Development of a Climate Warm-Wetting Evaluation Index and Its Application in Qinghai Province (Postprint)

Authors: Wang Yonghui, Ye Xiaojuan, Pan Hongzhong, Bai Yu, Dong Defu, Yao Huaming, Pan Hongzhong

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Abstract

A climate warming-wetting evaluation index was constructed by integrating meteorological elements, drought indices, and vegetation indices. Utilizing the Surface Humidity Index (Hi), Self-Calibrating Palmer Drought Severity Index (sc_{PDSI}), and annual Normalized Difference Vegetation Index (NDVI), a climate warming-wetting grade evaluation index was established based on data normalization methods. This index was then applied to comprehensively evaluate the spatiotemporal distribution grade changes of climate warming-wetting phenomena in Qinghai Province over the past 60 years, thereby verifying its applicability across different time series lengths and when incorporating various factors. The evaluation results indicate: (1) Over the past 60 years, the overall climate of Qinghai Province has been in a stage of significant warming and slight wetting; areas with significant warming-wetting are concentrated in parts of the southeastern Qilian Mountains, the southern to southeastern Yellow River basin, and the Lancang River basin; (2) Climate change over the past 60 years has not altered the climate warming-wetting and water resources distribution patterns of Qinghai Province; (3) This type of index exhibits good applicability and practicality for evaluating regional climate warming-wetting trends over long-term scales, and can objectively and timely reflect the climate warming-wetting conditions of the evaluated region.

Full Text

Construction of Climate Warming and Humidification Evaluation Index and Its Application in Qinghai Province

WANG Yonghui[1,2], **YE Xiaojuan**[1,2], **PAN Hongzhong**[1,2], **BAI Yu**[3], **DONG Defu**[3], **YAO Huaming**[1,2,4]

[1]Hubei Key Laboratory of Petroleum Geochemistry and Environment, Yangtze University, Wuhan 430000, Hubei, China
[2]College of Resources and Environmental Engineering, Yangtze University, Wuhan 430000, Hubei, China
[3]Huanghe Hydropower Development Co., Ltd., Xining 810000, Qinghai, China
[4]China Yangtze Power Co., Ltd., Yichang 443000, Hubei, China

Abstract

This study constructs a comprehensive climate warming and humidification evaluation index by integrating meteorological elements, drought indicators, and vegetation indices. Using the surface humidity index (Hi), self-calibrating Palmer Drought Severity Index (sc_{PDSI}), and annual Normalized Difference Vegetation Index (NDVI), we developed a climate warming-humidification grade evaluation index based on data normalization methods. This index was applied to comprehensively evaluate the spatiotemporal distribution and grade changes of climate warming-humidification phenomena in Qinghai Province over recent decades, verifying its applicability across different time series lengths and factor coverages. The evaluation results demonstrate: (1) Over the past 60 years, Qinghai Province' s climate has been in a stage of significant warming and slight humidification, with affected regions concentrated in parts of the Qilian Mountains in the southeast, the southern to southeastern Yellow River Basin, and the Lancang River Basin. (2) Climate change has not altered the fundamental distribution pattern of climate warming and water resources in Qinghai Province. (3) This index exhibits good applicability and practicality for evaluating regional long-term climate warming-humidification trends, capable of objectively and timely reflecting the warming-humidification status of the study area.

Keywords: Qinghai Province; climate warming and humidification; evaluation index

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1.1 Study Area Overview

Qinghai Province is located between 89°35 -103°04 E and 31°9 -39°19 N, situated in the alpine temperate semi-arid region with a plateau continental climate. The terrain is generally high in the west and low in the east, with high elevations in the north and south and lower elevations in the central region. The northwestern part of Qinghai is primarily the Qaidam Basin area, the western part is mainly the Hoh Xil Basin area, the southern part is the Three-River Headwaters region (including the Yellow River source area in southeastern Qinghai, the Yangtze River source area in southwestern Qinghai, and the Lancang River source area), and the northeastern part is the Qilian Mountains area. The province has complex topography, is far from the coast, and receives limited water vapor. Precipitation is scarce and concentrated mainly in spring and summer. The province' s multi-year average total water resources amount to approximately 629$×10^{8}$ m^3, accounting for about 2.2% of the national total, with rainfall as the primary source of water replenishment. Qinghai supplies water to downstream regions, accounting for 49% of the Yellow River' s total runoff, 25% of the Yangtze River' s total runoff, and 15% of the Lancang River' s total runoff, making it a crucial water source conservation area in China.

[Figure 1: see original paper] Map of Qinghai Province

1.2 Data Sources and Processing

Meteorological data were obtained from the CRU TS v.4.05 dataset provided by the Climate Research Unit at the University of East Anglia, with a temporal resolution of one month, spatial resolution of 0.5°$×0.5°, *andatimeserieslengthof*1960–2020.*Previousresearchhasdemonstratedthatthisdatasetcanbeeffec* for calculation and analysis. For this study, annual average values were extracted from the monthly and annual data using the maximum value composition method.

1.3 Methodology Construction

Taking Qinghai Province as the evaluation object and comprehensively considering meteorological factors, drought indicators, and vegetation changes, we employed data standardization methods to construct evaluation indices characterizing climate warming trends and comprehensive climate humidification trends based on multi-year average trends.

1.3.1 Climate Warming Trend Index (CWT) The climate warming trend index must intuitively indicate the degree of regional warming. Temperature is the primary factor in climate warming, significantly influencing regional evapotranspiration, glacier melt, and river runoff processes. There is a positive correlation between temperature and climate warming trend: higher temperatures indicate more significant warming trends, and long-term temperature changes can directly reflect the degree of climate warming. Considering the intuitiveness and representativeness of temperature elements and the simplicity of index calculation, we selected multi-year average temperature values for normalization processing to calculate the annual climate warming trend index using the following formula:

$$CWT = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}}$$

where x_i is the annual average temperature for year i; $x_{\max}$ is the maximum annual average temperature in the time series of length T years; $x_{\min}$ is the minimum annual average temperature in the time series of length T years; and CWT is the warming trend index for year i, with a value range of [0,1]. Larger values indicate more significant climate warming trends for year i within the T-year time series.

1.3.2 Climate Comprehensive Humidification Trend Index Climate humidification trends are more complex than warming trends, with more influencing factors. Single-factor trend changes cannot comprehensively evaluate humidification trends. Therefore, we integrated drought indices and vegetation indices with good applicability to characterize humidification trends and constructed a more comprehensive climate humidification trend index.

(1) Climate Humidification Trend Index (CHT)

The surface humidity index (Hi) is a key factor in evaluating humidification trends. Its significant increase indicates regional climate humidification, but because annual evaporation in Qinghai far exceeds annual precipitation, increased precipitation alone is insufficient to demonstrate climate humidification trends. Potential evapotranspiration (PET) was calculated using the Penman-Monteith method to obtain the surface humidity index (Hi = PRE/PET), which serves as a comprehensive factor of heat and water that can indicate surface climate dryness and wetness conditions. The Palmer Drought Severity Index (PDSI) demonstrates good adaptability in drought evaluation in Northwest China, but the self-calibrating Palmer Drought Severity Index (sc_{PDSI}) significantly improves spatial applicability by considering regional climate characteristic differences. This index incorporates not only precipitation and evapotranspiration but also soil water and runoff factors, providing a more comprehensive depiction of dry-wet climate changes in regional underlying surfaces. As an influencing factor, sc_{PDSI} can more comprehensively indicate spatiotemporal changes in regional humid climates.

The surface humidity index and sc_{PDSI} have different indicative meanings: the former indicates climate dry-wet changes, while the latter characterizes regional drought severity. Long-term climate dryness does not necessarily mean drought disasters will occur, and drought disaster areas are not always accompanied by climate dryness. Climate drought is often a long-term cumulative process that requires a certain lag time to respond to meteorological changes; regions with short-term climate wetness still have drought risk. Therefore, evaluating climate humidification must consider not only short-term climate dry-wet changes but also long-term drought risks. The CHT index includes both Hi and sc_{PDSI}, and its construction significance lies in comprehensively evaluating short-term climate dry-wet changes and long-term drought risks. In summary, higher values and annual increases in both indices indicate more significant climate humidification trends. The annual climate humidification trend index CHT is calculated as:

$$CHT = \frac{x_i y_i - (x_k y_k)_{\min}}{(x_k y_k)_{\max} - (x_k y_k)_{\min}}$$

where x_i is the annual average Hi value for year i; y_i is the annual average sc_{PDSI} value for year i; $(x_k y_k)_{\max}$ is the maximum product of annual average Hi and sc_{PDSI} values in the T-year time series; $(x_j y_j)_{\min}$ is the minimum product in the T-year time series; and CHT is the humidification trend index for year i, with a value range of [0,1]. Larger values indicate more significant climate humidification trends for year i within the T-year time series.

(2) Climate Comprehensive Humidification Trend Index (CHT*)

Climate warming and humidification leads to increased vegetation coverage. The Normalized Difference Vegetation Index (NDVI) can indicate regional vegetation coverage and is one of the most widely applied vegetation indices. Based on the climate humidification trend index CHT, adding an index representing vegetation coverage area (NDVI) to the humidification trend evaluation supplements ecological response elements and can more comprehensively reflect climate humidification degrees. Accordingly, we constructed the climate comprehensive humidification trend index CHT*, which includes the humidity index Hi, self-calibrating Palmer drought index sc_{PDSI}, and NDVI. Higher values and annual increases in these three factors indicate more significant climate humidification trends. The annual climate comprehensive humidification trend index CHT* is calculated as:

$$CHT^{*} = \frac{x_i y_i z_i - (x_k y_k z_k)_{\min}}{(x_k y_k z_k)_{\max} - (x_k y_k z_k)_{\min}}$$

where x_i is the annual average Hi value for year i; y_i is the annual average sc_{PDSI} value for year i; z_i is the annual average NDVI value for year i; $(x_k y_k z_k)_{\max}$ is the maximum product of the three indices in the T-year time series; $(x_j y_j z_j)_{\min}$ is the minimum product in the T-year time series; and CHT^{*} is the comprehensive humidification trend index for year i, with a value range of [0,1]. Larger values indicate more significant climate humidification trends for year i within the T-year time series.

Based on the climate warming trend index and climate comprehensive humidification trend index, we determined trend change grades according to numerical values. The grade classification standards are shown in . To better understand the temporal grade changes of warming-humidification indices in Qinghai Province over the past 60 years, we conducted annual grade change analysis to grasp the overall climate warming-humidification trends. Since different regions within the province have significantly different climatic and geographic conditions, leading to varying warming-humidification trends and degrees, we also evaluated spatial grade changes across different regions over the past 60 years to reveal regional patterns of spatial warming-humidification changes. The analysis period was 1960–2020.

Evaluation criteria and influencing factors of climate warming and humidification trend index

Warming Trend Index	Humidification Trend Index	Comprehensive Humidification Trend Index	Influencing Factors
(0,0.2]	(0,0.2]	(0,0.2]	Grade 1
(0.2,0.4]	(0.2,0.4]	(0.2,0.4]	Grade 2
(0.4,0.6]	(0.4,0.6]	(0.4,0.6]	Grade 3
(0.6,0.8]	(0.6,0.8]	(0.6,0.8]	Grade 4
(0.8,1]	(0.8,1]	(0.8,1]	Grade 5

2.1 Climate Warming Trend Evaluation

2.1.1 Temporal Variation Analysis Comparing different time series lengths (60-year and 33-year annual average temperature sequences), we calculated Qinghai Province’ s annual climate warming trend index CWT. The grade change trends of both indices ([Figure 2: see original paper]) show that Qinghai Province’ s climate warming trend is very significant, with 1998 being an important turning point. Before this year, grade 3 was the dominant warming grade with low frequency of grade 4; after 1998, grade 4 appeared frequently, showing a fluctuating increasing trend. The 60-year and 33-year warming grade comparisons ([Figure 3: see original paper]) show that after 1998, the frequency of grade 4 increased significantly. The annual warming evaluation grades over the past 33 years are very similar to those over the past 60 years, indicating that time series length has minimal impact on the climate warming trend index CWT. This stability is one manifestation of the index’ s good applicability.

The minimum annual average temperature in Qinghai Province in recent years is also a major reason for the significant warming trend. The spatial distribution of high warming grade areas in 2020 is mainly located in the northwestern Qaidam Basin area and the eastern Yellow River source area of Qinghai Province, with warming grade 4. Low-value areas are mainly located in the western Hoh Xil Basin area and the northeastern Qilian Mountains area, with warming grade 2. The remaining areas are medium-value areas with grade 3, covering most of Qinghai Province. The spatial distribution of warming grades in 2020 shows a polarization trend, with grade 4 areas significantly expanding while grade 3 areas within medium and low-value zones also increasing substantially. This indicates significant warming trends in the northwestern Qaidam Basin and southeastern Yellow River source area, while cooling trends expand in the Qilian Mountains, Hoh Xil Basin, and parts of the Yangtze River source area. In subsequent years, the warming range of high-value areas decreased, but the warming grade distribution pattern remained relatively stable. By 2020, except for local areas in the western Hoh Xil Basin, all other regions in Qinghai Province reached warming grade 3 or above. The spatial distribution pattern of warming grade 3 and above has not changed significantly over the past 60 years ([Figure 3: see original paper]).

[Figure 2: see original paper] Grade change of CW60 and CW33 climate warming trend index in Qinghai Province from 1960 to 2020

[Figure 3: see original paper] Spatial trend change of CW60 climate warming trend index in Qinghai Province from 1960 to 2020

2.2 Climate Humidification Trend Evaluation

2.2.1 Temporal Variation Analysis Based on CHT The CHT index changes ([Figure 4: see original paper]) show that Qinghai Province' s humidification trend grade remained at grade 2 from 1960 to 2020, with periodic fluctuations and small variations, mainly concentrated in grades 1-2, with grade 3 appearing rarely. After 1988, the evaluation grade stabilized around grade 2, with variation amplitude not exceeding one grade. After 2002, years with grade 3 increased significantly; after 2010, the evaluation grade showed a fluctuating increasing trend, indicating that Qinghai Province' s climate had begun to show slight humidification, with subsequent years stabilizing. The grade first reached grade 3 in 2012, then decreased significantly in 2015, but remained at grade 2 in other years. Overall, the CHT grade changes over the past 60 years indicate that Qinghai Province' s climate has shown a slight humidification trend.

The evaluation grades of CHT60 and CHT33 in the same years show that CHT33 grades are lower than CHT60 grades, with grade differences maintained within one level. The main reasons for these differences are: first, the humidification trend during 1982-2015 was more significant than during 1960-2020; second, the time series is shorter. However, this does not affect CHT' s evaluation results for humidification trends in the same area with different time series lengths. This demonstrates that CHT evaluation results are minimally affected by time series length.

The spatial pattern distribution of CHT grades lacks obvious regularity ([Figure 5: see original paper]). In 2020, the humidification grade in Qinghai Province was extremely low, between grades 1-2. The Lancang River source area maintained grade 2, while local areas in the southeastern Yellow River source area and southwestern Yangtze River source area reached grade 3, showing a clear northwestward expansion of humid grades. In the 1980s, Qinghai Province' s climate humidification grade showed large-scale reduction, with the Yellow River source area reducing to grade 1 and the Lancang River source area maintaining grade 2. After the 1990s, the humidification grade showed no significant changes. In the 2000s, the humidification grade significantly increased, with the northwestern Qaidam Basin and Qaidam Basin area reaching grade 3, and the Qilian Mountains area showing a significant increasing trend to grade 3. The humidification grades in the Three-River Headwaters region and southwestern areas reached grade 3, with ranges expanding westward. Central areas remained at grade 2, with obvious north-south differentiation: southern areas had higher humidification grades than northern areas. In the 2010s, the humidification grade distribution was similar to the 2000s, with the Lancang River source area having higher grades than other regions. After 2015, Qinghai Province' s humidification grade showed large-scale improvement, with grades in the northern Qaidam Basin to northeastern Qilian Mountains area increasing to grade 3, and the trend spreading southward, with large-scale improvement in the Three-River Headwaters region. By 2020, humidification grades in southern and northeastern Qilian Mountains areas reached grade 3, while other areas remained at grade 2. This large-scale increasing trend did not continue, and by 2020, except for some eastern Qilian Mountains areas maintaining grade 3, all other areas remained at grade 2.

[Figure 4: see original paper] Grade change of CH60 and CH33 climate humidification trend index in Qinghai Province from 1960 to 2020

[Figure 5: see original paper] Spatial trend change of CH60 climate humidification trend index in Qinghai Province from 1960 to 2020

2.2.2 Temporal Variation Analysis Based on CHT* The CHT* index grade changes ([Figure 6: see original paper]) show that before 1982, Qinghai Province' s index grade change trend was unstable, maintaining grade 2. After 1982, the index grade stabilized at grade 2 and showed a slow increasing trend, with years above grade 3 increasing significantly after 1998. The humidification grade increased substantially after 2002, then declined after 2010, with grades maintaining grade 2. CHT* indicates that Qinghai Province' s climate entered a slight humidification stage in 1998.

[Figure 6: see original paper] Grade change of CH33* climate humidification trend index in Qinghai Province from 1981 to 2019

2.2.3 Spatial Variation Analysis Based on CHT* The spatial variation of CHT* grades in 2015 ([Figure 7: see original paper]) shows that humidification grades in the Qilian Mountains and parts of the Three-River Headwaters region increased significantly, with grades gradually increasing from northwest to southeast. CHT* shows good consistency with CHT.

[Figure 7: see original paper] Spatial trend change of CH33* climate humidification trend index in Qinghai Province from 1960 to 2020

2.2.4 Comparative Analysis of CHT and CHT* Evaluation Results Temporal Variation Comparison

Comparing the humidification grade indices CH33 and CH33* over the years ([Figure 8: see original paper]), under the same time series length, most years show consistent humidification grades. In 1998, the grade difference reached two levels, mainly due to the substantial decrease in Qinghai Province' s annual average NDVI value, reflecting the lagged response of vegetation changes to climate humidification. Both indices show that Qinghai Province' s humidification trend began to stabilize at grade 2 after 1998, with slight humidification trends stabilizing by 2010.

[Figure 8: see original paper] Grade change comparison of CH33 and CH33* climate humidification trend index in Qinghai Province from 1981 to 2019

Spatial Variation Comparison

Comparing the spatial changes of CH33 and CH33* grades (1982–2015), both show that in 2015, the Qilian Mountains area and parts of the Three-River Headwaters region experienced significantly increased climate humidification, with grades gradually increasing from northwest to southeast. CHT* shows good consistency with CHT.

3.1 Evaluation of Climate Warming-Humidification Trends in Qinghai Province Over the Past 60 Years

The CWT grade changes show that since 1998, the entire province has experienced continuous warming, particularly significantly in 1998. The spatial variation of annual average temperature grades shows different warming trends across regions: the Qaidam Basin area and eastern Yellow River source area of Qinghai Province have experienced continuous significant warming trends, the Lancang River source area shows continuous slight warming trends, while the Yangtze River source area and western Hoh Xil Basin show non-significant warming trends. The CWT index changes are primarily determined by annual average temperature, which aligns with findings by Yi Junlan et al. that annual average temperatures are higher in eastern agricultural areas and the Qaidam Basin of Qinghai Province, and lower in the Qilian Mountains and southern Qingnan areas.

The humidification grade shows a general improvement of one level across the province spatially, but the distribution pattern and interannual variation are very similar. The humidification trend became apparent after 1988, and after 2002, the province' s humidification grade showed fluctuating increases, indicating that Qinghai Province' s climate had entered a slight humidification stage, with subsequent grades stabilizing. By 2020, Qinghai Province' s climate humidification trend remained in a slight humidification state.

The spatial variations of the two humidification indices show different regional humidification degrees and amplitudes: over the past 60 years, Qinghai Province' s climate humidification trend spatial variation amplitude has been volatile, showing periodic changes. In the early 1980s, a humidification trend emerged in the Qilian Mountains area, Yellow River source area, Lancang River Basin, and parts of the Qaidam Basin to central areas. After the 1990s, the humidification trend weakened, with more humid areas shrinking to parts of the Three-River Headwaters region and northern Qilian Mountains area, while the Yellow River Basin' s southeastern region showed significant improvement. Qinghai Province' s climate humidification trend over the past 60 years has shown a pattern of non-significant—slightly significant—non-significant—slightly significant changes, while the spatial distribution pattern of regional humidification lacks obvious regularity.

High warming degree areas in the province are concentrated in the Qaidam Basin area and eastern Yellow River source area of Qinghai Province. The former is due to the unique geographical structure of the Qaidam Basin creating an arid climate with long-term temperatures higher than other regions, while the latter is due to urbanization construction in the region. The significant warming and humidification in the Three-River Headwaters region is likely caused by climate warming leading to snow and glacier melt, increasing total water resources and accelerating regional water vapor cycles, resulting in increased rainfall and vegetation coverage. Human factors also influence regional climate humidification trends: Qinghai Province began implementing the Grain for Green project in 2000 and the "Qinghai Three-River Headwaters Nature Reserve Ecological Protection and Construction Master Plan" in 2005, both playing significant roles. Liu Caihong et al., based on homogenized temperature and precipitation data in the Yellow River source area from 1960–2019, also pointed out that the climate warming-humidification trend in the Yellow River source area has been particularly significant in recent years, with annual precipitation being the main climatic factor affecting annual runoff. The significant warming-humidification trend has major implications for biodiversity conservation in the Three-River Headwaters region and development in Qinghai and downstream provinces, but how to utilize this trend for rational development planning has become a new challenge. Additionally, the intensifying warming-drying trend in the Qaidam Basin area remains unfavorable for ecological development in Qinghai Province in the new era.

Comprehensive comparison reveals that areas with climate warming-humidification in the province share characteristics of minimal human disturbance, high vegetation coverage, and abundant water resources. Among them, the Lancang River source area and Yellow River source area of Qinghai Province show the most significant warming-humidification trends, which is related to high vegetation coverage and abundant water resources (glaciers, snow, wetlands, etc.). However, according to Zhang Qiang et al.' s prediction analysis of future climate wetting trends in Northwest China, the wetting trend in Northwest China will slow down or even disappear, which aligns with the interannual climate humidification trend variation pattern proposed in this study for Qinghai Province. This poses a significant challenge for future water resource planning and utilization in the Three-River Headwaters region. Many studies have shown that the current climate warming-humidification trend has not changed the existing climate pattern in Northwest China, but the future development of this trend remains uncertain.

3.2 Applicability Analysis of Climate Warming-Humidification Indices

Climate warming-humidification trend evaluation indices show minimal differences in evaluation results under different time series lengths, which does not affect the overall trend evaluation results. Under the same spatiotemporal scale, the climate humidification index CHT* that covers different factors evaluates higher humidification grades and is more sensitive. The limitations of these indices are: first, the index calculation does not consider the weights of influencing factors. Assigning different weights to different influencing factors for different evaluation regions could make the evaluation results more reasonable. Second, in spatial variation analysis, the interpolation method used for the distribution of influencing factors across the province dilutes the local impacts of the special warming-humidification climate. Using meteorological data from corresponding meteorological stations for different regions could improve evaluation accuracy. The climate warming-humidification trend in Qinghai Province and even Northwest China is a complex change caused by the coupling of meteorology, ecology, and human activities. Future evaluations could consider more influencing factors to establish more comprehensive climate warming-humidification evaluation methods.

4 Conclusions

1) Over the past 60 years, Qinghai Province' s overall climate trend has been in a stage of significant warming and slight humidification. The most significant warming-humidification trends are found in parts of the southeastern Qilian Mountains, the southern to southeastern Yellow River source area, and the Lancang River source area. However, evaluation results from the past 60 years show that the basic climate warming-humidification distribution pattern in Qinghai Province has not changed.

2) The climate warming-humidification evaluation index based on data normalization processing demonstrates good applicability and practicality in evaluating climate warming-humidification changes in Qinghai Province over the past 60 years. It is not only suitable for evaluating warming-humidification trends in areas with limited data series and few indicator factors but also enables rapid evaluation of regional warming-humidification degrees annually. Compared with existing methods, even with low data series accuracy, this index can still determine regional warming-humidification status changes based on overall trends of indicator factors.

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