

Variation Characteristics and Differences of Climate Dry-Wet Conditions and Soil Moisture in China: Postprint

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Abstract

Climatic wetness/dryness is an important indicator characterizing climate features, while soil wetness/dryness is a complex, multi-dimensional hydroclimatic concept; the two exhibit both differences and certain consistency. Against the backdrop of global warming, it is necessary to further investigate their evolution trends and differences. In view of this, we analyze the variation characteristics and differences between climatic wetness/dryness and soil wetness/dryness in China, clarifying the similarities and differences between the two. Using the humidity index, we examine the overall status and regionalization of climatic wetness/dryness in China, and analyze concurrent trends in soil wetness/dryness. The study reveals: (1) Over the past 60-plus years, the boundaries between different climate zones in China have not changed significantly; however, compared with the 1961–1990 climate normal period, an extensive climatic drying belt exists from west to east in northern China, where the humidity index shows a slight decreasing trend, though the magnitude of change has not yet reached the level required to alter climate classification. (2) The intra-annual variations of climatic wetness/dryness and soil wetness/dryness differ across climate zones in China, with significantly better consistency in humid and semi-humid regions than in semi-arid and arid regions; monthly variations in the difference between potential evapotranspiration and precipitation show distinct patterns across climate zones. For arid and semi-arid regions, March–September and March–June represent climatic dry periods with higher drought probability; semi-humid climate zones enter a water surplus stage in July–August, whereas humid climate zones remain in water surplus throughout the year except for individual months. (3) Significant differences exist between long-term changes in regional climatic wetness/dryness and soil moisture in China; the multi-year humidity index shows a slight increasing trend across all climate zones, while soil moisture predominantly exhibits a drying trend, indirectly indicating that

the potential drought risk for agricultural and pastoral production is increasing in different climate zones of China. The findings contribute to a comprehensive understanding of meteorological wetness/dryness and soil wetness/dryness, promoting further research on their relationship; they also help strengthen awareness of drought risk prevention and control, and improve drought-resistance measures for agricultural and pastoral production.

Full Text

Preamble

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Analysis of Changing Characteristics and Differences Between Climate Dry-Wet Conditions and Soil Moisture in China

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Abstract: Climatic dry-wet conditions are important indicators of climate characteristics, whereas soil dry-wet conditions represent a complex, multidimensional hydroclimatic concept. While both exhibit certain consistencies, significant differences exist between them. Against the backdrop of global warming, further investigation into their evolution trends and differences is necessary. This study analyzes the changing characteristics and differences between climate dry-wet conditions and soil moisture in China to clarify their similarities and distinctions. Using the humidity index, we examine the overall climate dry-wet status and regional zoning in China, while simultaneously analyzing soil dry-wet trends during the same period. The results indicate that: (1) Over the past 60 years, the boundaries between different climate zones in China have not changed significantly. However, compared with the 1961–1990 climate normal period, a vast climate drying zone exists from west to east in northern China, where the humidity index shows a slight decreasing trend, though the magnitude of change has not yet reached the threshold for altering climate classification. (2) The intra-annual variations of climate dry-wet and soil dry-wet conditions differ across climate zones in China, with the consistency between climate and soil conditions in humid and semi-humid zones being significantly better than that in semi-arid and arid zones. The monthly variations of the difference between

potential evapotranspiration (PET) and precipitation vary markedly among climate zones. For arid and semi-arid zones, March–September and March–June represent dry periods, respectively, when drought occurrence is more likely. The semi-humid climate zone enters a water surplus stage from July to August, whereas the humid climate zone remains in a water surplus state throughout the year, except for a few months. (3) Significant differences exist between long-term climate dry-wet changes and soil moisture changes across China. While the annual humidity index in different climate zones shows a slight increasing trend, most soil moisture exhibits a drying trend, particularly in shallow soil layers, suggesting that the potential drought risk for agriculture and animal husbandry is increasing across China's climate zones. These findings contribute to a comprehensive understanding of the relationship between meteorological dry-wet conditions and soil dry-wet conditions and promote further research on their interconnections. They also help strengthen drought risk prevention and control awareness and improve drought response measures for agricultural and pastoral production.

Keywords: climate dry-wet; soil moisture; change characteristics; differences; China

Introduction

Climatic dry-wet conditions and their long-term trends have always been important topics in climate research, holding significant meaning for understanding climate issues and providing crucial reference value for ecological environment and socioeconomic studies. Since Hulme defined the humidity index as the ratio of precipitation to potential evapotranspiration to assess global dryland changes, this index has been widely applied in climate change research. Numerous studies have focused on the evolution of climate dry-wet boundaries under global warming and future trends in global climate dry-wet conditions. At the national scale, researchers have comprehensively reviewed advances in climate zoning indicators, potential evapotranspiration calculation methods, and climate classification standards in China, revealing that the western segment of the 400 mm isohyet shows a wetting trend. Other studies have deeply investigated the summer monsoon transition zone at the climate dry-wet boundary, noting that climate dry-wet conditions in this region are significantly influenced by summer monsoon activity, with dry-wet conditions directly corresponding to summer monsoon strength.

On the other hand, research indicates that soil moisture ranks second only to sea surface temperature in climate change impacts, and over land, its role may even exceed that of sea temperature. Given that soil moisture can influence atmospheric circulation and climate by altering surface albedo, heat capacity, and atmospheric sensible and latent heat, while also affecting surface energy and water balance, scholars have paid considerable attention to soil moisture

climatology and conducted numerous studies. These studies have found that soil moisture in China shows an overall drying trend, with more significant drying in Northeast and southern China than in mid-latitude regions, and deeper soil layers drying more significantly than shallow layers. Analysis of decadal evolution characteristics of soil moisture in Northeast China, North China, and eastern Northwest China has revealed a drying trend in autumn soil moisture in northern China. Other research has documented regional characteristics and vertical distribution changes of soil moisture across China.

Although these studies have achieved remarkable results, climate dry-wet conditions focus on meteorological aspects, while soil dry-wet conditions, despite their significant role in climate change, emphasize agricultural aspects. Although closely related, significant differences exist between them. Recent research suggests that while drought and drylands both correspond to dry climates, sparse vegetation, and water shortages, terrestrial drought represents a complex, multidimensional hydroclimatic concept, whereas drought indices measure atmospheric aridity. These concepts must be distinguished in climate impact studies. Other studies have found that in the 21st century, temperate drylands may shrink and transform into subtropical drylands, and deep soils may become increasingly dry as vegetation adapts to climate change and transpiration intensifies. Therefore, comparative research on climate dry-wet and soil dry-wet conditions in China is necessary to analyze their changing characteristics and differences and clarify their trends. This study uses the humidity index to investigate overall climate dry-wet status and zoning changes in China while analyzing simultaneous soil dry-wet trends, aiming to draw attention to research on the differences and causes between climate dry-wet and soil dry-wet conditions in China.

2.1.1 Climate Zoning and Changes Based on Humidity Index

Based on the humidity index, China's climate zoning shows little change in dry-wet boundaries over the past 60 years. Comparing the climate normal period of 1991–2020 (color-filled) with that of 1961–1990 (outlined), the boundaries almost completely overlap [Figure 1: see original paper]. This indicates that, as measured by the HI index, China's climate dry-wet zoning has not changed significantly, with only small-scale differences in individual locations, such as the eastern edge of the arid zone in western Xinjiang contracting, the semi-arid zone in southern Hebei merging with the northern semi-arid zone in the 1991–2020 period, and the area of the closed semi-arid zone in the southwest shifting northward compared to the 1961–1990 period. Since the spatial pattern of dry-wet boundaries in China has changed little within the 60-year period, how have dry-wet conditions varied across climate zones in different periods? The following analysis addresses this question.

2.1.2 Temporal Trends of HI in Different Climate Zones

All climate zones in China show slight upward trends in HI over the years [Figure 2: see original paper]. The humid zone shows the most significant increase, followed by the semi-arid and semi-humid zones, while the arid zone shows the smallest upward trend in magnitude. Although the upward trends are slight across different climate zones in China, with climate tendency rates of only $0.003 \cdot (10a)^{-1}$, $0.005 \cdot (10a)^{-1}$, $0.005 \cdot (10a)^{-1}$, and $0.007 \cdot (10a)^{-1}$, respectively, the HI values themselves are very small, so these trends cannot be ignored in their impact on climate dry-wet degrees across different zones. The climate trend coefficients for arid and semi-arid zones pass the t-test at the $\alpha = 0.05$ significance level, while those for semi-humid and humid zones do not.

2.1.3 Spatial Changes of HI and Its Influencing Factors

Although [Figure 1: see original paper] shows that climate zoning in China remained essentially unchanged across the two climate normal periods, HI values in different regions are not static; the changes simply have not reached the magnitude required to alter climate classification. The difference in annual average humidity between the 1991–2020 and 1961–1990 climate states reveals a distinct climate drying zone extending from west to east across northern China [Figure 3: see original paper]. This zone includes parts of eastern Xinjiang and western Gansu, most areas east of the Yellow River in Gansu, Ningxia, Shaanxi, Shanxi, Beijing-Tianjin-Hebei, eastern Shandong, southwestern Liaoning, eastern Inner Mongolia, Chongqing, Henan, northern Hubei, most of Yunnan, Hainan, and most of Guangdong. Although the climate classification type has not changed in these regions, they exhibit a slight drying trend. This climate drying zone is also evident in climate state difference maps for other periods (figures omitted), with only slight variations in boundary range and overall coverage area. In contrast, the HI difference in the remaining regions of China shows an increase [FIGURE:3, green areas], indicating a slight wetting trend under unchanged climate types.

Since HI changes are directly related to precipitation and potential evapotranspiration, we analyze the changes in HI and its directly related factors—precipitation and PET—across the two climate states. Comparing precipitation across the two climate states in China, we characterize the change using precipitation change percentages. Although stations are sparse in arid and semi-arid zones, they generally show increasing precipitation trends, with the most recent climate state showing increases of less than 25% compared to the 1961–1990 period. In western and northern parts of the arid zone in Xinjiang, precipitation increases reach 25%–50%, which is significant. However, due to the small precipitation base, this cannot change the basic climate pattern of arid water shortage. In the humid climate zone, most areas show significant precipitation increases of less than 25% compared to the 1961–1990 period, though parts of southern Yunnan, Guangxi, and Guangdong show significant decreasing trends, corresponding to frequent droughts in southwestern China

in recent years. Most notably, in the semi-humid climate zone, most areas from southwestern China to the central and eastern regions show significant precipitation decreases ranging from -13% to -31%, far exceeding the -25% to 55% range of PET changes. Meanwhile, PET changes show less clear patterns than precipitation changes. Generally, PET in the arid climate zone tends to decrease, favoring relative wetting, while in the semi-arid zone, PET increases slightly by less than 10%, hindering wetting. In the semi-humid zone, PET decreases significantly in most areas, including eastern Northeast China, which, combined with precipitation increases, indicates wetting in eastern Northeast China. In contrast, other parts of the semi-humid zone show decreased precipitation and reduced PET, making the net effect on climate dry-wet conditions dependent on their relative changes. In the humid climate zone, PET increases and decreases are mixed without clear distribution patterns.

Since the relative changes in precipitation and PET determine climate dry-wet changes, we further clarify the causes of climate dry-wet changes across China. By comparing the increase/decrease patterns of precipitation and PET and their relative magnitudes, combined with HI changes, we classify the changes into categories [Figure 3: see original paper]. Different colors represent wetting (green) and drying (red) changes, with different symbols indicating corresponding precipitation and PET changes. In the arid climate zone (within red outlines), wetting is mainly type A (precipitation increase and PET decrease). In the semi-arid zone, patterns are unclear. In the semi-humid zone, eastern Northeast China, the Shandong Peninsula, and northern Yunnan are mainly type A, while southern Northeast China, southern Shaanxi, and eastern Gansu are mainly type D (precipitation decrease and PET increase). To clarify the results, we list the classification of changes and corresponding station proportions. Wetting stations account for nearly 46.6% of analyzed stations, while drying stations account for slightly more at 53.4%. Among wetting stations, those with precipitation increase and PET decrease account for the highest proportion at 35.7%, significantly higher than stations that become wet due to precipitation increase exceeding PET increase or precipitation decrease being less than PET decrease. Among drying stations, those becoming dry due to precipitation decrease and PET increase account for 33.1%, while stations where precipitation decrease exceeds PET decrease account for 14.6%. Stations where precipitation increase is outweighed by greater PET increase, leading to drying, are very rare at only 5.7% of all stations.

2.2 Soil Moisture Change Characteristics in China

Current research indicates that climate dry-wet conditions and soil moisture have a feedback relationship and mutually influence each other. Given the aforementioned climate dry-wet change characteristics across China's climate zones, how does soil moisture change, and are the characteristics consistent? We further analyze this question. Before using reanalysis soil moisture data, we compare it with measured soil moisture from selected agricultural meteorologi-

cal observation stations across different climate zones in China. The comparison shows good linear relationships [Figure 4: see original paper]. Taking four representative stations (Shouxian, Aihui, Youyang, Huailai) as examples, correlation coefficients between reanalysis soil moisture and measured soil water content percentage are 0.88, 0.82, 0.85, and 0.86, respectively, all passing significance tests at $\alpha = 0.001$. Combined with conclusions from other studies, reanalysis soil moisture data demonstrate good credibility for trend analysis, consistent with accuracy analyses conducted when using this data for China's terrestrial water budget research.

2.2.1 Soil Moisture Trends

Analyzing soil moisture climatic trends across China shows that soil moisture at different depths (0–7 cm, 7–28 cm, 28–100 cm, 100–289 cm) exhibits a consistent drying trend [Figure 5: see original paper]. The 7–28 cm layer shows the most significant drying trend, with climate trend coefficients consistently negative across all regions except individual areas where moisture increases, indicating uniformly decreasing soil moisture. The 0–7 cm layer shows a similar pattern. The 28–100 cm layer differs slightly in Northwest China, Sichuan, and parts of Northeast China. The 100–289 cm layer shows some differences, with slight increases in soil moisture across most of Northwest China, more pronounced in the 100–289 cm layer than in the 28–100 cm layer, primarily located in China's arid climate zone. In contrast, eastern Northeast China shows the opposite pattern, with the 0–7 cm layer showing wetting while deeper layers show drying. Overall, over the past 40 years, soil moisture has gradually decreased across most of China, with more pronounced drying trends in shallow soil layers. Using t-tests, stations passing significance tests account for 96.5% for the 0–7 cm layer, 90.3% for the 7–28 cm layer, 93.2% for the 28–100 cm layer, and 78.4% for the 100–289 cm layer, indicating widespread significant drying.

To further clarify regional soil moisture changes, we subtract the 1961–1990 climate state from the 1991–2020 period [Figure 6: see original paper]. Most regions in Northwest China show slight soil moisture increases in the climate state difference map, more pronounced in the 100–289 cm layer than in the 28–100 cm layer. Conversely, eastern Northeast China shows wetting in the 0–7 cm layer but drying in deeper layers. Overall, most of China shows a drying trend.

2.2.2 Temporal Changes of Soil Moisture in Different Climate Zones

Averaging soil moisture across four layers and analyzing multi-year trends by climate zone reveals that the arid climate zone shows a significant increasing trend from 1981–1995, with little change in subsequent decades. Due to this anomalous increase during 1981–1995, the linear trend appears upward but does not represent the actual soil moisture change trend in recent decades. In contrast, semi-arid, semi-humid, and humid climate zones all show consistent drying trends, most pronounced in the semi-humid zone [Figure 7: see original paper]. Climate tendency rates are $-0.003 \cdot (10a)^{-1}$, $-0.005 \cdot (10a)^{-1}$, $-0.005 \cdot (10a)^{-1}$, and

$-0.007 \cdot (10a)^{-1}$, respectively, all passing significance tests at $\alpha = 0.01$ (the arid zone rate is calculated from 1996 due to the 1981–1995 突变, while others are calculated from 1981).

2.3 Differences Between Climate Dry-Wet and Soil Moisture Changes

2.3.1 Intra-Annual Variations of HI and Soil Moisture in Different Climate Zones

The previous analysis shows spatial differences between HI and soil moisture across China's climate zones, and their multi-year changes are also inconsistent. Since main precipitation periods differ significantly across climate zones, intra-annual climate dry-wet differences are substantial, and soil moisture changes correspond with precipitation periods. How do climate dry-wet and soil moisture vary intra-annually across different climate zones? Does the impact of precipitation concentration periods on climate dry-wet and soil moisture remain consistent? We address these questions through analysis.

Comparing intra-annual variations of HI and soil moisture at different depths across climate zones reveals distinct patterns [Figure 8: see original paper]. In arid zones, 0–7 cm and 7–28 cm soil moisture fluctuates slightly, while 28–100 cm soil moisture shows almost no change throughout the year, and the 100–289 cm layer has higher moisture than deeper layers, indicating that deep soil moisture in arid zones never receives effective replenishment. This differs significantly from semi-arid zones. In semi-arid zones, soil moisture changes are relatively consistent across layers except for the deepest layer. In semi-humid and humid zones, HI and soil moisture changes are more consistent, though HI changes do not completely align with soil moisture trends.

2.3.2 Monthly Differences Between PET and Precipitation in Different Climate Zones

When precipitation exceeds PET in a given month, the corresponding period facilitates soil water replenishment. Comparing monthly PET minus precipitation differences across climate zones shows distinct patterns [Figure 9: see original paper]. In arid zones, PET minus precipitation is positive throughout the year, gradually increasing to a peak before decreasing. The increase begins in March, with differences exceeding 70 mm and rapidly rising to over 110 mm by May, then gradually decreasing from September back to 100 mm. This indicates that the main evaporation period in arid zones is March–September, with high evaporation causing greater drought likelihood, corresponding to the pattern that droughts can easily occur in all periods from spring to summer in this zone. Arid zones remain energy-dominated throughout most of the year, with precipitation consistently less than PET.

In semi-arid zones, the PET-precipitation difference peaks in March–June, ex-

ceeding 110 mm, then begins to decline from July but remains large, indicating that droughts are most likely in March–June, differing significantly from arid zones. The difference remains relatively stable at 40–60 mm. In semi-humid zones, PET exceeds precipitation from January to June. With the arrival of the concentrated rainfall period in July–August, precipitation surpasses PET, entering a water surplus stage. From September to December, PET and precipitation are very close, with differences maintained at about 20 mm. In humid zones, PET is less than precipitation throughout the year except for individual months, especially in July–August when PET is significantly lower than precipitation, maintaining a water surplus state. The maximum difference occurs in June–July, reaching 120 mm.

The intra-annual variations of PET-precipitation differences differ significantly across climate zones. Semi-humid zones show a clear rising-falling wave pattern, while humid zones show a clear falling-rising V-shaped pattern. Comparing [Figure 8: see original paper] and [Figure 9: see original paper] reveals that PET-precipitation difference trends are roughly opposite to HI intra-annual changes across climate zones.

2.3.3 Comparison of Climate Trend Coefficients Between HI and Soil Moisture

To further compare differences between climate dry-wet and soil moisture changes, we plot the percentage distribution of climate trend coefficients for HI and soil moisture across climate zones [Figure 10: see original paper]. Soil moisture climate trend coefficients are predominantly negative (left of the green line), showing a clear drying trend, with drying stations accounting for 96.5%, 90.3%, 93.2%, and 78.4% of analyzed stations for the 0–7 cm, 7–28 cm, 28–100 cm, and 100–289 cm layers, respectively. In contrast, HI climate trend coefficients are mostly positive (right of the green line), showing a wetting trend at 64.6% of stations, significantly different from soil moisture trends. This represents another major difference between climate dry-wet and soil dry-wet changes in China.

Although most regions show slight wetting trends, this does not fully correspond with soil moisture trends, indicating that climate wetting does not necessarily mean soil wetting. The two have essential differences, influenced by water cycle processes, surface energy, and vegetation effects, with clear mismatches between them. This reflects both the differences between climate dry-wet and soil moisture changes in China and the increasing potential drought risk for agricultural and pastoral production, corresponding to previous research conclusions that “agricultural drought is intensifying across China except in individual locations.”

3 Discussion

Global warming has increased surface evapotranspiration, intensified water cycle processes, and altered atmospheric circulation beyond current understanding.

The aforementioned analysis reveals clear differences between climate dry-wet and soil dry-wet conditions, influenced by multiple factors with complex causes. Clarifying their differences, especially their internal connections and influences, will be an important scientific research topic. Currently, several aspects require strengthening: (1) Fully recognize the differences between climate dry-wet and soil dry-wet conditions. (2) Strengthen research on water cycle processes under climate warming to deepen understanding of the mechanisms linking meteorological dry-wet and soil dry-wet conditions. (3) Given the gradual soil drying trend, promote adaptive agricultural technologies, rationally plan agricultural and pastoral layouts, improve drought resistance capacity, and strengthen risk prevention awareness. (4) Enhance water resource management, promote water-saving technologies, and improve water use efficiency.

Additionally, this study only analyzes the differential characteristics of climate dry-wet and soil dry-wet changes in China, without conducting quantitative analysis of their relationships or precise analysis of how meteorological elements quantitatively influence PET and resulting climate dry-wet changes. Future research will deepen these investigations and incorporate atmospheric circulation and oceanic factors affecting China's climate, such as the East Asian summer monsoon, Pacific Oscillation (PDO), Indian Ocean Basin Mode (IOBM), and Atlantic Multidecadal Oscillation (AMO), for multi-factor correlation studies to more comprehensively understand the differences between climate dry-wet and soil dry-wet changes in China.

4 Conclusions

Through analysis of changing characteristics and differences between climate dry-wet conditions and soil moisture in China, this study reaches the following main conclusions:

1. Over the past 60 years, boundaries between different climate zones in China have remained relatively stable. Although a vast climate drying zone exists from west to east in northern China, with HI showing a slight decreasing trend, the magnitude has not reached the threshold for changing climate classification, indicating that HI remains a stable and practical indicator for climate zoning.
2. Although climate zone boundaries remain stable, comparing different climate normal periods reveals that the vast climate drying zone in northern China has a slightly decreasing HI trend, though not sufficient to alter climate classification. Analysis of precipitation and PET changes shows that wetting due to precipitation increase combined with PET decrease, or precipitation increase exceeding PET increase, accounts for 63.4% of stations, while drying due to precipitation decrease combined with PET increase, or PET increase exceeding precipitation increase, accounts for 53.3% and 33.1% of stations, respectively.
3. Intra-annual variations of climate dry-wet and soil dry-wet conditions dif-

fer across climate zones, with better consistency in humid and semi-humid zones than in semi-arid and arid zones. Monthly PET-precipitation differences vary significantly: March–September and March–June are dry periods for arid and semi-arid zones, respectively; semi-humid zones enter water surplus in July–August; and humid zones remain in water surplus year-round except for a few months. Semi-humid zones show a rising-falling wave pattern in intra-annual PET-precipitation differences, while humid zones show a falling-rising V-shaped pattern.

4. Significant differences exist between long-term climate dry-wet changes and soil moisture changes across China. While HI shows slight increasing trends across climate zones, most soil moisture shows drying trends, particularly in shallow soil layers, indicating increasing potential drought risk for agriculture and animal husbandry across China's climate zones.

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Note: Figure translations are in progress. See original paper for figures.

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