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Characteristics of Dry-Wet Climate Change in China during the Past 60 Years and Its Trends Projection

Cunjie Zhang [1,2,*], Yuyu Ren [1,2,*], Lijuan Cao [3], Jia Wu [1,2], Siqi Zhang [1,2], Chuanye Hu [1,2] and Sangbu Zhujie [4]

1 CMA National Climate Centre, Beijing 100081, China; wujia@cma.gov.cn (J.W.); zhangsq@cma.gov.cn (S.Z.); hucy@cma.gov.cn (C.H.)
2 CMA Climate Studies Key Laboratory, Beijing 100081, China
3 CMA Meteorological Information Center, Beijing 100081, China; caolijuan@cma.gov.cn
4 CMA Meteorological Bureau of Nanmulin County, Tibet Autonomous Region, Shigatse 857000, China; xzqxzjsb@163.com
* Correspondence: zhangcj@cma.gov.cn (C.Z.); renyuyu@cma.gov.cn (Y.R.)

Abstract: Based on the homogenized daily data of 2255 meteorological stations during the past 60 years from 1961 to 2020, the potential evapotranspiration was calculated using the revised FAO56 Penman–Monteith model, and then the annual AI (aridity index, the ratio of annual potential evapotranspiration to annual precipitation) was employed to analyze the dry-wet climate change in China. The GCM models' prediction data was used to analyze the possible trends of dry-wet climate in China by the end of this century. The results showed that in the past 60 years, the climate in China was getting wetter, especially in the western regions of China, including Xinjiang, western Qinghai, Gansu, western Inner Mongolia, and northwestern Tibet. In the last 10 years, China's climate has become more humid. Compared with the 1960s, the total area of aridity has decreased by about 650,000 square kilometers. The changes of different climate zones have regional and periodical characteristics. There was a tendency to get wet periods in all four seasons, especially in summer. Analysis of GCM model projection data shows that by the end of this century, the climate in China would have a general trend of becoming drier. The drier regions are mainly located in the central and eastern parts of China, while the western regions of China continue to maintain the wetting trends. In the case of high emissions, the trends of drying in the central and eastern and wetting in the west are more significant than in the case of medium emission.

Keywords: dry-wet climate change; aridity index; potential evapotranspiration; China

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1. Introduction

In the context of globalization, more and more attention has been paid to research on dry-wet climate change. Feng et al. [1] used the aridity index defined by UNEP [2] to analyze the global arid and semi-arid regions in the past 60 years and in the 21st century. The results show that, in the context of global warming, the global arid and semi-arid regions display a tendency to expand. Shi et al. [3] pointed out at the beginning of this century that since 1987, in northwest China, especially to the west of the Hexi Corridor, there had been a trend of continued rise in temperature and a significant increase in precipitation compared with that of 100 years ago. Facts have proved that in the mid-west region of northwest China, there has been a process of transition from a warm and dry to a warm and humid climate. Observational data from 1961 to 2008 used by Zhang et al. [4] showed that in the past 50 years, the overall warming and drying trend in the northwest China was pretty clear, with regional warm and humid climate phenomena. Zheng al. [5,6] applied the aridity index to study the climate zoning of China in different years, and pointed out that the semi-arid and semi-humid zones in north China and the arid zones in Inner Mongolia had a general trend of becoming drier in the past 60 years (1951–2010).

The arid and semi-arid regions in west China such as Gansu, Xinjiang, the Qinghai-Tibet Plateau, and the eastern parts of the southern humid region became generally more humid, and most of the southwestern region became drier.

Fu and Ma, et al. [7,8] analyzed China's regional surface moisture index and other indicators to find that, since the 1980s, the eastern region of northwest China and north China have been characterized by aridification, which has intensified in the past 15 years. The decrease in precipitation and increase in temperature were the main reasons. Yuan et al. [9] analyzed the temporal and spatial characteristics of the dry-wet climate in China from 1961 to 2015, and pointed out that precipitation was the most important factor of dry-wet climate change in most regions, especially in north China, which was highly correlated with precipitation. Ding [10,11] believed that the cause of humidification and precipitation increase in west China was still inconclusive, and that there was no concrete evidence to prove that this type of precipitation change in China was closely related to human activities. The paradigm of "wet gets wetter, dry gets drier", "warm gets wetter" or "northward expansion of subtropical zone" [12] could not reasonably explain the characteristics of long-term changes in the regional precipitation pattern.

At present, the research on the prediction of the future dry-wet climate mainly uses the results of different model simulations under different IPCC emission scenarios to carry out analysis, and mostly focuses on the analysis of individual factors such as temperature and precipitation [13,14]. Zhao [15] analyzed future climate change scenarios in global typical arid and semi-arid regions under different typical paths, and the results showed that the arid and semi-arid regions in north China were likely to be one of the regions with the most significant increase in global temperatures and precipitation. To reflect the dry-wet climate conditions of an area, the comprehensive influence of temperature, precipitation, wind speed, and other factors needs to be considered. Ma [16] used the prediction results of five models and the dry-wet index to estimate the trend of China's dry-wet areas in the next 100 years under the RCP8.5 scenario, showing that the changes in China's dry-wet pattern were mainly characterized by a significant decrease in the humid area and a significant expansion of the dry-wet transitional area. However, the extent to which future climate change will affect China's dry-wet climate is still uncertain due to the different data and methods that researchers applied.

In recent years, the warming and humidification in northwest China has been widely discussed. Due to the constraint of data and other factors, the time and space scales of some studies are very limited, making it impossible to identify the spatial scope and time scale of this change. It is necessary to use observational data from a longer period to explore the temporal and spatial characteristics of this change from a larger scale. The research on climate zoning still needs to be deepened, especially when the research on the dry-wet changes in China since 2011 is scarce, hence it is necessary to use the latest observational data to conduct in-depth research on the dry-wet climate changes in China in recent decades. Many studies have divided the dry-wet climate into four levels: humid, sub-humid, semi-arid and arid, but they did not consider climate change in the extreme arid climate zones and the super humid zone. As more and more attention has been paid to the climate in extreme arid zones and the extreme humid zones in south China, it is necessary to use more refined dry-wet climate zoning standards for research.

Based on the above considerations, this paper applies the latest homogenized observational data and climate projection data provided by the China Meteorological Administration, as well as the revised FAO56 Penman–Monteith model was applied to calculate potential evapotranspiration, and combines precipitation to construct an aridity index and adopts the 6-level dry-wet classification standard to carry out in-depth research on the overall characteristics, regional characteristics, interdecadal, and seasonal changes of China's dry-wet climate changes in the past 60 years (1961–2020), revealing the pattern of dry-wet climate changes in China's different regions from a deeper level, and its possible trends by the end of this century, providing a scientific basis for China's response to climate change and its related risks.

2. Data and Methods

2.1. Aridity Index

Many studies have shown that the aridity index (or humidity index) can comprehensively reflect the actual conditions of dry-wet climate [17–20]. The key issue in calculating the aridity index is to determine the potential evapotranspiration. Due to the limitation of observational data, models are usually used for simulation, mainly including Thornthwaite [21], Holdridge [22], Penman–Monteith [23] and other methods. The Thornthwaite method and Holdridge method calculates potential evapotranspiration only, based on the monthly average temperature, and the assumption that the evapotranspiration equals zero when the average temperature of the month is below 0 °C. The FAO56 Penman–Monteith model, recommended by the Food and Agriculture Organization of the United Nations [24], takes into account temperature, sunshine, wind speed, humidity, and other environmental factors on evapotranspiration. It has a strong theoretical basis and clear physical significance and is widely used in classification analysis and climate zoning [25–28]. Due to the large amount of meteorological element data required for calculation, it is subject to certain restrictions in application. This paper adopts the FAO56 Penman–Monteith method recommended in the Grades of Meteorological Drought [29] to calculate the potential evapotranspiration of 2255 weather stations nationwide.

There are roughly two calculation methods for the aridity index: one is the annual potential evapotranspiration to annual precipitation (generally called the aridity index, AI), and the other is the annual precipitation to the annual potential evapotranspiration (generally called the humidity index). This paper adopts the first method to calculate the aridity index, and the calculation formula is as shown in Formula (1):

$$\mathrm{AI} = \frac{\mathrm{E_0}}{\mathrm{P}} \tag{1}$$

In the formula, AI stands for the aridity index; P stands for the annual precipitation; and E_0 stands for the annual potential evapotranspiration (PET) calculated by the FAO56 Penman–Monteith method. The calculation formula is as shown in Formula (2):

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

In the formula, PET stands for daily potential evapotranspiration (mm); G stands for soil heat flux density ($\mathrm{MJm^{-2}d^{-1}}$); T stands for daily average temperature at the height of 2 m (°C); u_2 stands for the wind speed at the height of 2 m ($\mathrm{ms^{-1}}$); e_s stands for the average saturation vapor pressure (kPa); e_a stands for the actual vapor pressure (kPa); Δ stands for the slope of the saturation vapor pressure curve ($\mathrm{kPa^\circ C^{-1}}$); γ stands for the psychometric constant ($\mathrm{kPa^\circ C^{-1}}$); and R_n stands for the net surface radiation ($\mathrm{MJm^{-2}d^{-1}}$). R_n is calculated from the short-wave net surface radiation (R_{ns}) and the long-wave net surface radiation (R_{nl}). In this paper, R_{ns} is calculated according to Formula (3):

$$\mathrm{R_{ns}} = 0.77 \times \left[\mathrm{a_s} + \mathrm{b_s}\left[\frac{\mathrm{n}}{\mathrm{N}}\right]\right]\mathrm{R_a} \tag{3}$$

In the formula, R_a stands for the extraterrestrial radiation (MJ $\mathrm{m^{-2}day^{-1}}$); n stands for the actual sunshine hours (h); N stands for the maximum possible sunshine hours (h); the coefficient a_s stands for the penetration of the extraterrestrial radiation reaching the ground on cloudy days; and a_s + b_s stands for the transmittance rate of extraterrestrial radiation reaching the ground on sunny days. This paper utilizes the monthly a_s and b_s values in different years in China, according to the national standard of Grades of dry/wet Climate [30] to obtain the national monthly values, which are shown in Table 1:

Table 1. Monthly average a_s and b_s values in China.

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
a_s	0.205	0.187	0.175	0.167	0.169	0.173	0.179	0.178	0.175	0.177	0.192	0.206
b_s	0.535	0.571	0.583	0.586	0.584	0.577	0.559	0.555	0.568	0.576	0.556	0.525

In this paper, the Penman revised formula recommended by Yin [31] is used to calculate R_{nl}. The calculation formula is as shown in Formula (4):

$$R_{nl} = \sigma\left[\frac{T_{max,k}^4 + T_{min,k}^4}{2}\right] \times \left(0.56 - 0.25\sqrt{e_a}\right)\left[0.1 + 0.9\left[\frac{n}{N}\right]\right] \quad (4)$$

In the formula, σ stands for the Boltzmann constant (4.903×10^{-9} MJ $K^{-4}m^{-2}day^{-1}$); $T_{max,k}$ stands for the highest daily absolute temperature (K); and $T_{min,k}$ stands for the lowest daily absolute temperature (K).

2.2. Criteria for Dry-Wet Climate Divisions

The division standards and named methods of dry and wet degree are different because scientists use different research priorities or focus on different research regions. Holdridge [22] proposed the division of the dry and wet climate using eight grades, namely super-wet, extremely humid, humid, sub-humid, semi-arid, drought, extreme drought and ultra-arid areas, in 1947. Thornthwaite [21] proposed to divide it into six grades, namely extreme wet, moist, wet, semi-wet, semi-dry and dry areas, in 1948. Chen [18] proposed a five-level method, namely humid, sub (half)-humid, sub (semi)-drought, drought and extreme drought. Zheng et al. [5] used the annual aridity index as a main indicator and annual precipitation as an auxiliary indicator to divide the Chinese climate into four belts including humid, semi-humid, semi-arid and drought in China from 1981 to 2010. Besides this, even if the dry–wet degree is the same, the name is different. For instance, the name for a semi-humid area could be semi-humid, sub-humid or slightly weak humid area, etc.

On the basis of comparing various dryness indices and grading standards of dry and wet climate, and considering the extreme dry climate in northwest China and the extreme humid climate in southeast China, Zhang [32] divided the wet-dry climate zone into six levels according to the calculated aridity index (AI), namely extreme humid, humid, sub-humid, sub-arid, arid and extreme arid. The specific classification criteria are shown in Table 2.

Table 2. The grades of dry-wet climate division.

Grades	1	2	3	4	5	6
Zone name	Extreme humid	Humid	Sub-humid	Sub-arid	Arid	Extreme arid
AI	<0.5	0.5~1.0	1.0~1.5	1.5~3.5	3.5~20.0	≥20.0

2.3. Data and Climatic Regions

This paper, when calculating the aridity index from 1961 to 2020, uses the daily precipitation, average temperature, maximum temperature, minimum temperature, relative humidity, average wind speed, and sunshine hours observed by 2255 meteorological observation stations provided by the National Meteorological Information Center of the China Meteorological Administration. Among them, the average temperature, maximum temperature, minimum temperature, relative humidity, and average wind speed have undergone homogenization inspections and corrections [33,34]. The projected data for future climate change scenarios comes from forecast data of global model BCC-CSM1.1 (2.5° × 2.5° grid) provided by the National Climate Center of China and is downscaled to a resolution of 0.5° × 0.5° through regional climate model RegCM4.0 [35,36]. This paper uses the data of RCP4.5 and RCP8.5 scenarios from 1 January 2021 to 31 December 2099, and includes precipitation, average temperature, maximum temperature, minimum temperature, total radiation, relative humidity, and average wind speed.

The annual means and season averages are calculated using data from 1981 to 2010, and linear trend analysis uses data from 1961 to 2020. This paper uses the Mann–Kendall trend test method [37] to test the significance of calculated linear trend. In order to analyze the decadal variations, we stipulated that every 10 years is a decade. For example, the 1960s refers to 1961 to 1970, and the 2010s refers to 2011 to 2020. The season division stipulates that January, February of this year and December of the previous year are winter, March to May is spring, June to August is summer, and September to November is autumn. In order to analyze the characteristics of regional climate change, China is divided into seven regions, which are as follows: northwest China, which includes the five provinces of Xinjiang, Gansu, Qinghai, Ningxia, and Shaanxi; north China, which includes the five provinces (or municipalities) of Beijing, Tianjin, Hebei, Shanxi, and Inner Mongolia; northeast China, which includes the three provinces of Liaoning, Jilin, and Heilongjiang; east China, which includes the seven provinces (or municipalities) of Shanghai, Jiangsu, Anhui, Shandong, Zhejiang, Jiangxi, and Fujian; central China, which includes the three provinces of Henan, Hubei, and Hunan; south China which includes the three provinces (regions) of Guangdong, Guangxi, and Hainan; and southwest China which includes the five provinces (or municipalities) of Sichuan, Chongqing, Guizhou, Yunnan, and Tibet.

3. Characteristics of Dry-Wet Climate Change in China during the Past 60 Years

3.1. Overall Characteristics of Dry-Wet Climate Change in China

Judging from the annual average aridity index of 2255 stations across the country (Figure 1a), we can see a decreasing trend, which means the climate is becoming more humid, from 1961 to 2020. The aridity indices for each time are: 2.69 in the 1960s, 2.36 in the 1970s, 2.11 in the 1980s, 1.99 in the 1990s, 1.95 in the 2000s, and 1.74 in the 2010s. The linear changing trend shows a decrease of 0.17 every 10 years, and statistical significance has passed the 99% confidence level. The turning point occurs in the mid-1980s, when most of the stations occurred around 1987, from the early high index to the low index, and the climate becomes more humid.

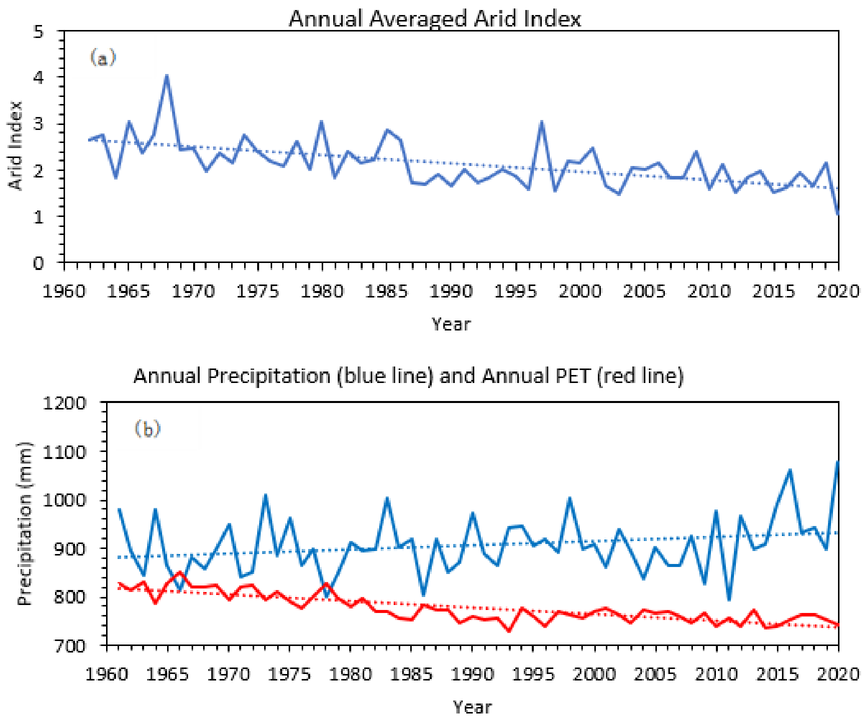

Figure 1. The annual averaged aridity index ((**a**)); annual precipitation ((**b**), blue line); annual PET ((**b**), red line) and their linear trend ((**a**,**b**), dotted line) in China from 1961 to 2020.

In order to explore the reasons for the climate getting wetter in the past 60 years, we analyzed the variation trends of precipitation and PET, as well as the variation trends of temperature, relative humidity, wind speed, sunshine duration, and other factors related to potential evapotranspiration in China during the past 60 years. From Figure 1b, in the past 60 years, we see that China's annual average precipitation has shown an increasing trend, with an average increase of 8.15 mm every 10 years, while the annual average evapotranspiration has shown a significant decreasing trend, with an average decrease of 13.43 mm every 10 years. On analysis of the reasons for the decrease of PET, we found that average relative humidity, average sunshine duration and average wind speed all have decreasing trends in the past 60 years, having decreased by 0.14%, 39.22 h and 0.21 m/s on average every 10 years, respectively, and 0.21%, 1.88% and 8.94% relative to average from 1981 to 2010, among which the annual average wind speed has decreased most obviously. Although the average temperature in China has increased by 0.22 degrees per decade over the past 60 years, the PET has generally shown a declining trend when factors such as relative humidity, wind speed, and sunshine duration are taken into account.

The results obtained here are consistent with the results of Fan [27], but different to those of Wu [28], although their studies were based on meteorological observation data and the FAO model to calculate PET. Wu's results show that the trend of PET changed from decreasing to increasing in 1993, and it was considered that the decreasing trend in the early stage was due to the decrease of sunshine duration, and the increasing trend in the later stage was due to the decrease of relative humidity. The results of this study showed that PET had an obvious decreasing trend before 1993, but it did not show an increasing trend after 1993, and showed an overall decreasing trend in the past 60 years. On analyzing the reasons, we considered the fact that the homogenized wind speed data were used to calculate PET. The national average wind speed showed an obvious decreasing trend in the past 60 years, and maintained this trend after 1993.

The distribution of the average aridity index from 1981 to 2010 (Figure 2a) shows that dry climate regions are located in Northern and Western China, including sub-arid, arid and extreme arid zones, and wet climate regions are located in Eastern and Southern China, including sub-humid, wet and extremely wet zones. Judging from the linear trend of the annual aridity index (Figure 2b), we can see decreasing trends in most parts of China, that means the climate is getting more humid in China, especially in west China, including most parts of Xinjiang, the west of Qinghai, Gansu and Inner Mongolia and northwest Tibet, all were showing the most obvious humidification trend with an average aridity index falling by more than 2.0 every 10 years, of which some areas in south Xinjiang have fallen by 8.0–16.0. The regions with increased aridity (Figure 2b, the yellow areas) are located in some parts of east Inner Mongolia, west Jilin, south Gansu, southwest Shaanxi, central Sichuan, west and southeast Yunnan, and west Guangxi, but with a smaller magnitude. The statistically significant test shows (Figure 2b, slant line areas) that most of the decreasing trend areas have passed the 95% confidence level, while the increasing trend areas have not passed this level. The western part of China (including most areas of Xinjiang and Qinghai, west Gansu, north and central Tibet, etc.), Jianghuai, Jiangnan, and Heilongjiang have obvious trends of humidification, where the significance test passed the 95% confidence level, and west Xinjiang, central Qinghai, and central Tibet, where the significance test passed the 99% confidence level.

From Figure 3a, the linear trend map of annual precipitation in China from 1961 to 2020 shows an increasing trend in northwest China, Tibet and western Sichuan, western North China, most of northeast China, and southeastern China, while in western Xinjiang, central Tibet, northeastern Qinghai and northeastern Inner Mongolia it shows a significant increasing trend. From the southern part of southwest China to the southern part of northeast China, there is a little rain belt, which is also the area where drought events have occurred frequently in recent decades. From Figure 3b, the decreasing trend of annual PET is in most parts of China except central and northeastern Inner Mongolia, northwestern

Sichuan Basin, and southern Yunnan, and the significance test of linear trends passes the 95% confidence level.

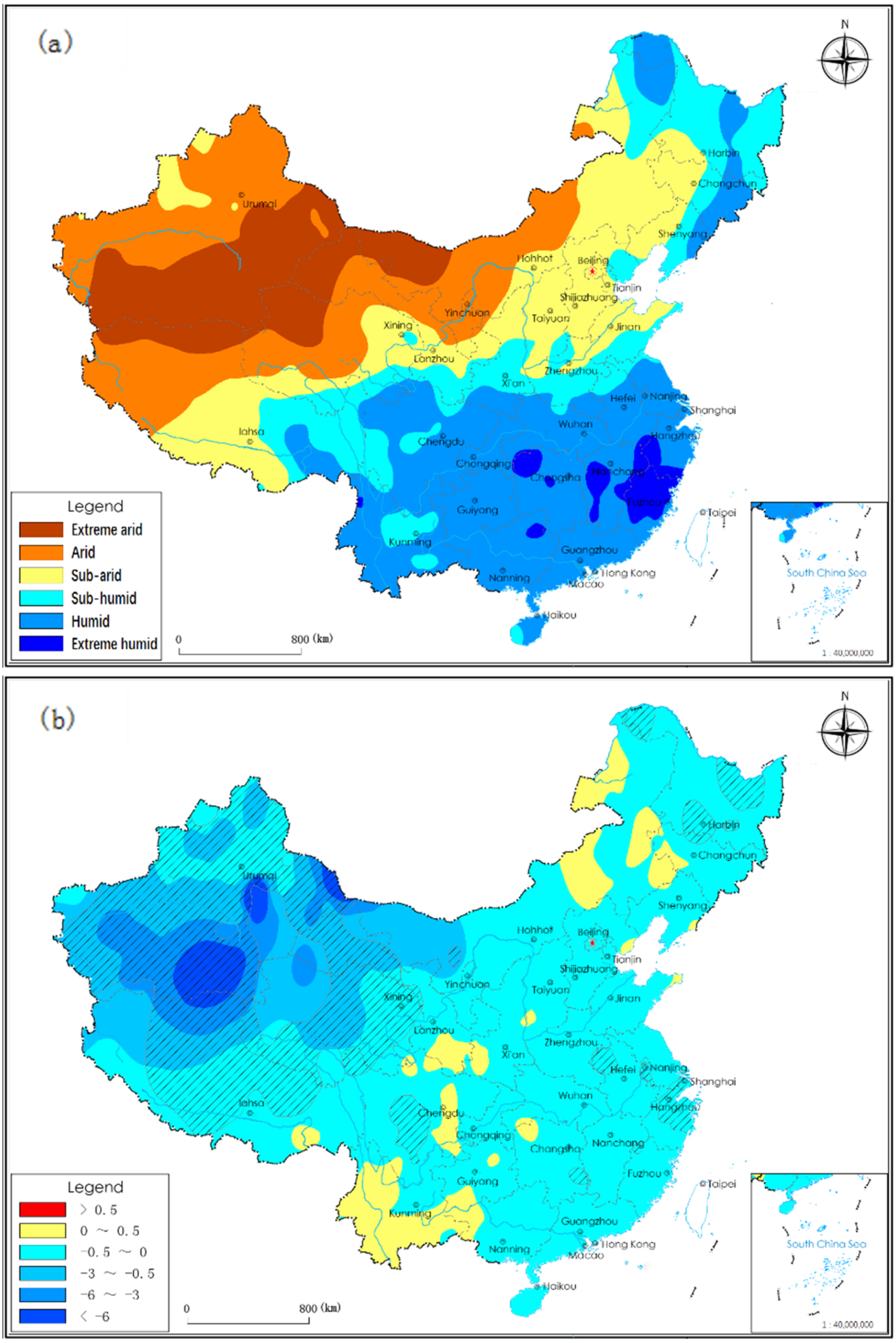

Figure 2. Dry and wet climate zone during 30 years from 1981 to 2010 ((**a**)); linear trends of the annual aridity index ((**b**), color filled areas); and the significance test passed the 95% confidence level area ((**b**), slant line areas) in China from 1961 to 2020.

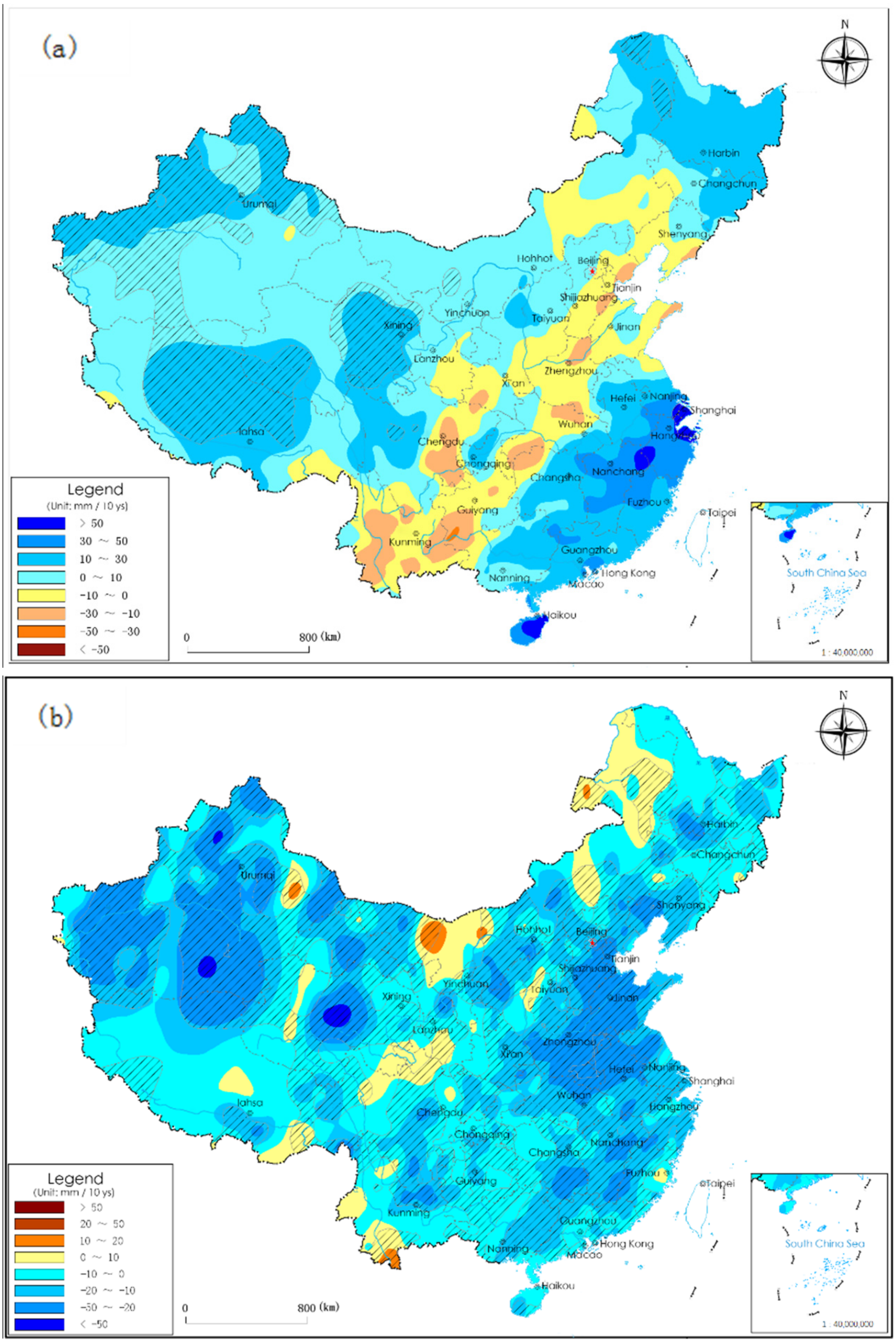

Figure 3. Linear trends of annual precipitation ((**a**), color filled areas); and annual PET ((**b**), color filled areas); the significance test passed the 95% confidence level area ((**a**,**b**), slant line areas) in China from 1961 to 2020.

Our analysis showed that the influencing factors of dry and wet climate changes in different regions of China are not the same. The decrease in the aridity index (climate getting humid) in western and southeastern China, and northeast China is due to the combined effect of precipitation increase and PET decrease, while the climate humidification in North China, northern Central China and northern Southwest China is mainly caused by PET decrease.

Ma [8] analyzed the trend of aridity in northern China from 1951 to 2004, and concluded that since the 1980s, the eastern part of northwest China and North China presented an aridification trend. To analysis the differences from the conclusion in this paper, there are three reasons: first, the length of data is different. The latest observation data from 2011 to 2020 are used in this paper; secondly, the precipitation situation in northern China has changed since 2011, changing from decreasing trend to increasing trend; and third, the FAO56 Penman–Monteith model was used in this paper, but Ma applied the Thornthwaite model to calculate PET, that only considered the influence of temperature. However, according to the analysis results in this paper, wind speed, sunshine duration, relative humidity, and other factors have a great influence on PET.

Based on meteorological observations from 1961 to 2015, Yuan [9] used the FAO model to analyze PET and dry and wet climate change in China. According to their study, the overall dry and wet conditions in China fluctuated around the average, and the linear trend was not obvious. The aridity indices in Yunnan-Guizhou Plateau, Sichuan Basin and Loess Plateau showed an increasing trend. These results are inconsistent with the results of this study. The analysis of the reasons includes two aspects. Firstly, the data length is different. The data used in this study includes the least observation data from 2016 to 2020. However, the precipitation in the Loess Plateau and Sichuan Basin has been increasing continuously in this period, making the aridity index show a downward trend. Secondly, homogenized meteorological observation data from 1961 to 2020 were used in this paper. The decreasing trend of factors such as annual mean wind speed was more obvious, leading to a decreasing trend in the aridity index. Although these regions have different variation trends between two study, they all fail to pass the significance test, and the regions with obvious wetting are the same, mainly located in northwest China and the western part of the Qinghai-Tibet Plateau.

3.2. Spatio-Temporal Evolution Characteristics of China's Dry-Wet Climate Zones

3.2.1. Characteristics of Interdecadal Change in China's Dry-Wet Climate Regions

Judging from the averages from 1981 to 2010, China's arid climate regions (include extreme arid, arid, and sub-arid zones) are mainly located in west and north China, accounting for 48.1% of China's land area; humid climate regions (including extreme humid, humid and sub-humid zones) are mainly located in east and south China, accounting for 51.9% of China's land area. It can be seen from Figures 4 and 5 that since the 1960s, the arid climate areas in China have shown a decreasing trend. In the 1960s, the arid climate areas accounted for about 54.46% of the total land area of China, but by the 2010s, it decreased to 47.57%, a decrease of 6.89% with about 650,000 square kilometers in the past 60 years. The humid climate area has shown an increasing trend. From 1961 to 2000, the total arid climate area in China was larger than that of the humid climate area, but in the last 10 years it was the opposite, while the climate was becoming more humid. Especially in 2020, this trend of humidification was even more obvious when the humid climate area accounted for 60% of the total, the largest since the 1960s.

In the past 60 years, the characteristics of interdecadal changes in China's dry-wet climate regions were obvious (Table 3). The area of extreme arid climate zones has decreased about 10% in the past 10 years, compared with that in the 1960s. The main reason is that the precipitation in Xinjiang and nearby area has increased significantly, turning the extreme arid areas into arid areas. Since the 1980s, the arid area has shown a significant expansion trend. On the one hand, extreme arid regions have turned into arid regions, and on the other hand, the arid regions in central and east Inner Mongolia have expanded. The trend of the sub-arid area is not obvious. Before 2010, the sub-arid area in east Inner Mongolia and west part of the northeast Inner Mongolia had expanded. In the past 10 years, the climate in the east part of northwest China and north China has become more humid, and the sub-arid area has decreased. The trend of sub-humid area is not obvious, but its interdecadal characteristics are significant. It was small in the 1960s, expanded rapidly in the 1970s, decreased in the 1980s, and gradually expanded after the 1990s. Since 2000, the eastern part of northwest China and parts of north China have been transformed from sub-arid to sub-humid. The humid regions in south China have shown an increasing trend, from 26.66% in the 1960s to 30.2% in the 2010s, an increase of 3.56%, which is about 336,000 square kilometers. The extreme humid area in south China has shown an expanding trend, with an increase of about 407,500 square kilometers in the 2010s compared with that in the 1960s, and the trend of humidification is obvious.

Table 3. The proportions of the area of different climate zones to the area of China in different periods from 1961 to 2020 (unit: %).

	Extreme Humid	Humid	Sub-Humid	Sub-Arid	Arid	Extreme Arid
1960s	1.31	26.66	17.56	19.98	16.28	18.2
1970s	2.14	25.4	18.48	20.78	16.51	16.69
1980s	3.51	29.26	15.4	19.03	18.31	14.48
1990s	6.15	26.62	15.12	20.22	20.35	11.54
2000s	2.33	29.78	16.32	19.77	21.03	10.76
2010s	5.61	30.2	16.62	17.5	21.8	8.27
1981~2020	1.47	43.80	17.51	16.56	17.42	0.24

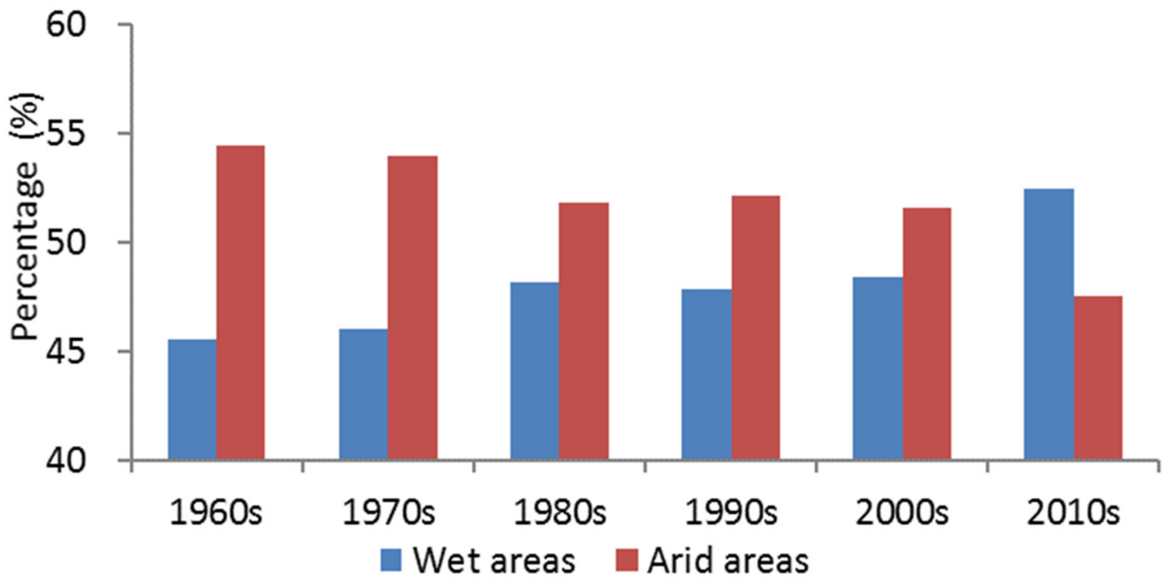

Figure 4. The proportions of the whole dry area and the whole wet area to the area of China in different decades from 1961 to 2020 (unit: %).

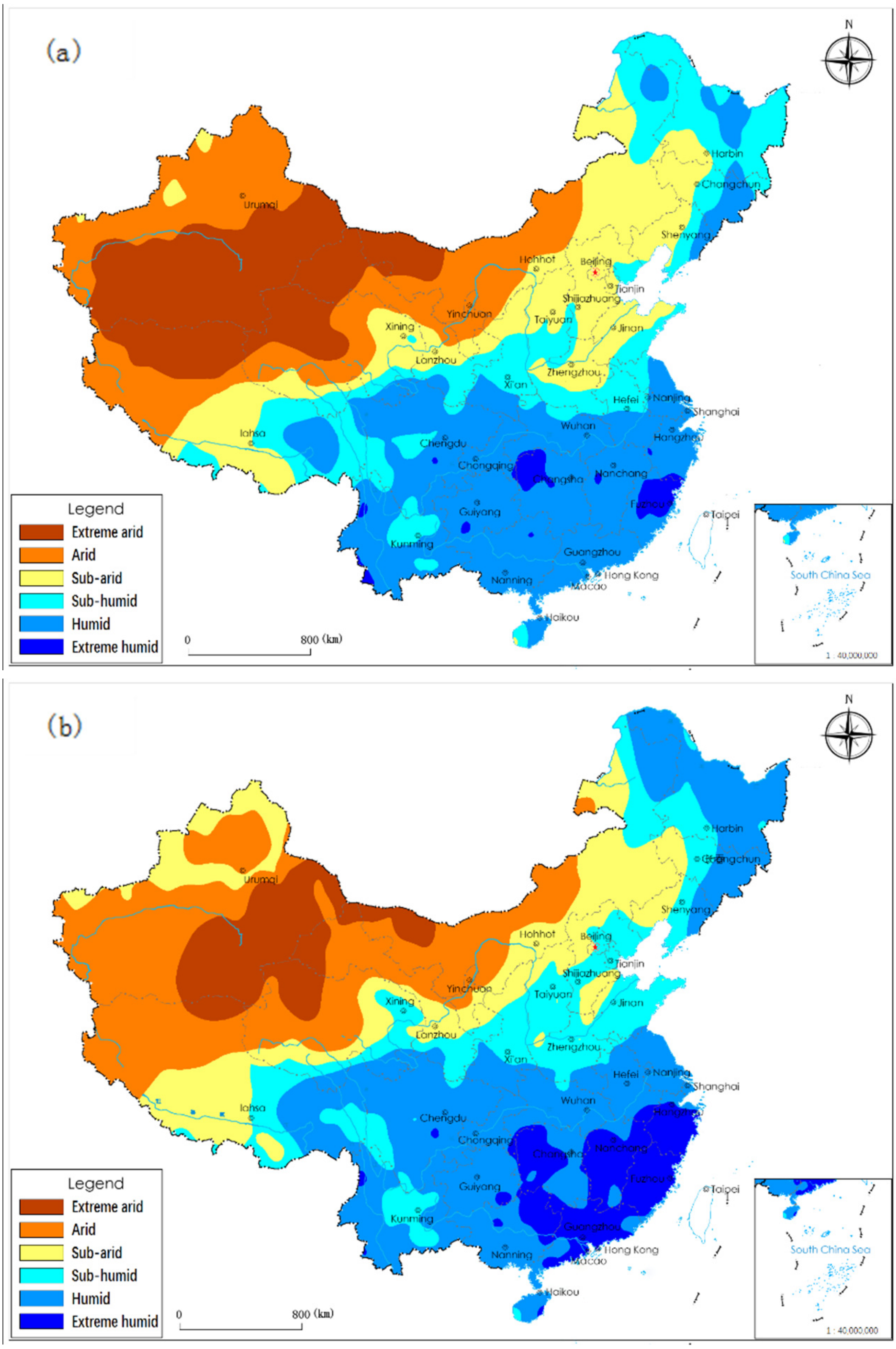

Figure 5. Dry and wet climate zones during 10 years from 1961 to 1970 (**a**); and from 2011 to 2020 (**b**) in China.

3.2.2. Characteristics of Spatial Changes in China's Dry-Wet Climate Regions

In order to study the characteristics of dry-wet climate changes in different regions of China, we calculated the proportions of different dry and wet climate zones in seven regions, including northwest China, north China, northeast China, east China, central China, south China, and southwest China to the whole area of the region (Table 4) in the periods of from 1981 to 2010, and analyzed the areas' linear trend in each dry and wet climate zones in the past 60 years (Table 5). The following is an analysis of evolutionary characteristics for different dry and wet climate zones.

Table 4. The proportions of the area of different climate zones to the whole area of China in different regions from 1981 to 2010 (unit: %).

	Extreme Humid	Humid	Sub-Humid	Sub-Arid	Arid	Extreme Arid
Northwest China	0	4.31	9.24	15.15	36.19	34.51
North China	0	3.49	14.95	51.05	23.39	7.12
Northeast China	0	33.70	48.11	18.19	0	0
East China	22.77	56.43	13.67	7.13	0	0
Central China	9.93	60.35	15.24	5.48	0	0
South China	16.25	83.22	0.49	0.04	0	0
Southwest China	1.47	43.80	17.51	16.56	17.42	0.24
China	3.61	28.63	15.89	19.48	19.51	12.88

Table 5. The linear trends of the areas of different climate zones and proportions to the whole area of China in different regions from 1961 to 2020 (unit: Km^2 (%)/10 year).

	Extreme Humid	Humid	Sub-Humid	Sub-Arid	Arid	Extreme Arid
Northwest China	0.02 (0.01)	1.05 (0.35)	1.26 (0.42) **	2.84 (0.94) **	5.55 (1.84) **	−10.7 (−3.56) **
North China	0.02 (0.01)	0.9 (0.59)	1.02 (0.67)	−1.0 (−0.66)	−0.18 (−0.12)	−0.76 (−0.5)
Northeast China	0.09 (0.12)	3.69 (4.67) **	−1.84 (−2.33) *	−1.98 (−2.5) **	0.04 (0.05)	0
East China	2.59 (3.27) **	−1.28 (−1.62)	−0.5 (−0.64)	−0.75 (−0.95)	−0.05 (−0.06)	0
Central China	1.39 (2.47) *	−0.51 (−0.91)	−0.26 (−0.47)	−0.58 (−1.02) *	−0.05 (−0.07)	0
South China	1.5 (3.36) *	−1.31 (−2.94) *	−0.17 (−0.38)	−0.02 (−0.04)	0	0
Southwest China	0.7 (0.30)	1.24 (0.53)	−0.14 (−0.06)	0.02 (0.01)	1.49 (0.64)	−3.32 (−1.43) **
China	6.35 (0.67) **	3.94 (0.42)	−0.82 (−0.09)	−1.49 (−0.16)	6.81 (0.72)*	−14.78 (−1.56) **

Notes: Statistical significance has passed the 99% confidence level (**) and the 95% confidence level (*).

The extreme arid zones in China cover an area of about 1,222,100 square kilometers, accounting for about 12.88% of the country's land area. It is mainly located in the center and west of northwest China, the west of North China (generally in the western part of Inner Mongolia), and the west of southwest China (generally in the western part of Tibet). Northwest China has the largest extreme arid zone, accounting for 34.51% of the region. In the past 60 years, the extreme arid zones in China have shown a significant decrease, with an average reduction of 147,800 square kilometers (about 1.56%) every 10 years. The area in northwest China has the largest decrease, with an average reduction of 107,000 square kilometers (about 3.56%) every 10 years. The extreme arid zones in southwest China have also decreased significantly, with an average decrease of 33,200 square kilometers (about 1.43%) every 10 years. The significance test shows that the changes of extreme arid zones in northwest and southwest China passed the 99% confidence level. The extreme arid zones in north China have also decreased but not past the significance test.

China's arid climate zones cover an area of about 1,850,400 square kilometers, accounting for about 19.5% of the country's land area. The zones are mainly located in the northwest, north and southwest China, accounting for 36.19%, 23.39%, and 17.42% of the region's land area, respectively, and there are also arid climate zones in northeast China and other places, but relatively small in proportion. In the past 60 years, the area of arid climate zones in northwest and southwest China has shown an increasing trend, increasing by 1.84% and 0.64%, respectively. The significance test in northwest China has passed the 99% confidence level. The main reason is due to the transition from an extreme arid climate to an arid climate. The areas of arid climate zones in north, east and central China show a decreasing trend, but the changes are not significant.

China's sub-arid climate zones cover an area of about 1,848,300 square kilometers, accounting for 19.48% of the country's land area. It is mainly located in north, northeast, southwest, and northwest China, accounting for 51.05%, 18.19%, 16.56% and 15.15% of the region's land area, respectively. Among them, the area of sub-arid zones in north China is the largest, accounting for more than half of the region's land area. In the past 60 years, the area of sub-arid zones in northwest and southwest China has shown an increasing trend, increasing by 0.94% and 0.01%, respectively. That in northwest China has increased by 28,400 square kilometers every 10 years, passing the 99% confidence level. The area of sub-arid zones in northeast, north, east and central China has shown a linear decrease, with an average decrease of 2.5%, 0.66%, 0.95%, and 1.02%, respectively, every 10 years. Among them, northeast China has passed the 99% confidence level, and central China has passed the 95% confidence level, while other areas have failed the test.

China's sub-humid climate zones cover an area of about 1,507,100 square kilometers, accounting for about 15.88% of the country's land area. It is mainly located in the northeast, southwest, central, north, east and northwest China, accounting for 48.11%, 17.51%, 15.24%, 14.95%, 13.67% and 9.24% of the region's land area, respectively, of which the sub-humid zones in northeast China are the largest in area. In the past 60 years, the area of sub-humid zones in northwest China has shown an increasing trend, with an average increase of 28,400 square kilometers (about 0.94%) every 10 years, passing the 99% confidence level. That in north China has also shown an increasing trend, with an average increase by 0.67% every 10 years, but failed the significance test. The area of sub-humid zones in northeast, east, central, south, and southwest China has shown a decreasing trend, with an average decrease of 2.33%, 0.64%, 0.47%, 0.38%, and 0.06%, respectively, every 10 years, of which the northeast China has the most significant decrease, passing the 99% confidence level, while other regions have failed the test.

Most areas of southeast China belong to the humid climate zone, covering an area of about 2,715,900 square kilometers. It has the largest proportion in the dry-wet climate zone, accounting for 28.63% of China's total land area, mainly located in the south, central, east, southwest and northeast China. The area of humid zones in south China is the largest, exceeding 80% of the land area of this region. In the past 60 years, the area of humid climate zones has increased by an average of 39,400 square kilometers (about 0.42%) every 10 years, but is still not significant. That in the northeast, north, northwest and southwest China has shown an increasing trend, with an average increase of 4.67%, 0.59%, 0.35%, and 0.53%, respectively, every 10 years. The increase in northeast China is the most significant, passing the 99% confidence level. The area of humid climate zones in south, central and east China has shown a decreasing trend, with an average of 2.94%, 0.91%, and 1.62% every 10 years, of which south China has passed the 95% confidence level.

The area of China's extreme humid climate zones is about 343,400 square kilometers, around 3.61% of China's land area. It is mainly located in the east, south and central China, accounting for 22.77%, 16.25% and 9.93% of the area, respectively. Over the past 60 years, the area of extreme humid zones in the east, south and central China has increased significantly, with an average increase of 3.27%, 3.36%, and 2.47%, respectively, every 10 years. Among them, east China has passed the 99% confidence level, while south and central China have passed the 95% confidence level. Although the area of extreme humid climate zones in other regions of China is also increasing, but the increase is relatively small and has not passed the significance test.

The characteristics of dry-wet climate change in different regions of China are obvious (Table 5). In northwest China, the area of extreme arid zones has decreased most significantly. In the 2010s, the area of extreme arid zones decreased by about 660,000 square kilometers compared to the 1960s. However, in northwest China, the areas of other climate zones have shown increasing trends with different ranges and the area increase of arid, sub-arid, and sub-humid zones has passed the 99% confidence level. In north China, the area of arid climate zones has shown a decreasing trend, and that of humid climate zones has shown an increasing trend, but the confidence level has not passed the significance test. In northeast China, the area of sub-arid and sub-humid climate zones has decreased significantly, and that of sub-humid zones has increased significantly, indicating that the climate humidification has become more significant in this area. The area of extreme humid climate zones in east, central and south China has increased significantly, indicating that the southeast part of China has also become more humid. In southwest China, the area of extreme arid zones has decreased significantly, mainly in west Tibet, and its area of sub-humid zones has decreased slightly, and the areas of other climate zones have increased, but not significantly. From the above analysis, the climate in China's different regions all show a tendency to become more humid with different ranges.

3.2.3. Characteristics of Seasonal Variation of Dry-Wet Climate in China

In order to study the seasonal variation characteristics of the dry and wet climate in China, we analyzed the linear trend of the national annual and seasonal aridity index (Table 6). From Table 6 we found that the aridity index in the four seasons all show a decreasing trend, indicating that the climate in the four seasons is getting more humid. Summer is the most obvious one, in which the aridity index decreased by 0.28 on average every 10 years, passing the 99% confidence level. The humidification in spring and autumn is also significant, with the aridity index decreased by 1.54 and 0.95, respectively, passing the 95% confidence level. In winter, it decreased by 0.79, which was not significant.

Table 6. The linear trends of annual and seasonal mean aridity index in China from 1961 to 2020.

	Winter	**Spring**	**Summer**	**Autumn**	**Year**
Average	14.45	13.69	2.44	9.11	2.14
Trend	−0.79	−1.54 *	−0.28 **	−0.95 *	−0.17 **

Notes: Statistically significant and has passed the 99% confidence level (**) and the 95% confidence level (*).

4. Projection of Future Dry-Wet Climate Changing Trend in China

Using projection data from GCM model BCC-CSM1.1, this paper calculates China's regional aridity index (AI) from 2021 to 2099, and analyzes the trend of dry-wet climate changes in China under RCP4.5 and RCP8.5 scenarios.

Figure 6a shows the variations and linear trends of the national annual average aridity index from 2021 to 2099 under the two scenarios. It can be seen from the Figure that the future aridity index shows an increasing trend in both scenarios, meaning that the climate of China will become drier in the future. It increases by 0.008 every 10 years under the RCP4.5 scenario (Figure 6, the blue triangle marked line), and increases by 0.01 every 10 years under the RCP8.5 scenario (Figure 6, the red circular marked line), indicating that the future national climate will tend to become drier in the high emission scenario than in the medium emission scenario. There are differences in the interdecadal characteristics of the aridity index under the two scenarios. Under the RCP4.5 scenario, the aridity index from 2021 to 2040 is relatively low, and the national climate is relatively humid, and that from 2040 to 2080 is relatively high, indicating that the national climate is relatively dry, and the index has a downward trend after 2080, showing that the climate becomes relatively humid in the last 20 years of this century. Under the RCP8.5 scenario, the rising trend of the national aridity index is not obvious before 2060, but significant after 2060 to the end of this century, indicating that the national dry-wet climate change in the early 21st century under the RCP8.5 scenario is not obvious, but has a significant trend of becoming dry in the late 21st century.

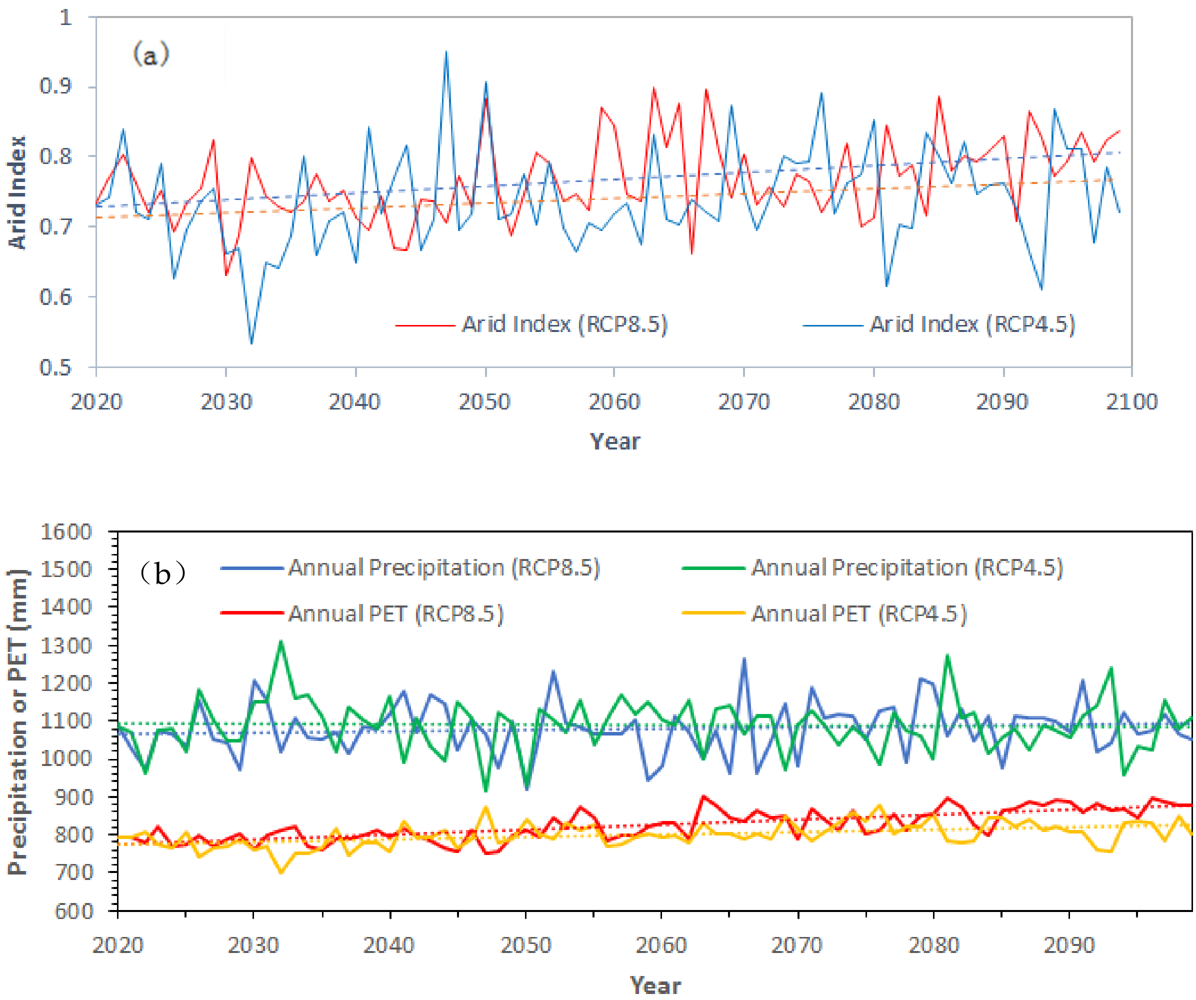

Figure 6. The annual averaged aridity index under RCP4.5 ((**a**), blue line) and RCP8.5 ((**a**), red line); the annual precipitation under RCP4.5 ((**b**), green line) and RCP8.5 ((**b**), blue line); annual PET under RCP4.5 ((**b**), yellow line) and RCP8.5 ((**b**), red line) in China from 2021 to 2099. The dashed line shows a linear trend.

The variation trends of annual precipitation and annual PET under scenarios R4.5 and R8.5 from 2021 to 2099 are also presented here (Figure 6b). Under the R8.5 scenario, annual precipitation shows an increasing trend, increasing by 3.4 mm every 10 years, while under the R4.5 scenario, the linear trend is not obvious. The annual PET showed an increasing trend under both scenarios, with an increase of 6.5 mm per decade under the R4.5 scenario and 13.3 mm per decade under the R8.5 scenario. The increasing trend of annual precipitation and annual PET under the R8.5 scenario is more obvious than that under the R4.5 scenario, resulting in a more obvious increasing trend of annual aridity index under the R8.5 scenario than that under the R4.5 scenario.

In order to analyze the spatial characteristics of China's future dry-wet climate change, we calculated the linear trends of the annual average aridity index of 2255 stations in China from 2021 to 2099 under two scenarios (Figure 7). It can be seen from the Figure that under the two scenarios, the spatial pattern of future dry-wet climate change in China is almost the same. The western regions of China (including the central and western parts of northwest China, the west of Inner Mongolia, and Tibet) maintain a tendency of getting more humid, and the central and eastern regions (including the central and eastern parts of northwest China, most of north, south and southwest China, east, and central China) have shown a tendency of getting more arid.

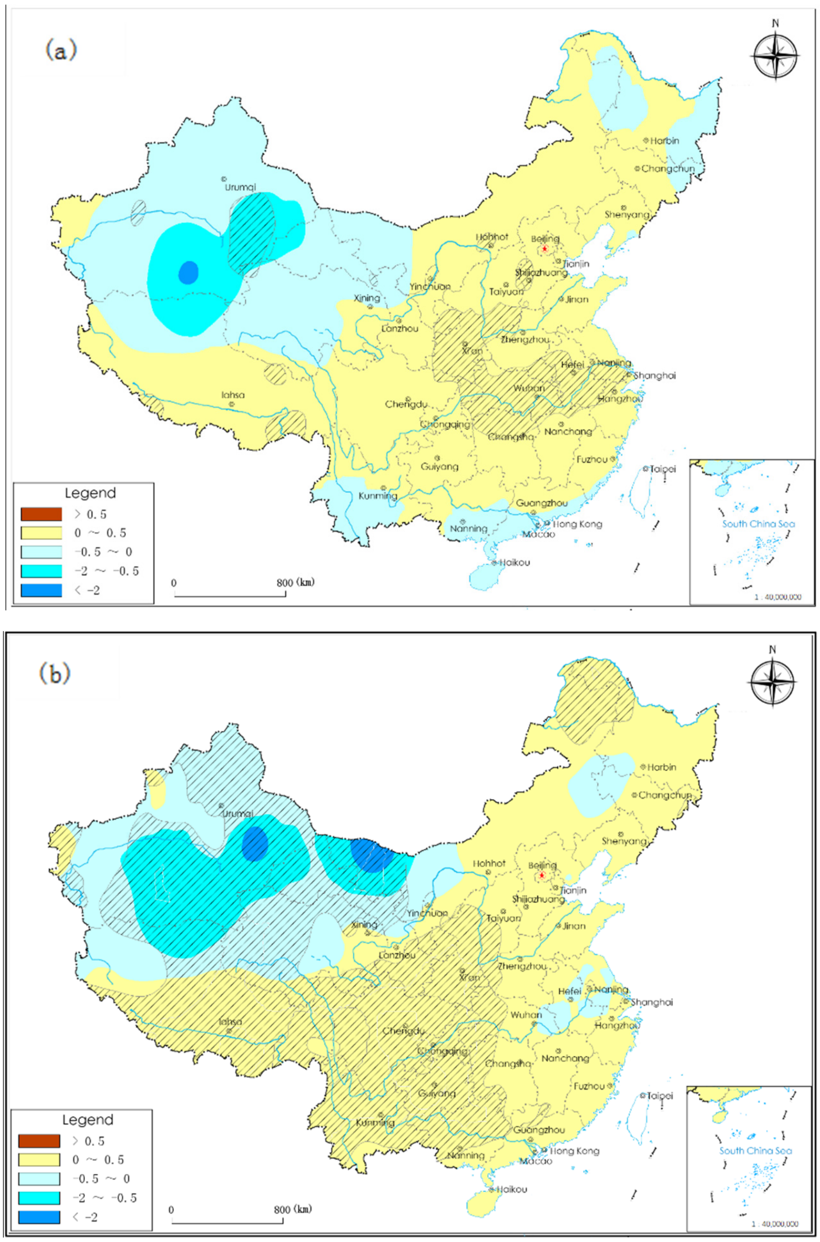

Figure 7. The linear trends of aridity index under RCP4.5 ((**a**), color filled area); and RCP8.5 ((**b**), color filled area), the significance test passed the 95% confidence level area ((**a**,**b**), slant line area) in China from 2021 to 2099.

Comparing Figure 7a,b under the two scenarios, there are also many differences. Firstly, although west China has a tendency of becoming humid under the two scenarios, it has a more obvious and wider range of humidification under the RCP8.5 scenario. The significance test shows (diagonal lines covered areas), under the RCP4.5 scenario, only the southeastern part of Xinjiang has become significantly humid, but under the RCP8.5 scenario, most of Xinjiang, western Inner Mongolia and other places have a more obvious and wider range of humidification. Secondly, the amplitude and scope of aridification in the central and east China are different. Under the high emission scenario (RCP8.5), the trend of aridification in the central and east China is more obvious, especially in the southwest China. The significance test shows that under the RCP4.5 scenario, areas with significant aridification are mainly located in the eastern part of northwest China, southern part of north China, and the middle and lower reaches of the Yangtze River. However, under the RCP8.5 scenario, areas with a significant aridification trend are obviously larger, including southwest China, the eastern part of northwest China, the western part of central China, and the northern part of northeast China.

Compared with the results of other researchers, the main conclusions of the future dry-wet climate changing trends in China are consistent with the results of Ma [16], but some regions are different, such as in north China and northwest China, where the climate will become more humid in their study, contrary to our results. The differences may be caused by the different modes selected and the uncertainty of the simulation results.

5. Conclusions and Discussion

Analysis of the variation and linear trend of the annual average aridity index in China from 1961 to 2020 shows that the overall climate in China has become more humid in the last 60 years. Areas with obvious humidification are mainly located in west China, including most of Xinjiang, west Qinghai, Gansu and Inner Mongolia, and northwest Tibet. Some areas in northeast and east China also become humid, but not significantly. There is a trend of aridification in some parts of north and southwest China, but not a significant one. In the past 10 years, the climate in China has become more humid. Compared with the 1960s, the total area of arid areas (include extreme arid, arid and sub-arid zones) has decreased by about 650,000 square kilometers.

In the past 60 years, the dry-wet climate zones have obvious characteristics of inter-decadal variation. Due to the precipitation increasing, the areas of extreme arid zones in China have continued to decrease, with an average decrease of 147,800 square kilometers (about 1.56%) every 10 years, mainly in the northwest China. The area of arid climate zones has shown a significant expansion since the 1980s, mainly due to the transformation of extreme arid zones to arid zones. The general tendency of the sub-arid zones is not obvious. Before 2010, the area of the sub-arid zones in east Inner Mongolia and the western part of the northeast China has expanded. In the past 10 years, the climate in the eastern part of northwest China and north China has shown a trend of humidification, and the area of sub-arid zones has decreased. The general tendency of the area of sub-humid zones is not obvious, but the characteristics of regional variations are significant, with a prominent increase in northwest China and a prominent decrease in northeast China. The area of humid and extreme humid zones in south China and northeast China has shown an increasing trend. Among them, the area of humid climate zones in northeast China has increased significantly, and the area of extreme humid climate zones in east, south and central China has increased significantly.

The characteristics of dry-wet climate change in different regions of China are different. In northwest China, the area of extreme arid zones has decreased significantly, meanwhile the area of other climate zones has shown an increasing trend. In north China, the area of all arid zones has decreased, and that of all humid zones has increased. In northeast China, the area of sub-arid and sub-humid climate zones has decreased significantly, and that of humid zones has increased significantly, indicating that the humidification has become more significant in this region. In east, central and south China, the area of extreme humid climate zones has increased significantly, meanwhile the areas of other climate zones have shown a decreasing trend, those indicating that the area of southeast China has also become more humid. The western part of southwest China (generally the western part of Tibet) has become significantly more humid, meanwhile other areas have not changed significantly. Overall, the climate in most regions of China had a humidification tendency in the past 60 years.

The seasonal variations of the dry-wet climate in China have distinctive characteristics. The results show that the climate in all four seasons has a humid tendency, with the significance test passing the 99% confidence level in summer.

Through the analysis of the annual aridity index from 2021 to 2099 under the two given scenarios, the results show a trend of aridification in the future in China. Under the two scenarios, the spatial pattern of future dry-wet climate change in China is generally consistent. The aridification areas are mainly located in the central and east China, while west China continuously maintains the tendency of humidification. These variation trends are more significant under the high emission scenario than under the medium emission scenario.

Dong [38] analyzed PET in Xinjiang by the end of this century using simulation data of four CMIP5 GCM models (BCC-CSM-1 M, GFDL-ESM2M, HadgEM2-ES, Microc-EsMchem), and the results are basically consistent with the results of this study. It shows that PET in Xinjiang will increase by the end of this century, and the increase of PET will be more significant under the high emission scenario. Qi [39] used the CNRM-CM5 model simulation data of CMIP5 to analyze PET in the Heihe River Basin after scaling down and deviation correction, and the results were consistent with the results of this study. PET in the Heihe River Basin showed an increasing trend in this century. Liu [40] and Zhao [41] chose CMIP5 and CMIP6 climate models to conduct comparative analysis on PET, and compared the future changes of PET and the relative contributions of each driving factor in the 21st century. The results show that both CMIP5 and CMIP6 models can accurately simulate the increasing trend of PET. The above comparative analysis explains that although this study only applied a GCM model data to analyze the PET change trend in China, the results were basically consistent with the results of multiple models.

To compare and analysis the reasons of the differences between the aridity index change trends of past 60 years in China and the trends of 21st century projection, especially in the central and eastern regions of China, the climate changes from warm and humid to warm and arid, and mainly includes several aspects. First, the main driving factors were different. In recent decades, the main factors of humidification in central and eastern China was a decrease in wind speed and sunshine duration. The main driving factor of PET increase in the 21st century is surface net radiation (Rn), which increases by 8.2 $MJm^{-2}d^{-1}$ per decade in China, with an obvious increasing trend in this century. The second factor is the influence of urbanization. Although homogenized observation data are used in this study, the influence of urbanization is not removed. For example, the rapid decline of average wind speed and the rapid rise of surface temperature observed in recent decades are inseparable from the influence of urbanization. Third, although the prediction of a dry and wet climate in China in the 21st century in this study is basically consistent with the research results of other researchers using multiple models, the uncertainty of models and future emission scenarios will lead to the uncertainty of climate prediction. These aspects of the above analysis will need to be considered in the future in dry and wet climate change analysis, so as to improve the credibility and validity of the research results.

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