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The Progress of Dry–wet Climate Divisional Research in China

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Abstract: The dry–wet climate regionalization index, potential evapotranspiration calculation methods, standard and named methods of dry–wet climate regionalization, etc., since the middle of the 20th century are reviewed in this paper. Using the arid index, climate regionalization and class standards were given on the basis of former review. Then, the characteristics of wet–dry climate division were analyzed using observed data at 2207 national meteorological stations from 1981 to 2010. The results showed that the total arid area (including extreme arid, arid and semi-arid areas) was 4.692 million hm^2 in China, accounting for 48.8% of the land area in China, which included 878,000 hm^2 (9.1%), 2.092 million hm^2 (21.8%) and 1.722 million hm^2 (17.9%) for extreme arid, arid and semi-arid area, respectively. The arid areas were mainly distributed in Xinjiang, Inner Mongolia, Tibet, Qinghai, Gansu and other western regions. Sub-humid area, wet area and excessive wet area accounted for 1.6%, 27.8% and 8.8% of China's land area, respectively, mainly located in the south of the Yangtze River and Northeast China. Since 1961, the overall characteristics of dry-wet climate change in China are that the total arid areas shows a decreasing trend, while the total wet areas shows an increasing trend.

Keywords: Dry-wet Climate Division, Arid Index, Potential Evapotranspiration, Climate Change

1. Introduction

The water cycle and the distribution of precipitation and water resources will change in the context of global climate change. Some areas are becoming humid and others are becoming dry. Ding et al. [1] have suggested that in the context of global warming, the global and regional water cycles have been undergoing significant changes in the past 100 years. Shi et al. [2] and Zhang et al. [3] have pointed out that since 1987, there is actually a process of climate change from warm-dry to warm-humid in the mid-eastern regions of Northwest China. The research on the laws of climate change is suitable for local and related industries to make use of climate resources, avoiding disadvantages and adapting to climate change (Chen et al. [4]). The dry and wet conditions in an area are closely related to the amount of precipitation and evaporation. This is usually reflected by the aridity index. The annual aridity index is the ratio of annual evaporation to annual precipitation. It is otherwise referred to as the wetness index. The air is humid when the amount of precipitation exceeds the amount of evaporation. The more precipitation exceeds evaporation, the greater the degree of wetting. Similarly, the air is dry when the amount of evaporation exceeds the amount of precipitation. In the past 100 years, the proposed methods and indicators, grade naming and the division of dry and wet climate zone standards, have changed due to the different understandings of dry and wet climate zones, the different studied regions and purposes, and the limitations of scientific and technological development levels and observational data at a given time. Thus, this paper mainly reviews and summarizes the research results of dry and wet climate division indicators, potential evapotranspiration calculation methods, dry and wet climate grades and their naming methods since the middle of the 20th century. Then, the grading standards of dry and wet climate zones are given. At the same time, the latest meteorological observations in China and the spatial characteristics of dry and wet climates in the past 30 years are analyzed as well.

2. The Progress of Dry and Wet Climates in China

In the 1950s, the old generation of scientists, such as Zhu Kezhen [5], Tu Changwang et al. [6], and Huang Bingwei [7], compiled the preliminary draft of the China Comprehensive Natural Regionalization [8] and China Climate Division [9] using a hydrothermal coefficient as an aridity index, combining this with the heat index and average monthly temperature in July simultaneously. The potential evapotranspiration and aridity were calculated by the Penman formula [10, 11] and the climatic zoning scheme was enriched and revised in the 1960s with the needs of agricultural production and socio-economic development and the continuous accumulation of meteorological observations [12, 13]. As a result, the China Climate Atlas [14] was published officially in 1979 using the data from 1951 to 1970 to amend the demarcation line [15], which divided the country into 10 climatic zones, 22 climates districts and 45 climate zones. Later, through a series of comparative experimental studies, Chinese scientists improved various zoning indicators [16–19] and finally formed a three-level climate division system including dividing a temperature band with a daily heat index, such as a daily average temperature stability greater than 10 °C etc., dividing dry and wet areas by aridity index, and dividing climate zones by the hottest monthly average temperature index. The Central Meteorological Administration, now the China Meteorological Administration, organized experts to compile the national climate division atlases of 1951–1980 and 1961–1990 by this method [20, 21], and identified it as a national standard [22]. The Chinese Academy of Sciences used this method to compile China's climate division from 1971 to 2000 and from 1981 to 2010 [23, 24], which was referenced in the National Assessment Report on Climate Change [25, 26] and the monograph on China's Natural Geography [27].

There are many studies on the characteristics of dry and wet climate change in the context of global changes. Feng et al. [28] used the dryness index defined by the United Nations Environment Programme (UNEP) [29] to analyze the trend in global arid and semi-arid areas in the past 60 years and in the 21st century under the context of global warming. The results showed that the climate is warming and global arid and semi-arid areas are expanding. Huang et al. [30] pointed out that the warming effects are more obvious during the winter half of the year in global arid and semi-arid areas. Fu et al. [31] pointed out that the aridification situation in northern China is severe and the ecological environment continues to deteriorate. Ma et al. [32] discovered that Northwestern and Northern China have been characterized by aridification trends since the 1980s which have intensified in the past 15 years because the precipitation has reduced and the temperatures have risen by analyzing the land surface wetness index and other indicators. Yang et al. [33] pointed out that China's dry and wet climate boundary has shown overall movement and fluctuation between East and West and North and South over the last 50 years. Shi et al. [34] divided Chinese climate change into five changed trend zones from 1961 to 2010, named Northeast China–North China warming, the dry trend belt, the East China–Huazhong wet warming trend belt, the Southwest-South China dry warming belt, the Southeastern–Southwestern wetting and warming trend belt and the Northwest–Qinghai–Tibet plateau warming and wetting trend belt, based on the analysis of the trend value and fluctuation characteristic values of temperature and precipitation, combining China's topography and administrative regions. Yuan et al. [35] have analyzed the spatio-temporal characteristics of dry-wet climate in China from 1961 to 2015, and have pointed out that precipitation is the most important factor for dry-wet changes in most regions. By using the prediction results of five models, Ma et al. [36] have analyzed the characteristics of the area change of dry-wet regions in China by the end of the 21st century (2070-2099) compared with that in the reference period (1981-2010), Wu et al. [37] have conducted a comprehensive climate change risk regionalization of China under the future scenario.

3. The Progress of the Aridity Index

Precipitation was used as an alternative indicator of dryness before the 1950s because it could be calculated conveniently. Thus, it was widely used in climate division and dry and wet climate change research [38–40]. Generally, an area with annual precipitation of less than 200 (or 250) mm was classed as an arid area, 200 (or 250) mm~400 (or 500) mm of precipitation was classed as a semi-arid area, 400 (or 500) mm~800 (or 900) mm of precipitation was classed as a semi-humid area and greater than 800 (or 900) mm was classed as a wet area. Although the calculation of precipitation is simple, the dry and wet conditions in an area cannot be truly reflected if only the income of water is considered and the expenditure of water is not considered.

In order to reflect the dry and wet conditions in an area, the potential evapotranspiration was introduced to calculate the aridity index in the 1950s. The aridity index is an indicator of the degree of dryness and wetness in a region, which has been used in geography and ecology research for a long time and is becoming one of the climate indicators most often involved in global change research, especially in climate change, aridification and desertification, etc. Scientists have proposed many methods for calculating aridity indexes, which have various calculation principles, each with advantages and disadvantages, and are used for different regions and studies. The range of indicators is different due to the difference in the calculation principle, the method of the aridity index and the use areas and purposes, which make the comparison of different aridity indexes difficult; the results are also quite different.

There are two methods for calculating an aridity index. One is the annual evapotranspiration compared to the annual precipitation, generally referred to as the aridity index.

Another is the annual effluent of the annual evapotranspiration, generally referred to as the wetness index. In 1997, Ci et al. [41] used the ratio of annual precipitation to potential evapotranspiration as an indicator to determine the potential range of desertification in China for the first time according to the relevant provisions of the UN Convention to Combat Desertification [42]. The formula is as follows:

$$\mathrm{MI} = \frac{\mathrm{P}}{\mathrm{E}} \tag{1}$$

where *MI* stands for wetness index, *P* stands for annual precipitation and *E* stands for potential evapotranspiration calculated by the Thornthwaite method [43]. The United Nations Convention to Combat Desertification states that "arid, semi-arid and sub-humid dry areas refer to continental areas where the ratio of annual precipitation to evapotranspiration is between 0.05 and 0.65, excluding polar and subpolar regions".

4. Study of the Calculation Method of Evapotranspiration

There are various methods for estimating the potential evapotranspiration, including the Thornthwaite method, the Penman−Menteith method and the Holdridge method [44].

4.1. Thornthwaite Method

The Thornthwaite method, proposed in 1948, is an internationally accepted method for calculating potential evapotranspiration. It is widely used in climate classification and vegetation–climate relationship research. It has the great advantage that data is available easily. Tao Shiyan [45], and Zhang Baokun et al. [46] used the Thornthwaite method to calculate the potential evapotranspiration in the China climate zone, which was considered to be in line with China's natural landscape, and they used heat and water factors as indicators of the first and second class, which have become the principle and basis for climatic division in China. The Thornthwaite method calculates potential evapotranspiration based on monthly average temperature and considers the empirical formula established by the latitude factor, e.g., sunshine length. The formula is as follows:

$$PE\mathrm{T} = 16.0 \times \left(\frac{10T_i}{H}\right)^A \tag{2}$$

where *PET* stands for monthly potential evapotranspiration—*PET* is specified as 0 when the average monthly temperature is lower than 0°C—T_i stands for monthly average temperature, *H* stands for annual heat index, and *A* stands for the constant.

The method has a reasonable classification of dry and wet climate zones and is used widely around the world. It is also used widely in climate division in China and is especially suitable for calculating monthly data. However, the method has some limitations in replacing the evapotranspiration with temperature change due to the fact that changes of evapotranspiration are related to various environmental factors. In addition, the assumption that the evaporation will not play a role when the average temperature of the month is lower than 0 °C is not entirely correct.

4.2. Penman–Menteith Method

The formula for calculating the potential evapotranspiration recommended by the World Food and Agriculture Organization (FAO) in 1998, named the FAO Penman–Menteith method, is as follows:

$$E_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{3}$$

where E_0 stands for potential evapotranspiration, R_n stands for the net radiation, *G* stands for soil heat flux density, *T* stands for daily average temperature at the height of 2 m, u_2 stands for the wind speed at a height of 2 m, e_s stands for the saturated water vapor pressure, e_a stands for the actual water vapor pressure, Δ stands for the slope of the saturated water vapor pressure curve and *γ* stands for the constant of dry and wet meter.

The Penman–Menteith method is based on the theory of energy balance and aerodynamics. It uses water vapor pressure, net radiation and air drying force at a certain temperature and wind speed to determine potential evapotranspiration. It has a substantial theoretical and physical basis and has been used widely in climate and vegetation classification analysis and climate division in China [47–51]. At the same time, this method requires a much larger number of climate indicators, including the maximum temperature, the minimum temperature, water vapor pressure, sunshine hours, wind speed and other factors. Thus, there are some restrictions to applying this formula in practice, especially for those weather stations which do not have so many meteorological observation elements.

4.3. Holdridge Method

The Holdridge method is a method which was used by the American plant ecologist Holdridge to calculate potential evapotranspiration based on the temperature of plant organisms in 1947. The calculation formula is as follows:

$$PET = 59.93 \times T_{AB} \tag{4}$$

where *PET* stands for the monthly potential evapotranspiration and T_{AB} stands for the annual biological temperature, which is the average temperature during the vegetative growing period of plant. It is generally considered to be between 0 and 30°C, and if the monthly average temperature is lower than 0°C or greater than 30°C, T_{AB} will be treated as 0°C or 30°C.

Chinese scientists [52, 53] used the Holdridge method to map the distribution of evapotranspiration rate in China, which is considered to have a significant correspondence to the distribution of vegetation in China. Although this method is simple to calculate and has a certain physical meaning, it is developed in the tropical region of Central America and needs to be adjusted when used in the subtropical region of China. For instance, the T_{AB} can be calculated by the average temperature on a shorter time scale. It is also not reasonable to calculate the upper limit of the biological temperature at 30°C.

5. Dry and Wet Climate Divisions and Named Methods

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 [44] proposed the division of dry and wet climate rank into eight grades, namely super-wet, extremely humid, humid, sub-humid, semi-arid, drought, extreme drought and ultra-arid areas, in 1947. Thornthwaite [43] proposed to divide it into six grades, namely extreme wet, moist, wet, semi-wet, semi-dry and dry areas, in 1948. Chen [16], Mao [50] et al. proposed a five-level method, namely moist, sub (half)-humid, sub (semi)-drought, drought, extreme drought and highlight extreme drought. 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, while the name for a semi-arid area could be semi-arid, sub-arid, semi-dry and insufficiently wet area, etc.

The key to determining the division method appropriately is whether the dry–wet climate division results can reflect the local vegetation ecological status. If the dryness area contour is consistent with or close to the local natural landscape boundary, the dry and wet degree is indicated. Thus, it is not so important to divide the dry–wet degree and the named method. For instance, Chen [16] and Zhang et al. [17] calculated aridity index by the ratio of potential evapotranspiration using the Penman method for precipitation, and classified the China climate zone into five belts, including humid, sub-humid, sub-drought, drought and extreme drought belts. The contour line of 16.0 is consistent with the line of the Tarim Basin, Qaidam Basin and Bengtan Jilin Tengger Desert, above which the annual precipitation is less than 60 mm and is consistent with the desert landscape in China and can be used as a demarcation indicator between very arid and arid areas. The contour line of 3.5 with an annual precipitation if 200~250 mm is consistent with the western boundary of the dry agricultural area, which can be used as a boundary indicator between drought and sub-drought areas. The contour line of 1.6 with an annual precipitation of 450~500 mm can be used as a demarcation indicator between sub-humid and sub-drought areas. The contour line of 1.0 is a demarcation indicator for wet and sub-humid areas. The eastern segment of the line is equivalent to the Huaihe River in the Qinling Mountains and the annual precipitation is 800–950 mm. The annual precipitation in the western plateau and northeast region is 600–650 mm. The Climate Atlas of the People's Republic of China published in 2002 [20] used this method for dry–wet divisions. Zheng et al. [23, 24] used the annual aridity index as a main indicator and annual precipitation as an auxiliary indicator to divide the China climate into four belts including humid, semi-humid, semi-arid and drought degrees in the China Climate Regional Planning from 1981 to 2010. An arid area was defined by its aridity index exceeding 4.0 and an annual precipitation of less than 200 (or 250) mm. The aridity index of 1.5 and annual precipitation of 400 (or 500) mm was defined as the boundary between semi-humid and semi-arid areas. A dryness index below 1.0 and an annual precipitation exceeding 800 (or 900) mm was defined as a humidity area.

6. Dry-Wet Climate Divisions in China in the Past 30 Years

The final division results are different because different scientists target different research periods, use different sites' data and adopt different index methods and division standards. In this paper, we used data from 2207 ground observation weather stations from the China Meteorological Administration (http://cdc.cma.gov.cn/home.do) between 1961 and 2014 with quality control to analyze the spatial characteristics of dry and wet climates in China. We selected the aridity index commonly used in dry and wet analysis in the previous climate division atlas in China and divided the dry and wet zone into six levels.

The aridity index is calculated as follows:

$$AI = \frac{E_0}{P} \tag{5}$$

where AI stands for aridity index, E_0 stands for annual evapotranspiration calculated by the FAO Penman–Monteith method and P stands for annual precipitation.

The standards of dry–wet degree division according to the AI are as follows (Table 1):

Table 1. *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 Index	<0.5	0.5~1.0	1.0~1.5	1.5~3.5	3.5~20.0	≥20.0

The wet–dry areas are divided into six levels according to the calculated aridity index. Since the precipitation in Western China has increased since the 1980s, the climate has shown signs of warming and humidification [2, 3] and the area of extreme desert has shrunk. Therefore, the divided range of the extreme arid area should not be too large. In this paper, the areas of AI greater than 20 are defined as very arid areas, from 3.5 to 20 are defined as arid areas, from 1.5 to 3.5 are defined as sub-arid areas, from 1.0 to 1.5 are defined as sub-humid areas, from 0.5 to 1.0 are defined as wet areas and less than 0.5 are defined as extreme humid areas.

The distribution of the average aridity index from 1981 to 2010 (Figure 1) shows that most of Northern and part of Western China are arid areas, including sub-arid, arid and extreme arid areas, and most of Eastern and Southern China's areas are wet areas, including sub-humid, wet and extremely wet areas. The boundary of the dry–wet climate runs from Northeast to Southwest China, across Qiqihar, Daqing, Shuangliao, Fuxin, Chaoyang, Chifeng, Zhangbei, Beijing, West, Datong, Luliang, Yulin, Guyuan, Dingxi, Qinghai, Jianzha County, Dulan County, Germu, Nagqu Bangor County, Lhasa City, north of which is an arid climate area, with an overall area of 4.692 million km^2 and accounting for 48.8% of the total Chinese land area. The area has the characteristic that the precipitation is low, the precipitation variability is large and the seasonal distribution is uneven during the year, while the surface evaporation is large and the air is dry. The extremely arid areas are mainly located in parts of Eastern and Southern Xinjiang, part of Northwestern Inner Mongolia, the Hexi Corridor in Western Gansu and part of Western Qaidam Basin in Qinghai, most of which are desert and Gobi landforms with an area of about 878,000 km^2 (about 9.1% of land area). The arid areas are located in Junggar Basin of Xinjiang, part of Western and Northern South Xinjiang, Northwestern Tibet, Western Qinghai, Western Gansu, Central and Western Inner Mongolia and Northern Ningxia, the area of which is about 2.092 million km^2, accounting for 21.8% of the total land area. The sub-arid areas are mainly located in Central and Eastern Inner Mongolia, Western Heilongjiang, Western Jilin, Northwestern Liaoning, Northern and Southeastern Hebei, Northwest Shanxi, Western and Northern Shanxi, Northwestern Shaanxi, Central Ningxia, Central Gansu, Central Qinghai, Central Tibet and Tianshan Mountains and Altai Mountains in Xinjiang with an area of about 1.722 million km^2, accounting for 17.9% of the total land area.

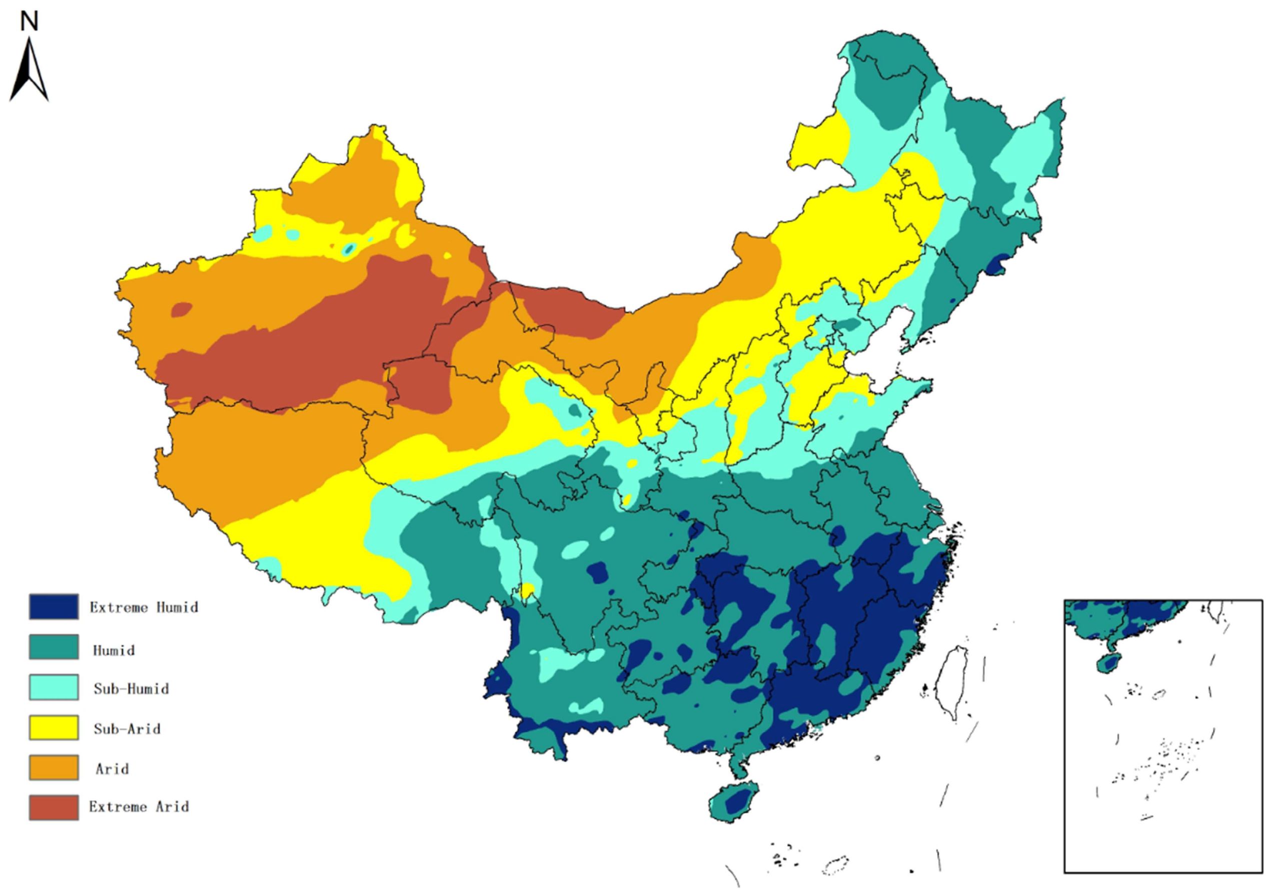

Figure 1. *The dry–wet climate division in China for 1981–2010. The arid areas, including sub-arid (yellow area), arid (orange area) and extreme arid areas (red area) located in Northern and Northwestern of China. The wet areas, including sub-humid (light blue area), wet (green area) and extremely wet areas (dark blue area) located in Eastern and Southern of China.*

The area located south of the dividing line is a humid climate zone including sub-humid, humid and extremely humid areas. The sub-humid areas are mainly located in Northeastern Inner Mongolia, Western and Eastern Heilongjiang, Central Jilin, Central and Western Liaoning, Northeastern and part of Central Hebei, majority of Beijing, Eastern Shanxi, part of Central Shaanxi, Eastern and Southern Gansu, Central and Southern Qinghai and Eastern Qilian Shan, part of Central and Eastern Tibet, etc. The humid areas are mainly located south of the Qinling and Huaihe Rivers in China, in the Southeastern Qinghai-Tibet Plateau, in part of Northeast China and Inner Mongolia. The extremely humid areas are mainly located in most of the Southern Yangtze River, in the east and north of Southern China and part of Yunnan. The proportions of sub-humid, humid and extremely humid areas accounting for China's land area are 14.6%, 27.8% and 8.8%, respectively.

7. Dry-wet Climate Change in China from 1961 to 2018

Since 1961, the overall characteristics of dry-wet climate change in China are that the total area of arid areas (including extremely arid, arid and sub-arid areas) shows a decreasing trend, while the total area of wet areas (including sub-humid, humid and over-humid areas) shows an increasing trend (figure 2). In the 1960s and 1970s, the total area of the wet area was larger than the total area of the arid area. However, the wetter trend has been more significant since 2011, when the total area of arid areas decreased by about 450,000 square kilometers on average from 2011 to 2018 compared with the 1960s. Among them, the area of extreme arid areas decreased the most, accounting for 13.1% in the 1960s and 7.9% in 2010, Nearly half a million square kilometers. The getting wet areas are mainly located in Northwest of China (including Xinjiang Uygur Autonomous Region, Gansu Province, Qinghai Province, etc.), mainly due to a significant increase of precipitation in these areas since the 1980s.

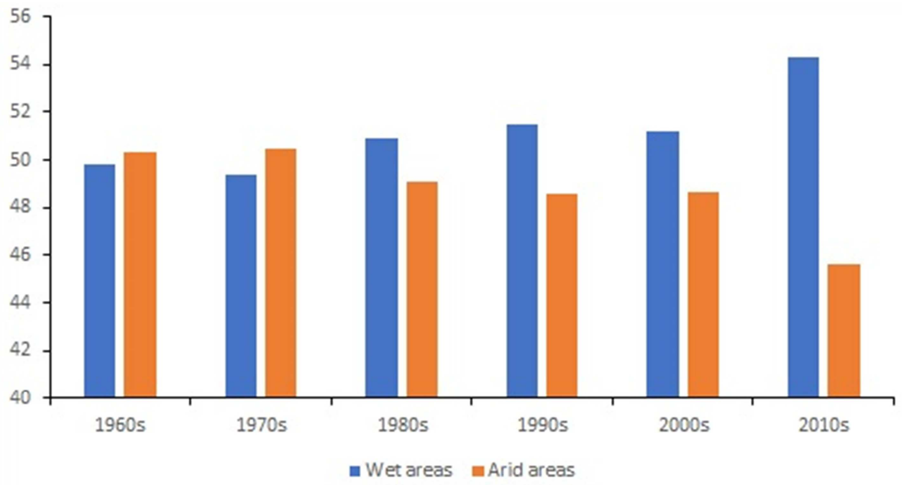

Figure 2. *The percentage change of arid areas (orange areas, including extremely arid, arid and sub-arid areas) and wet areas (blue areas, including sub-humid, humid and over-humid areas) in China from 1960s to 2010s. Unit: %.*

8. Discussion

Dry–wet climate division plays an important role in climate division work. With the progress of climate division work in China, dry–wet climate division has also experienced several development stages. Before the 1950s, people widely used precipitation to analyze the dry–wet climate in different regions when doing climate zone and dry-wet climate change research due to its simplicity and ease of use. Later, it was found that the amount of precipitation could not reflect the true dry–wet conditions in an area. Thus, scientists began to introduce evapotranspiration considering the water budget balance of a region comprehensively, and use an aridity index, or wetness index, to reflect dry–wet conditions and make a classification standard. The index considering evapotranspiration is applied to the analysis of national climate divisions, and the results are in good agreement with the natural landscape and natural geographical features in China.

The key to the calculation of the aridity index is determining the potential evapotranspiration. There are various calculation methods. This paper mainly compares the advantages and disadvantages of the Thornthwaite method, Holdridge method and Penman–Menteith method. Due to different research priorities or regions, the division standards and named methods for wet–dry degrees are also different.

There have been many discussions on the problem of evaporation paradox. Ding et al. [1] have proposed that the calculated potential evapotranspiration could not represent the actual evapotranspiration in one region. However, due to the limitation of observations on actual evapotranspiration in China, reasonable calculation models need to be constructed according to the evapotranspiration theory to obtain the actual evapotranspiration. Therefore, there is still much work to be done on the study of the laws and attributions of dry-wet climate change.

9. Conclusions

In order to reflect the climate change characteristics of the desert areas in Western China and the humid area in Southeast China, this paper divides the Chinese climate by the calculated aridity index into six degrees, namely extremely humid areas, with $AI<0.5$; wet areas, $0.5\leq AI<1.0$; sub-humid areas, $1.0\leq AI<1.5$; sub-arid areas, $3.5\leq AI<20.0$; and extremely arid areas with $AI\geq 20.0$.

The spatial distribution characteristics of the dry–wet climate in China were analyzed based on the average aridity index over the past 30 years, from 1981 to 2010. The results showed that the arid and semi-arid areas in China account for 48.8% of the total land area, which indicates that extremely arid area, arid area and sub-arid area account for 9.1%, 21.8% and 17.9% of the land area, respectively, mainly located in Xinjiang, Inner Mongolia, Tibet, Qinghai, Gansu and other western regions. The sub-humid, humid and extremely humid areas account for 14.6%, 27.8% and 8.8% of land area, respectively, and are mainly located in the South Yangtze River and part of Northeast China.

With the global climate change, the overall characteristics of dry-wet climate change is obvious in China from 1961 to 2018, the total arid areas show a decreasing trend, while the total wet areas show an increasing trend. The getting wet areas are mainly located in Northwest of China, due to a significant increase of precipitation in these areas since the 1980s.

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Conflicts of Interest

The author declares no conflict of interest.

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