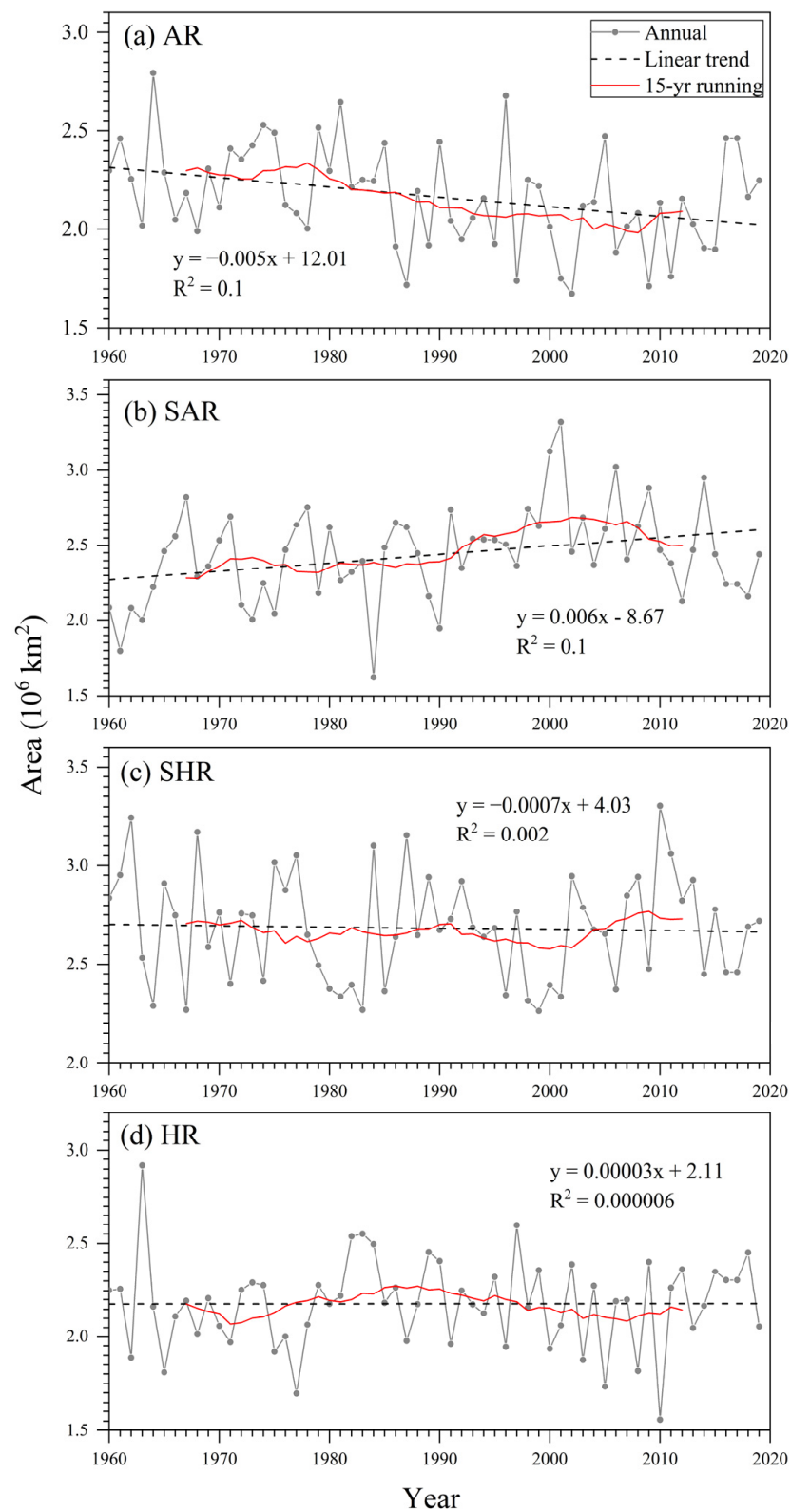
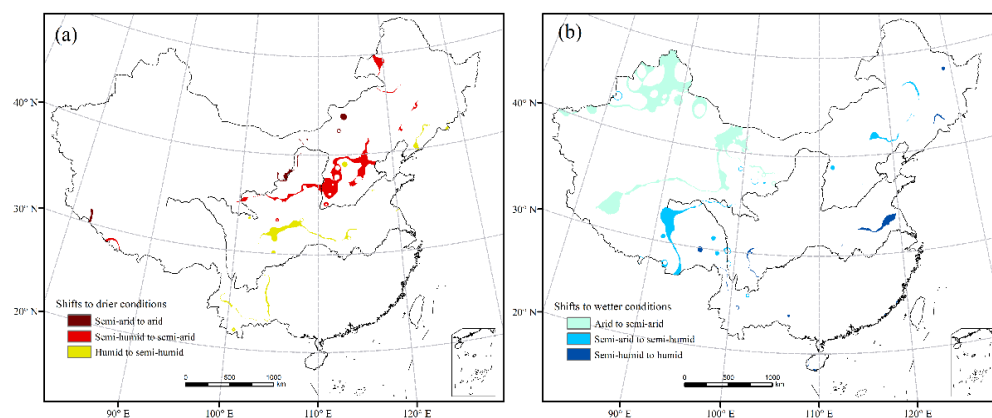


Figure 4. Temporal variations in the area (10^6 km^2) for different dry-wet climate regions in China during 1960–2019. (a) AR, (b) SAR, (c) SHR, and (d) HR, represent arid, semi-arid, semi-humid, and humid regions, respectively. A 15-year running smoothing (red curves) is applied to emphasize climate change.

Table 1. Areal changes of dry-wet climate regions in China from 1960–1989 to 1990–2019 (10^6 km^2).

Regions	Area		Difference	Relative Change
	1960–1989	1990–2019		
AR	2.46	2.10	−0.35	−14.39%
SAR	2.05	2.44	0.40	19.43%
SHR	2.82	2.80	−0.02	−0.58%
HR	2.15	2.12	−0.03	−1.31%

Climate change could lead to changes in the areal extent of dry-wet climate regions, which would be accompanied by a transition between dry-wet climate regions. Figure 5 demonstrates the spatial distribution of changes in dry-wet climate regions to drier and wetter conditions from 1960–1989 to 1990–2019. As shown in Figure 5, with 100° E as the dividing line, the shifts to drier conditions basically occurred in the monsoon regions (east of 100° E), while the transitions to wetter conditions were mainly distributed in western China (west of 100° E). The transition from SHR to SAR primarily occurred in the Yellow River basin, especially in the North China Plain; while the transition from HR to SHR mainly happened in the Yangtze River basin, especially in the Sichuan Basin. From 1960–1989 to 1990–2019, the total area of the shifts to wetter conditions was 5.2%, i.e., more than 2 times larger than that the shifts to drier conditions (Figure 6). Among all types of shifts to drier or wetter conditions, the area of the transition from other dry-wet regions to SAR was the largest. The newly formed SAR that transited from other dry-wet climate regions was $5.06 \times 10^5 \text{ km}^2$ (or 5.35%), and it was formed by two transitions from AR to SAR ($3.71 \times 10^5 \text{ km}^2$ or 3.92%) and SHR to SAR ($1.35 \times 10^5 \text{ km}^2$ or 1.42%). The reduced area of SAR that transited to other dry-wet regions was $1.08 \times 10^5 \text{ km}^2$ (or 1.14%), including the transitions from SAR to AR ($0.18 \times 10^5 \text{ km}^2$ or 0.19%) and SAR to SHR ($0.9 \times 10^5 \text{ km}^2$ or 0.95%). Therefore, the net change in SAR was 4.21% from 1960–1989 to 1990–2019. The transition from SHR to HR was $0.34 \times 10^5 \text{ km}^2$ (or 0.36%), while the shift from HR to SHR was $0.62 \times 10^5 \text{ km}^2$ (or 0.65%), thus the net change in HR was -0.29% from 1960–1989 to 1990–2019.

**Figure 5.** Spatial distribution of the transitions between dry-wet climate regions from 1960–1989 to 1990–2019: (a) shifts to drier conditions, and (b) shifts to wetter conditions.

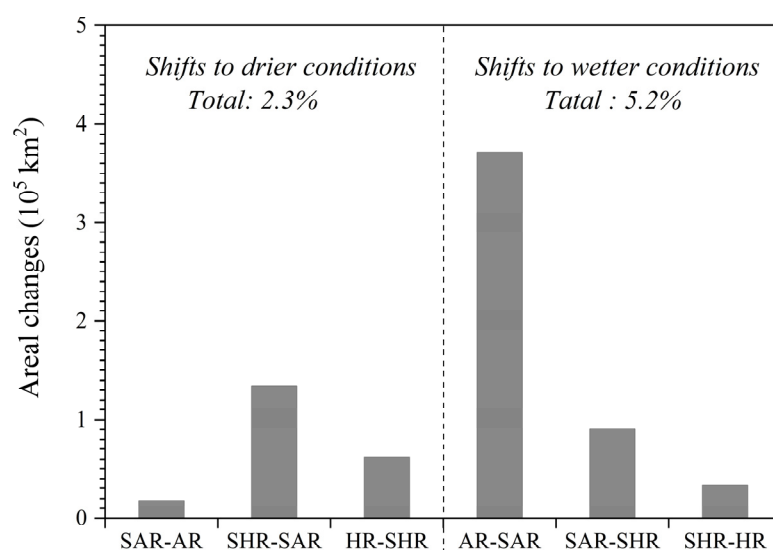


Figure 6. The area (10^5 km^2) of the transitions from semi-arid to arid region (SAR-AR), semi-humid to semi-arid region (SHR-SAR), humid to semi-humid region (HR-SHR), arid to semi-arid region (AR-SAR), semi-arid to semi-humid region (SAR-SHR), and semi-humid to humid region (SHR-HR) from 1960–1989 to 1990–2019.

3.2. Attribution Analysis

Changes in P , PET and other climate elements could lead to the variation of HI . From 1960–1989 to 1990–2019, P exhibited an “increase-decrease-increase” pattern from the southeast to the northwest over China (Figure 7a). In particular, the relative change rate of P was above 15% at the northwest inland area. The areas of increase and decrease of PET are comparable, and the positive relative change of PET is lower than that of P , mostly concentrated around 0–5% (Figure 7b). The trends of PET were influenced by several factors, i.e., Ta , Rn , WS , and RH . From the perspective of spatial distribution, Ta generally increased all over China, and increased by 0–1.5 °C in most areas (Figure 7c). By contrast, Rn , WS , and RH decreased in most areas of China (Figure 7d–f). Figure 8 shows the changes in HI due to changes in P (Figure 8a), PET (Figure 8b), Ta (Figure 8c), Rn (Figure 8d), WS (Figure 8e) and RH (Figure 8f). Compared with other climate elements, the spatial distribution of the contribution of P to the changes in HI is generally consistent (with partial regional differences) with that of the actual change of HI (Figure 3a). In contrast to P , an increase (a decrease) in PET led to a decrease (an increase) in HI . Meanwhile, changes in Ta , Rn , WS , and RH would lead to changes in PET and thus causing HI change. An increase in Ta (Figure 7c) caused a decrease in HI everywhere in China, and the contribution of Ta change to the changes in HI ranged between -0.05 and 0 (Figure 8c). The increase (decrease) of Rn and WS led to the decrease (increased) of HI , and the amount of HI change caused by the change of both was in the range of -0.02 to 0.05 in most areas (Figure 8d,e). Meanwhile, an increase (a decrease) of RH led to an increase (a decrease) of HI , and the contribution of RH change to the changes in HI was basically in the range of -0.02 to 0.05 (Figure 8f).

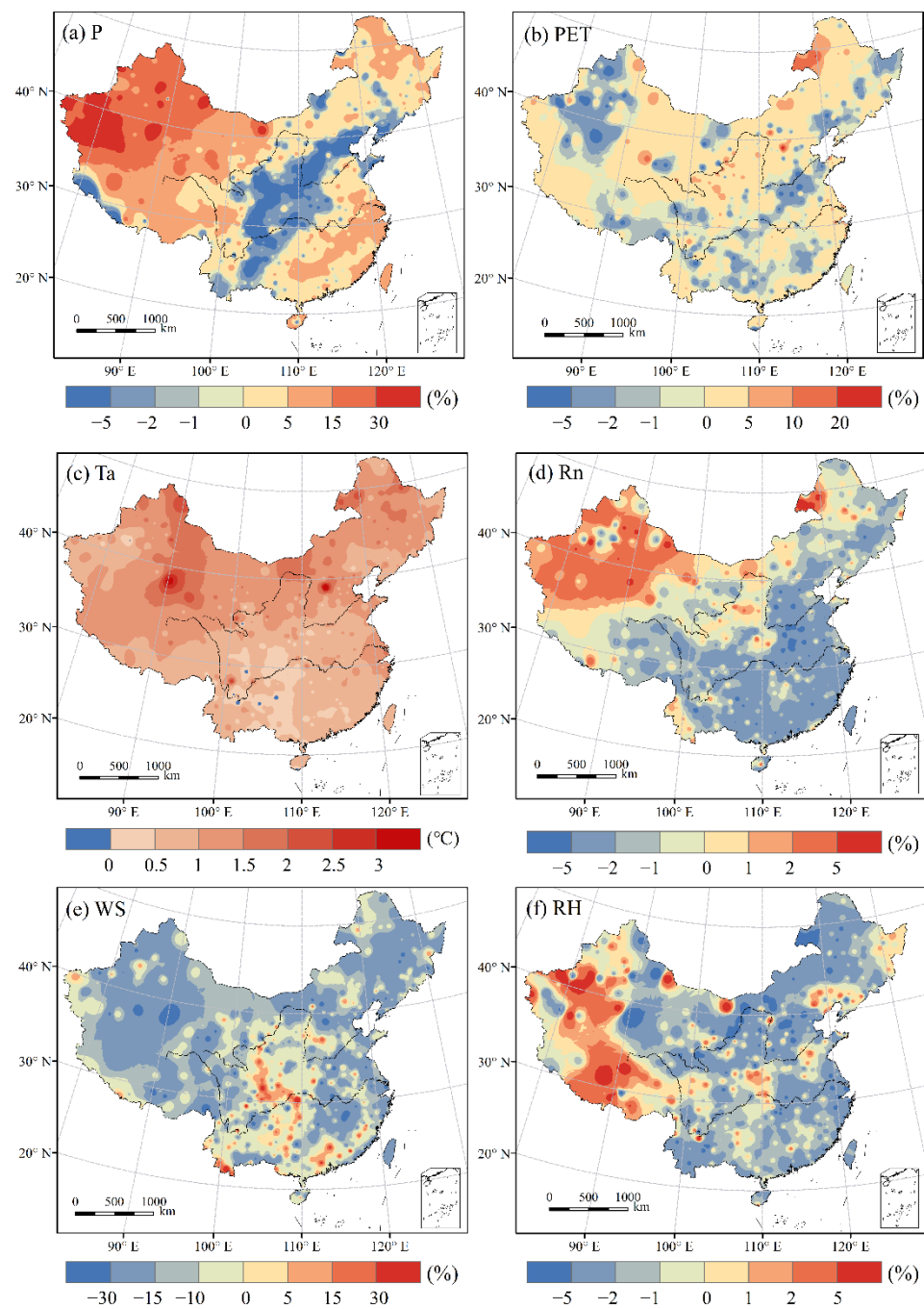


Figure 7. Spatial distributions of changes in (a) P (%), (b) PET (%), (c) Ta (°C), (d) Rn (%), (e) WS (%), and (f) RH (%) over China from 1960–1989 to 1990–2019.

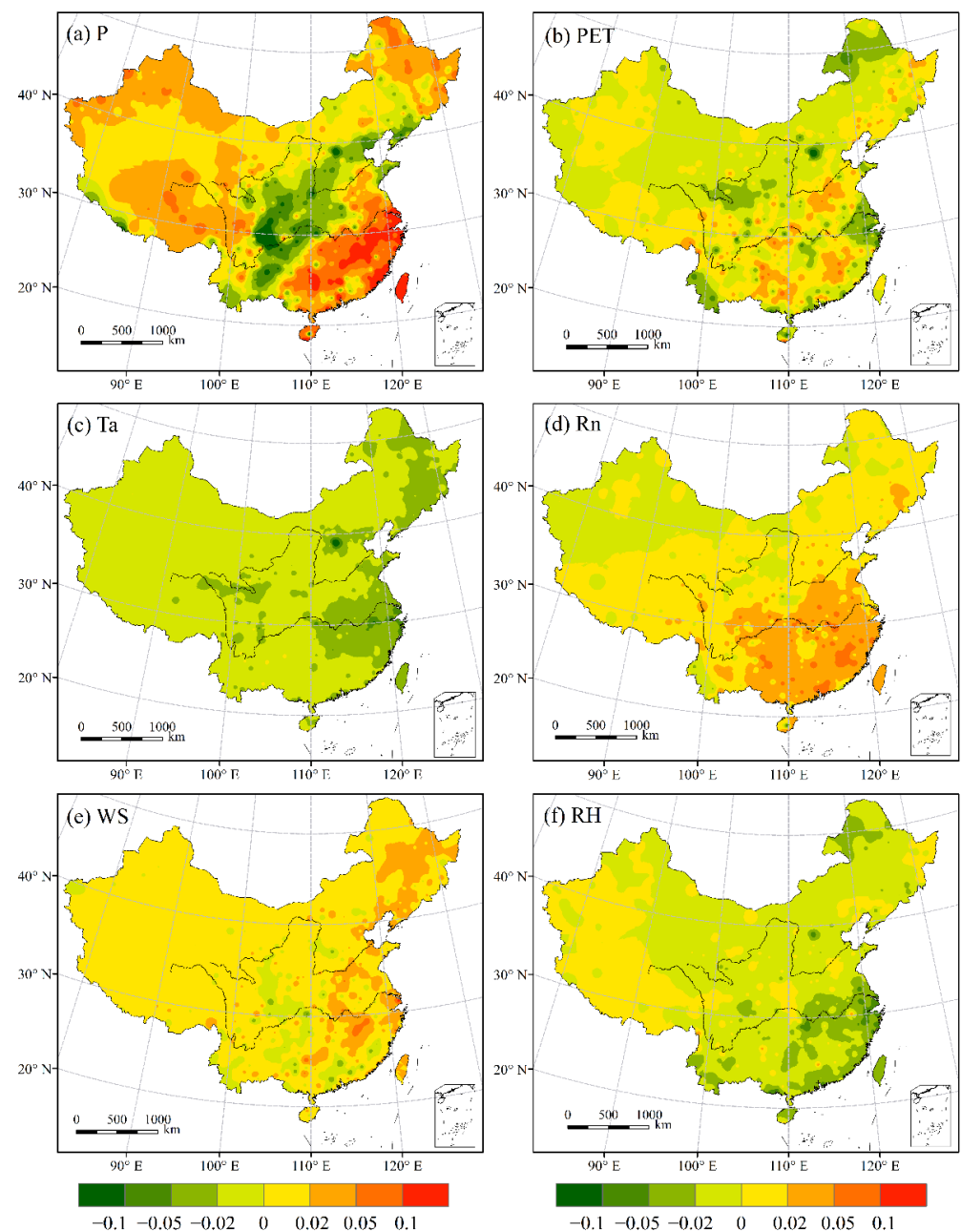


Figure 8. Spatial distributions of contributions of (a) P , (b) PET , (c) Ta , (d) Rn , (e) WS , and (f) RH to changes in HI over China from 1960–1989 to 1990–2019.

We further quantify the role of P , PET and other climate elements in HI changes that led to the shifts of dry-wet climate regions. Figure 9 shows the changes in HI , P , PET , Ta , Rn , WS , and RH , and the contributions of each climate element to HI changes, averaged over changed dry-wet climate regions. For regions converted to drier conditions, P , Rn , WS , and RH decreased uniformly, while PET and Ta increased uniformly. For regions converted to wetter conditions, P and Ta increased uniformly, but PET , Rn , WS and RH change trends were not uniform. In the six newly formed transition regions, Ta increased by about $1\text{ }^{\circ}\text{C}$ on average for 1990–2019 relative to 1960–1989; the relative change rate of WS was higher in the wet transition zones than in the dry transition zones. For the transitions to drier conditions, the decrease in P and increase in PET jointly dominated the decrease of HI in those from SAR to AR, while the decrease in P became more important for other shifts to drier regions. For three newly formed regions that shifted to wetter conditions, an increase

in *HI* was all dominated by increasing *P*. *PET* is directly affected by other climatic factors, among which, *Ta* was the most significant in this study. For the six transition regions, the *HI* change caused by *Ta* change was comparable to *PET* change in the newly formed AR transitioned from SAR, and was all higher than *PET* change in other transition regions to drier conditions.

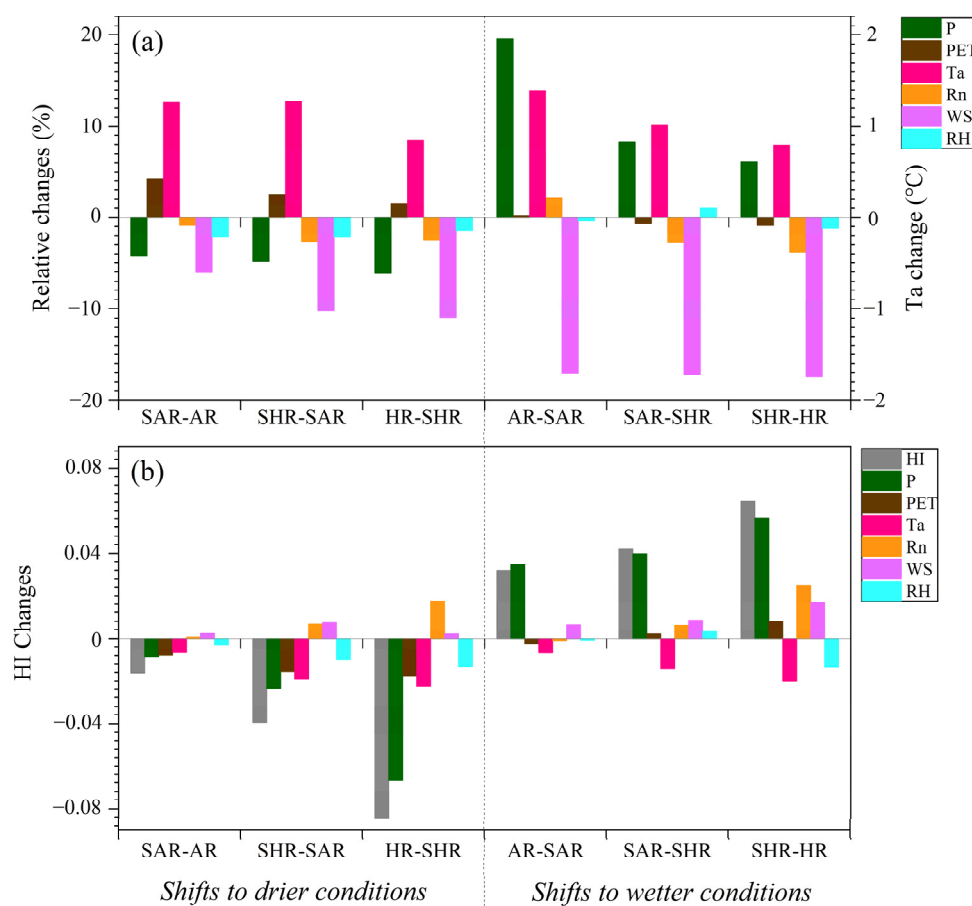


Figure 9. From 1960–1989 to 1990–2019, (a) relative changes of each climate element, and (b) changes in *HI* and contributions of each climate element to *HI* change, averaged over the newly formed areas transitioned from other dry-wet climate regions, such as, SAR-AR refers to the newly formed AR transitioned from SAR.

Nevertheless, the contribution analysis results were somewhat different in the non-transition regions of each dry-wet climate region. As displayed in Figure 10, *HI* showed an increase in varying degrees, *P* contributed positively to changes in *HI*, and *PET* contributed negatively to changes in *HI* in the non-transition areas of AR, SAR, SHR, and HR (named as U_AR, U_SAR, U_SHR, and U_HR, respectively) from 1960–1989 to 1990–2019. With the increase of climate wetness degree, the contributions of *Ta*, *Rn*, *WS* and *RH* to *HI* change gradually increased. In U_AR and U_SAR, the contribution of *P* to *HI* was the largest; while in U_SHR, *Ta* was the dominant factor that caused *HI* change, and the contributions of *Rn* and *WS* to *HI* changes also exceeded that of *P*. In U_HR, *Rn* dominated the changes in *HI*, followed by *P*, *Ta*, and *RH*.

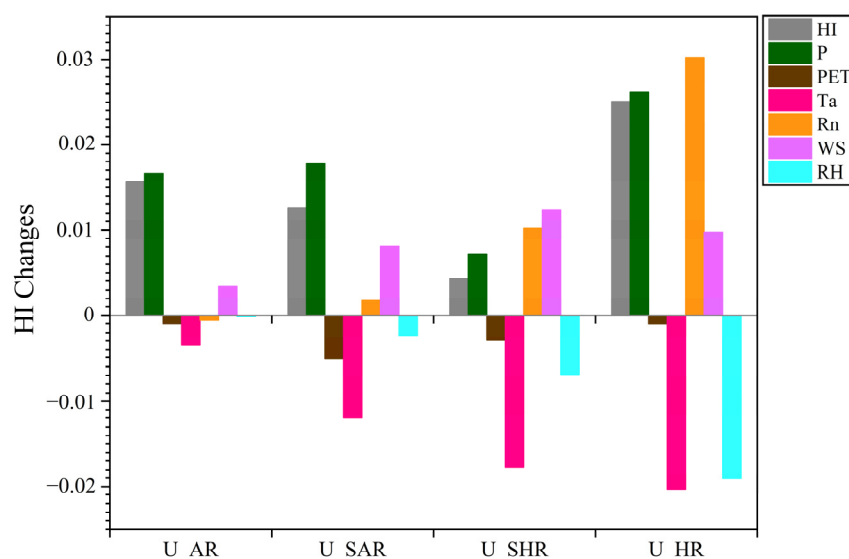


Figure 10. Changes in *HI* and contributions of each climate element to *HI* change, averaged over the non-transition areas of AR, SAR, SHR, and HR (denoted by U_AR, U_SAR, U_SHR, and U_HR, respectively) from 1960–1989 to 1990–2019.

4. Discussion and Conclusions

The hydroclimatic type of a certain area is determined jointly by the water input, i.e., *P*, and the water output, i.e., *PET*. When *P* and *PET* change for a sustained period of time, the type of dry-wet climate in the region may shift. Combining China's actual natural and geographical environment, we divided China into four dry-wet climate regions based on *HI*. A comparison of the two 30-year periods, i.e., 1960–1989 and 1990–2019, suggested that AR in China had dropped by about $0.35 \times 10^6 \text{ km}^2$ while SAR had expanded by $0.4 \times 10^6 \text{ km}^2$ (Table 1), which is mostly attributable to the shift of $3.71 \times 10^5 \text{ km}^2$ from AR to SAR (Figure 6). The SAR is the focus of global research on dry and wet changes, mainly because it is a climate transition zone connecting AR and SHR/HR. Hence, its convertible types are more diverse [25], and its ecosystems are more vulnerable and sensitive to climate change [44–46]. Regarding the shift of global dry-wet climate regions in the drylands, the expansion of the global semi-arid regions mainly stems from the transition of global sub-humid/humid regions [18,25]. However, comparing the two types of the newly formed SAR in China from 1960–1989 to 1990–2019, the newly formed SAR which transited from AR was almost 3 times larger than that from SHR (Figure 5). This indicates that the newly formed SAR in China for 1990–2019 relative to 1960–1989 primarily transited from AR, followed by SHR.

The area of the shifts to wetter conditions for dry-wet regions in China, including the transitions from semi-arid region (AR-SAR), semi-arid to semi-humid region (SAR-SHR), and semi-humid to humid region (SHR-HR), was more than two times larger than that of the shifts to drier conditions from 1960–1989 to 1990–2019 (Figure 6). Interestingly, we found that with 100° E as the dividing line, the shifts to drier types were basically distributed in the monsoon region (east of 100° E), while the shifts to wetter types were mostly distributed in the inland region (west of 100° E) (Figure 5). The shifts in the dry and wet climate types can significantly impact agricultural production. On the one hand, the transition of two regions to drier climate types in the east (i.e., one located in the North China Plain and the other in the middle and lower reaches of the Yangtze River; both are important agricultural production hubs), would destabilize agricultural production under a warmer climate. In particular, irrigated agriculture has been developed in the North China Plain where agricultural development heavily relies on irrigation [47,48], and the shift to a drier climate may put pressure on the agricultural water supply. This part of the country should further strengthen water-saving irrigation technology and consider changing agricultural planting

models. Moreover, our research results showed that most areas of the Junggar Basin (one of the major agricultural production areas in the northwest of China) have shifted from AR to SAR. The wetter climate there should bring more precipitation and improve the local ecological environment to some extent. Nonetheless, due to the relatively dry climate itself, the contradiction between the supply and demand of water resources still exists. Such a contradiction might continue with the ongoing socio-economic development. Therefore, the government and relevant departments should consider the actual situation of local production and environment, and be perceptive to the impact of the climate humidification in northwest China.

To determine the dominant factors causing the shifts in the dry-wet regions, a contribution analysis method was developed in this paper to quantify the impacts of each climate factor on *HI* changes. From the perspective of water input and output, the changes in *HI* caused by *P* change were greater than *PET* in the six newly formed transition regions. From the contribution of various impact factors, in the six transition regions, *P* contributed the most to the change of *HI*, followed by *Ta* whose contribution to *HI* was negative (Figure 9b). This is also consistent with recent reports about the dominance of *P* on dry and wet changes in most regions of China [26,27,31], and the significance of air temperature increase on climate drying over wet monsoon regions in China [15]. We further calculated the contribution of each factor to *HI* change in the non-transition zone of each dry-wet climate region. The results reflected that the *HI* change caused by *P* change was also significantly greater than that caused by *PET* in the four non-transition regions. However, from the perspective of the contribution of each climate factor, as the background climate becomes more humid, the contributions of *Ta*, *Rn*, *WS*, and *RH* to *HI* change gradually increased, and even the contribution of *Ta* (*Rn*) would exceed that of *P* to *HI* change in the SHR (HR) (Figure 10). In general, *P* dominated the *HI* change in the six newly formed transition regions. While in the non-transition regions, there were two situations. First, in the non-transition regions of AR and SAR, an increase in *P* dominated the increase of *HI*. Second, in the non-transition regions of SHR and HR with more humid background climate, the contribution of the thermal factors (e.g., *Ta*, *Rn* and *RH*) to *HI* change exceeded or was equivalent to that of *P*. Numerous studies suggested about the profound impact of climate warming on the expansion of drylands and climate drying in China and around the world [15,18,20,49], which escalated the challenges of coping with water shortages and land desertification. Our research reveals that clarifying the shifts in the regional dry-wet climate regions and their dominant factors in a warming climate should provide guidance for managing water resources and achieving sustainable agricultural production.

In the Sixth Assessment Report of the IPCC, it is projected that global temperature will continue to rise in the coming decades, and precipitation will increase over high latitudes, the equatorial Pacific, and some monsoon regions, while precipitation will decrease in some sub-tropical and tropical regions [5]. Based on historical observation data, it is found that temperature and precipitation showed an increasing trend in most areas of China, while net solar radiation, wind speed and relative humidity mainly showed a decreasing trend (Figure 7). That trend is likely to continue in the future. Based on the research results of future climate scenario model, the temperature and annual precipitation in most areas of China may continue to rise in the future [50], while the annual average wind speed, cloud cover and solar radiation may decrease in most areas [51,52], which means that the dry and wet climate will also change accordingly. Subsequent research can be combined with relevant climate prediction models to study the change of dry and wet climate zones in China and its dominant factors in future scenarios.

This study focused on the impact of climatic factors on the shifts in dry and wet climate regions but did not consider the impact of short-term meteorological system anomalies and human activities. Previous studies suggested that the fluctuations of the dry-wet climate boundaries in China could be affected by different types of anomalous atmospheric circulations, such as East Asian summer monsoon, Indian Monsoon, westerly circulation, plateau monsoon, and West Pacific Subtropical High [53]. In particular, the variation of

aridity over semi-arid region in northern China could be related to changes in the intensity of East Asian summer monsoon [45], and the drought in East China could be associated with ENSO [36,54]. In addition, human activities could affect the changes in dryness and wetness, and such an influence mechanism could be complicated. Some studies indicated that large-scale artificial irrigation, including agricultural irrigation and urban irrigation, could cause positive anomalies in soil moisture, which would affect the Indian Ocean monsoon and the East Asian monsoon, and perhaps cause abnormal precipitation [55–57]. The increase in aerosol loading caused by human-induced air pollution is also considered one of the important reasons for the rainfall changes in East Asia [58,59]. Furthermore, the recent global warming is mostly driven by anthropogenic greenhouse gas emissions [60]. In this sense, human activities contributed a lot to the climate drying or drought. Projections from global circulation models suggested that the global average temperature would continue to rise in the long-term [61,62]. In this context, the secondary impact of global warming and human activities would probably enhance the complexity and uncertainty of the mechanism and causes of dry and wet changes. With that in mind, more efforts would be needed to better understand and quantify the impact of changes in natural factors and human activities on dry-wet changes or shifts in dry-wet climate regions.

Author Contributions: Conceptualization, J.X., X.Z. and X.Q.; methodology and software, J.X. and M.L.; validation, X.Q.; formal analysis, J.X.; investigation, D.W.; data curation and writing—original draft, Z.X.; supervision, X.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by several grants from the National Key R&D Program of China [grant number 2019YFB2102003]; the National Natural Science Foundation of China [grant numbers 41805049].

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Annamalai, H.; Hafner, J.; Sooraj, K.P.; Pillai, P. Global warming shifts the monsoon circulation, drying South Asia. *J. Clim.* **2013**, *26*, 2701–2718. [\[CrossRef\]](#)
2. Mason, S.J. El Niño, climate change, and southern African climate. *Environmetrics* **2001**, *12*, 327–345. [\[CrossRef\]](#)
3. Preethi, B.; Mujumdar, M.; Kripalani, R.H.; Prabhu, A.; Krishnan, R. Recent trends and tele-connections among South and East Asian summer monsoons in a warming environment. *Clim. Dyn.* **2017**, *48*, 2489–2505. [\[CrossRef\]](#)
4. Weng, H.; Ashok, K.; Behera, S.K.; Rao, S.A.; Yamagata, T. Impacts of recent El Niño Modoki on dry/wet conditions in the Pacific rim during boreal summer. *Clim. Dyn.* **2007**, *29*, 113–129. [\[CrossRef\]](#)
5. Intergovernmental Panel on Climate Change (IPCC). 2021: *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., et al., Eds.; Cambridge University Press: Cambridge, UK, 2021.
6. Eriyagama, N.; Smakhtin, V.; Chandrapala, L.; Fernando, K. *Impacts of Climate Change on Water Resources and Agriculture in Sri Lanka: A Review and Preliminary Vulnerability Mapping*; International Water Management Institute: Colombo, Sri Lanka, 2010; 51p. [\[CrossRef\]](#)
7. Hamlet, A.F.; Lettenmaier, D.P. Effects of climate change on hydrology and water resources in the Columbia River Basin. *J. Am. Water Resour. Assoc.* **1999**, *35*, 1597–1623. [\[CrossRef\]](#)
8. Kumar, S.; Allan, R.P.; Zwiers, F.; Lawrence, D.M.; Dirmeyer, P.A. Revisiting trends in wetness and dryness in the presence of internal climate variability and water limitations over land. *Geophys. Res. Lett.* **2015**, *42*, 10867–10875. [\[CrossRef\]](#)
9. Piao, S.; Ciais, P.; Huang, Y.; Shen, Z.; Peng, S.; Li, J.; Zhou, L.; Liu, H.; Ma, Y.; Ding, Y.; et al. The impacts of climate change on water resources and agriculture in China. *Nature* **2010**, *467*, 43–51. [\[CrossRef\]](#)
10. Wentz, F.J.; Ricciardulli, L.; Hilburn, K.; Mears, C. How much more rain will global warming bring? *Science* **2007**, *317*, 233–235. [\[CrossRef\]](#)
11. Zhang, Y.; Yu, Z.; Niu, H. Standardized Precipitation Evapotranspiration Index is highly correlated with total water storage over China under future climate scenarios. *Atmos. Environ.* **2018**, *194*, 123–133. [\[CrossRef\]](#)

12. Allan, R.P.; Soden, B.J.; John, V.O.; Ingram, W.; Good, P. Current changes in tropical precipitation. *Environ. Res. Lett.* **2010**, *5*, 025205. [\[CrossRef\]](#)
13. Liu, C.; Allan, R.P. Observed and simulated precipitation responses in wet and dry regions 1850–2100. *Environ. Res. Lett.* **2013**, *8*, 034002. [\[CrossRef\]](#)
14. Rubel, F.; Kottke, M. Observed and projected climate shifts 1901–2100 depicted by world maps of the Köppen-Geiger climate classification. *Meteorol. Z.* **2010**, *19*, 135–141. [\[CrossRef\]](#)
15. Park, C.-E.; Jeong, S.-J.; Ho, C.-H.; Park, H.; Piao, S.; Kim, J.; Feng, S. Dominance of climate warming effects on recent drying trends over wet monsoon regions. *Atmos. Chem. Phys. Discuss.* **2017**, *17*, 10467–10476. [\[CrossRef\]](#)
16. Tabari, H.; Amini, A.; Talaei, P.H.; Some'e, B.S. Spatial distribution and temporal variation of reference evapotranspiration in arid and semi-arid regions of Iran. *Hydrol. Process.* **2012**, *26*, 500–512. [\[CrossRef\]](#)
17. Xing, W.; Wang, W.; Shao, Q.; Yu, Z.; Yang, T.; Fu, J. Periodic fluctuation of reference evapotranspiration during the past five decades: Does Evaporation Paradox really exist in China? *Sci. Rep.* **2016**, *6*, 39503. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Feng, S.; Fu, Q. Expansion of global drylands under a warming climate. *Atmos. Chem. Phys.* **2013**, *13*, 10081–10094. [\[CrossRef\]](#)
19. Huang, J.; Yu, H.; Guan, X.; Wang, G.; Guo, R. Accelerated dryland expansion under climate change. *Nat. Clim. Chang.* **2016**, *6*, 166–171. [\[CrossRef\]](#)
20. Li, Y.; Huang, J.; Ji, M.; Ran, J. Dryland expansion in northern China from 1948 to 2008. *Adv. Atmos. Sci.* **2015**, *32*, 870–876. [\[CrossRef\]](#)
21. Hulme, M. Recent climatic change in the world's drylands. *Geophys. Res. Lett.* **1996**, *23*, 61–64. [\[CrossRef\]](#)
22. Middleton, N.J.; Thomas, D.S.G. *UNEP: World Atlas of Desertification*; Edward Arnold: London, UK, 1992; ISBN 0340691662.
23. Mortimore, M. *Dryland Opportunities*; International Union for Conservation of Nature (IUCN): Gland, Switzerland; International Institute for Environment and Development (IIED): London, UK; United Nations Development Programme (UNDP): New York, NY, USA, 2009.
24. Spinoni, J.; Vogt, J.; Naumann, G.; Carrao, H.; Barbosa, P. Towards identifying areas at climatological risk of desertification using the Köppen-Geiger classification and FAO aridity index. *Int. J. Climatol.* **2015**, *35*, 2210–2222. [\[CrossRef\]](#)
25. Huang, J.; Ji, M.; Xie, Y.; Wang, S.; He, Y.; Ran, J. Global semi-arid climate change over last 60 years. *Clim. Dyn.* **2016**, *46*, 1131–1150. [\[CrossRef\]](#)
26. Gao, Y.; Li, X.; Ruby Leung, L.; Chen, D.; Xu, J. Aridity changes in the Tibetan Plateau in a warming climate. *Environ. Res. Lett.* **2015**, *10*, 034013. [\[CrossRef\]](#)
27. Yuan, Q.Z.; Wu, S.H.; Dai, E.F.; Zhao, D.S.; Zhang, X.R.; Ren, P. Spatio-temporal variation of the wet-dry conditions from 1961 to 2015 in China. *Sci. China Earth Sci.* **2017**, *60*, 2041–2050. [\[CrossRef\]](#)
28. Lu, E.; Takle, E.S.; Manoj, J. The relationships between climatic and hydrological changes in the upper Mississippi river basin: A SWAT and multi-GCM study. *J. Hydrometeorol.* **2010**, *11*, 437–451. [\[CrossRef\]](#)
29. Ramarao, M.V.S.; Sanjay, J.; Krishnan, R.; Mujumdar, M.; Bazaz, A.; Revi, A. On observed aridity changes over the semiarid regions of India in a warming climate. *Theor. Appl. Climatol.* **2019**, *136*, 693–702. [\[CrossRef\]](#)
30. Roderick, M.L.; Sun, F.; Lim, W.H.; Farquhar, G.D. A general framework for understanding the response of the water cycle to global warming over land and ocean. *Hydrol. Earth Syst. Sci.* **2014**, *18*, 1575–1589. [\[CrossRef\]](#)
31. Chai, R.; Chen, H.; Sun, S. Attribution analysis of dryness/wetness change over China based on SPEI. *J. Meteorol. Sci.* **2018**, *38*, 423–431.
32. Sun, S.; Chen, H.; Wang, G.; Li, J.; Mu, M.; Yan, G.; Xu, B.; Huang, J.; Wang, J.; Zhang, F.; et al. Shift in potential evapotranspiration and its implications for dryness/wetness over Southwest China. *J. Geophys. Res.* **2016**, *121*, 9342–9355. [\[CrossRef\]](#)
33. Wang, S.P.; Li, Y.H.; Feng, J.Y.; Wang, J.S.; Wang, J. Changes and Driving Factors of Surface Wetness Index in Gansu, China from 1961 to 2012. *J. Desert Res.* **2014**, *34*, 1624–1632. [\[CrossRef\]](#)
34. Yin, Y.; Wu, S.; Chen, G.; Dai, E. Attribution analyses of potential evapotranspiration changes in China since the 1960s. *Theor. Appl. Climatol.* **2010**, *101*, 19–28. [\[CrossRef\]](#)
35. Sheffield, J.; Wood, E.F.; Roderick, M.L. Little change in global drought over the past 60 years. *Nature* **2012**, *491*, 435–438. [\[CrossRef\]](#)
36. Dai, A. Drought under global warming: A review. *Wiley Interdiscip. Rev. Clim. Chang.* **2011**, *2*, 45–65. [\[CrossRef\]](#)
37. Hulme, M.; Marsh, R.; Jones, P.D. Global changes in a humidity index between 1931–60 and 1961–90. *Clim. Res.* **1992**, *2*, 1–22. [\[CrossRef\]](#)
38. Hu, Q.; Dong, B.; Pan, X.; Jiang, H.; Pan, Z.; Qiao, Y.; Shao, C.; Ding, M.; Yin, Z.; Hu, L. Spatiotemporal variation and causes analysis of dry-wet climate over period of 1961–2014 in China. *Trans. Chin. Soc. Agric. Eng.* **2017**, *33*, 124–132. [\[CrossRef\]](#)
39. Sheng, S.; Zhang, F.; Sheng, Q. Spatio-temporal changes of wetness index in China from 1975 to 2004. *Trans. Chin. Soc. Agric. Eng.* **2009**, *25*, 11–15. [\[CrossRef\]](#)
40. Allen, R.G.; Pereira, L.S.; Raes, D.; Smith, M. *Crop Evapotranspiration: Guidelines for Computing Crop Requirements*; Food and Agriculture Organization (FAO): Rome, Italy, 1998; ISBN 0254-5284.
41. Chattopadhyay, N.; Hulme, M. Evaporation and potential evapotranspiration in India under conditions of recent and future climate change. *Agric. For. Meteorol.* **1997**, *87*, 55–73. [\[CrossRef\]](#)
42. Dinpashoh, Y.; Jhajharia, D.; Fakheri-Fard, A.; Singh, V.P.; Kahya, E. Trends in reference crop evapotranspiration over Iran. *J. Hydrol.* **2011**, *399*, 422–433. [\[CrossRef\]](#)

43. Han, S.; Xu, D.; Wang, S. Decreasing potential evaporation trends in China from 1956 to 2005: Accelerated in regions with significant agricultural influence? *Agric. For. Meteorol.* **2012**, *154*, 44–56. [\[CrossRef\]](#)
44. Rotenberg, E.; Yakir, D. Contribution of semi-arid forests to the climate system. *Science* **2010**, *327*, 451–454. [\[CrossRef\]](#)
45. Zhang, H.; Zhang, Q.; Yue, P.; Zhang, L.; Liu, Q.; Qiao, S.; Yan, P. Aridity over a semiarid zone in northern China and responses to the East Asian summer monsoon. *J. Geophys. Res.* **2016**, *121*, 13901–13918. [\[CrossRef\]](#)
46. Xue, Y. The impact of desertification in the Mongolian and the Inner Mongolian grassland on the regional climate. *J. Clim.* **1996**, *9*, 2173–2189. [\[CrossRef\]](#)
47. Kendy, E.; Gérard-Marchant, P.; Walter, M.T.; Zhang, Y.; Liu, C.; Steenhuis, T.S. A soil-water-balance approach to quantify groundwater recharge from irrigated cropland in the North China Plain. *Hydrol. Process.* **2003**, *17*, 2011–2031. [\[CrossRef\]](#)
48. Leng, G.; Tang, Q.; Huang, M.; Leung, L.; Yung, R. A comparative analysis of the impacts of climate change and irrigation on land surface and subsurface hydrology in the North China Plain. *Reg. Environ. Chang.* **2015**, *15*, 251–263. [\[CrossRef\]](#)
49. Cook, B.I.; Smerdon, J.E.; Seager, R.; Coats, S. Global warming and 21st century drying. *Clim. Dyn.* **2014**, *43*, 2607–2627. [\[CrossRef\]](#)
50. Qin, D.; Ding, Y.; Su, J.; Ren, J.; Wang, S.; Wu, R.; Yang, X.; Wang, S.; Liu, S.; Dong, G.; et al. Assessment of Climate and Environment Changes in China (I): Climate and environment changes in China and their projection. *Adv. Clim. Chang. Res.* **2005**, *1*, 4–9.
51. Yang, L.; Jiang, J.; Liu, T.; Li, Y.; Zhou, Y.; Gao, X. Projections of future changes in solar radiation in China based on CMIP5 climate models. *Glob. Energy Interconnect.* **2018**, *1*, 452–459.
52. Jiang, Y.; Luo, Y.; Zhao, Z. Projection of Wind Speed Changes in China in the 21st Century by Climate Models. *Chin. J. Atmos. Sci.* **2010**, *34*, 323–336.
53. Yang, J.; Ding, Y.; Chen, R.; Liu, L. Fluctuations of the semi-arid zone in China, and consequences for society. *Clim. Change* **2005**, *72*, 171–188. [\[CrossRef\]](#)
54. Zhang, W.; Jin, F.F.; Turner, A. Increasing autumn drought over southern China associated with ENSO regime shift. *Geophys. Res. Lett.* **2014**, *41*, 4020–4026. [\[CrossRef\]](#)
55. Chou, C.; Ryu, D.; Lo, M.H.; Wey, H.W.; Malano, H.M. Irrigation-induced land-atmosphere feedbacks and their impacts on Indian summer monsoon. *J. Clim.* **2018**, *31*, 8785–8801. [\[CrossRef\]](#)
56. Guimberteau, M.; Laval, K.; Perrier, A.; Polcher, J. Global effect of irrigation and its impact on the onset of the Indian summer monsoon. *Clim. Dyn.* **2012**, *39*, 1329–1348. [\[CrossRef\]](#)
57. Shukla, S.P.; Puma, M.J.; Cook, B.I. The response of the South Asian Summer Monsoon circulation to intensified irrigation in global climate model simulations. *Clim. Dyn.* **2014**, *42*, 21–36. [\[CrossRef\]](#)
58. Menon, S.; Hansen, J.; Nazarenko, L.; Luo, Y. Climate effects of black carbon aerosols in China and India. *Science* **2002**, *297*, 2250–2253. [\[CrossRef\]](#)
59. Xu, Q. Abrupt change of the mid-summer climate in central east China by the influence of atmospheric pollution. *Atmos. Environ.* **2001**, *35*, 5029–5040. [\[CrossRef\]](#)
60. Intergovernmental Panel on Climate Change (IPCC). *IPCC Climate Change 2007: The Physical Science Basis*; Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M.M.B., Miller, H.L., Jr., Chen, Z., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2007.
61. Intergovernmental Panel on Climate Change (IPCC). *IPCC Summary for Policymakers*; Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013.
62. Huang, J.; Yu, H.; Dai, A.; Wei, Y.; Kang, L. Drylands face potential threat under 2 °C global warming target. *Nat. Clim. Chang.* **2017**, *7*, 417–422. [\[CrossRef\]](#)