Climatic Warming and Humidification in the Arid Region of Northwest China: Multi-Scale Characteristics and Impacts on Ecological Vegetation

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ABSTRACT

The climatic warming and humidification observed in the arid region of Northwest China (ARNC) and their impacts on the ecological environment have become an issue of concern. The associated multi-scale characteristics and environmental responses are currently poorly understood. Using data from satellite remote sensing, field observations, and the Coupled Model Intercomparison Project phase 6, this paper systematically analyzes the process and scale characteristics of the climatic warming and humidification in the ARNC and their impacts on ecological vegetation. The results show that not only have temperature and precipitation increased significantly in the ARNC over the past 60 years, but the increasing trend of precipitation is also obviously intensifying. The dryness index, which comprehensively considers the effects of precipitation and temperature, has clearly decreased, and the trend in humidification has increased. Spatially, the trend of temperature increase has occurred over the entire region, while 93.4% of the region has experienced an increase in precipitation, suggesting a spatially consistent climatic warming and humidification throughout the ARNC. Long-term trends and interannual changes in temperature and precipitation dominate the changes in climatic warming and humidification. Compared to interannual variations in temperature, the trend change of temperature contributes more to the overall temperature change. However, the contribution of interannual variations in precipitation is greater than that of the precipitation trend to the overall precipitation change. The current climatic warming and humidification generally promote the growth of ecological vegetation. Since the 1980s, 82.4% of the regional vegetation has thrived. The vegetation index has a significant positive correlation with precipitation and temperature. However, it responds more significantly to interannual precipitation variation, although the vegetation response varies significantly under different types of land use. The warming and humidification of the climate in the ARNC are probably related to intensifications of the westerly wind circulation and ascending air motions. They are expected to continue in the future, although the strength of the changes will probably be insufficient to significantly change the basic climate pattern in the ARNC. The results of this study provide helpful information for decision making related to China’s “Belt and Road” development strategies.

Key words: arid region of Northwest China (ARNC), climatic warming and humidification, ecological vegetation, multi-scale, synergistic effect

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1. Introduction

The arid region of Northwest China (ARNC) is located in the midlatitude and comprises complex terrains of the Gobi Desert and its surrounding arid areas. The ecosystems of this area are fragile and sensitive to climate change, which makes it one of the world’s key locations for studying the effects of global climate change on the environment (Zhang et al., 2010). The eco-environment and water resources in this region respond significantly to climate change, leading to distinct impacts on social and economic developments. Therefore, climate change and its impact on the ecological environment in this region have long been issues of concern for both scientists and the government (Ye and Huang, 1991; Qian et al., 2001).

Many studies have been carried out on climate change in the ARNC (Xu, 1997; Li et al., 2003). In the past, a consensus was that the climate of the ARNC had been drying throughout the 20th century. Although a few studies revealed an increase in precipitation (Zhai et al., 1999), it received little attention. At the beginning of the 21st century, Shi et al. (2002) proposed that climate change in the ARNC was shifting from warm–dry to warm–wet, which aroused a widespread concern. However, the increase in precipitation was relatively small and only occurred during a short period. No convincing explanation for the mechanism behind the precipitation increase has been proposed, and no broad consensus on climatic warming and humidification in the ARNC has been reached (Zhang et al., 2010).

More recently, progress has been made in the study of climatic warming and humidification in the ARNC (Ma et al., 2018). Based on analysis of measured data, Ren et al. (2016) demonstrated that precipitation in the ARNC has a significant increasing trend in the past 60 years. Zhang et al. (2019) also found that precipitation in the western part of the ARNC has been increasing all the time, which shows a seesaw variation pattern with precipitation in the semi-arid area of the eastern part of the ARNC during flood seasons. Meanwhile, some other studies investigated vegetation responses to temperature and precipitation changes in different regions and seasons (Wei et al., 2014; Zhou et al., 2015). Correlations of vegetation with temperature and precipitation are more significant over longer timescales (Jia et al., 2019). The precipitation increase in the ARNC has occurred on a timescale longer than the 30-yr climatology, and has visibly affected ecological vegetation. Therefore, the issue of climatic warming and humidification in the ARNC is now fully recognized and has attracted much attention.

However, climate change in the ARNC is a relatively complex issue. The observed warming and humidification changes are not a linear process at a single scale. Instead, they demonstrate nonlinear and multi-scale features. At small scales, increases in precipitation may accelerate, decelerate, or even change abruptly. Moreover, the factors that control climate change may differ at different timescales. The vegetation in the ARNC is very sensitive to changes in temperature and precipitation (Asrar et al., 1984), and therefore can behave as an indicator of climate change (Zheng, 2002). Due to the coupling and optimal matching between the physiological and ecological characteristics of vegetation and the hydrothermal characteristics of climate, impact of climate change on ecological vegetation is often a double-edged sword. The relationship between them is not simple and is often constrained by synergistic effects between climate conditions, vegetation types, and climate factors (Fang et al., 2004). In addition, climate change in the ARNC is affected by not only different atmospheric circulation systems, but also thermal–dynamic effects of the Qinghai–Tibetan Plateau. The regional land–atmosphere interaction is also an essential factor that cannot be ignored when discussing climate change in the ARNC. The current internationally popular viewpoint that “dry areas will become drier, and wet areas will become wetter” [i.e., climate change is following its current trend (Nicholson et al., 1998)] and the explanation of this climate change trend (Nicholson and Grist, 2001) are widely accepted by the scientific community. However, the phenomenon of warming and humidification in the ARNC is not consistent with this hypothesis, which imposes a challenge for climate change study in this region.

The acceleration of climatic warming and humidification in the ARNC and the factors controlling this trend are therefore worthy of studying. Also, there is still little understanding of the general impact of climatic warming and humidification on ecological vegetation under different types of land use. Therefore, the mechanisms for the warming and humidification trend in the ARNC, whether these changes will continue, and what impact they may have in the future, remain to be discovered.

In the present study, satellite remote sensing data, field observations, and integrated data from the Coupled Model Intercomparison Project phase 6 (CMIP6) are combined to analyze the characteristics and scales of the warming and humidification process in the ARNC. We focus on the synergistic impact of temperature and precipitation changes on ecological vegetation under the climatic warming and humidification. Exploration of the
mechanisms behind these changes and discussion of the climatic warming and humidification trend in the ARNC can provide essential scientific and technological support to the planning of long-term development in the ARNC and implementation of China’s “Belt and Road” development strategies.

2. Data and methods

2.1 Study area

The ARNC refers to the area with annual mean precipitation below 250 mm (Fig. 1; Huang et al., 2017a). It covers a total area of about 2.8 million km², which accounts for about 27.3% of China’s land area. This region includes the Xinjiang Uygur Autonomous Region, the Hexi Corridor of Gansu Province, the Qaidam basin, the Qilian Mountains of Qinghai Province, the Alashan Plateau of Inner Mongolia, and the western section of Ningxia Autonomous Region to the west of the Yellow River.

The ARNC has complex geomorphology and diverse topography such as mountains, inland basins, and deserts. The vegetation in the area is poor, and the limited vegetation is mainly distributed in the mountains and oasis areas. Desert, grassland, and cultivated land account for about 65.13%, 25.10%, and 2.07% of the entire region, respectively.

2.2 Data

The calculations and analyses in this paper are based on four types of data: 1) observed data collected at meteorological stations, 2) atmospheric circulation data, 3) vegetation data retrieved from satellite remote sensing, and 4) climate prediction data for future climate change scenarios. The observed data collected at meteorological stations are provided by the National Meteorological Information Center of China Meteorological Administration. These data are collected at 91 stations in the ARNC, including routine meteorological measurements such as the average daily temperature, maximum temperature, minimum temperature, precipitation, wind speed, relative humidity, and number of sunshine hours for the period of 1961–2018. The data went through uniform quality control and homogenization to ensure the representativeness and the consistency of time series (Li et al., 2010; Yang and Li, 2014). The atmospheric circulation data, including geopotential height, wind, and vertical velocity fields in 1961–2018 (Kalnay et al., 1996), are extracted from the NCEP/NCAR reanalysis product (http://www.cdc.noaa.gov/data/gridded/data.ncep.reanalysis.html).

The satellite remote sensing data of vegetation are extracted from the third-generation, global coverage Normalized Difference Vegetation Index dataset (NDVI 3g) released by NASA’s Global Inventory Modeling and Mapping Studies (GIMMS). The dataset includes daily global gridded data generated after various processing of orbit screening, radiation calibration, cloud detection, atmospheric correction, satellite drift correction, and the bidirectional reflectance distribution function (BRDF). The original dataset is collected by the Advanced Very High-Resolution Radiometer (AVHRR) sensor onboard the NOAA series of meteorological satellites. The spatial and temporal resolutions of the data are about 8 km and 15 days, respectively. The data cover the period of 1981–2015. It is the world’s most extensive remote sensing data of vegetation. This dataset has used the Maximum Value Composite (MVC) method to maximize the semi-monthly synthetic standard NDVI data and obtain annual NDVI data. The measurement error of the data is constrained within ±0.005 (Pinzon and Tucker, 2014). In order to facilitate the analysis of temperature and precipitation in this paper, the NDVI gridded data are interpolated to the 91 weather stations in the ARNC.

Estimates of future climate change scenarios are obtained from multi-model ensemble simulation of 13 climate models that participated in CMIP6, in the medium development Shared Socioeconomic Pathway and stable
Representative Concentration Pathway (SSP2-RCP4.5). The SSP2 scenario is the closest to the present climate and the RCP4.5 may represent the scenario in the future. In addition, there are significant differences between the estimation results of temperature and precipitation under different emission scenarios. As the emission intensity increases, the increases in temperature and precipitation become more significant (Eyring et al., 2016; O’Neill et al., 2016). The model data cover the period of 2015–2099. The gridded data from the ensemble model simulations (https://esgf-node.llnl.gov/projects/cmip6/) are interpolated to the 91 meteorological stations in the ARNC. Due to the large uncertainties in the estimated results of a single model, we choose as many as possible model members to perform ensemble averaging, which effectively reduces the uncertainties and the impacts of internal variability. Since the results of ensemble model members uploaded to the CMIP6 website are still relatively small, all the simulations of the 13 models uploaded have been selected for ensemble averaging. In order to improve the applicability of the CMIP6 multi-model ensemble results in the ARNC, we have performed comparative analyses of monthly correlations between the CMIP6 multi-mode ensemble data and the observed station data for the period 2015–2018 (Fig. 2). It is found that the model data are well correlated with observations, but the temperature values of the CMIP6 multi-model ensemble results are slightly lower than the observations. In contrast, precipitation values in the CMIP6 multi-model ensemble results are significantly higher than the observations. Therefore, we applied linear fitting algorithms to the CMIP6 multi-model ensemble data and the station observed data to correct temperature and precipitation for the period 2019–2099, respectively.

\[ T = 0.96 \times t_y + 1.99, \]  
(1) 
\[ P = 0.66 \times p_y - 3.85, \]  
(2)
where \( T \) and \( P \) are the corrected temperature and precipitation values in units of °C and mm, respectively; while \( t_y \) and \( p_y \) are the original temperature and precipitation values of the CMIP6 multi-model ensemble results in units of °C and mm, respectively.

2.3 Methods

2.3.1 Factors

The dryness index is defined by following the approach of Zhang et al. (2016):

\[ I_{AI} = \frac{E_{TO} - P_{RE}}{E_{TO}}, \]  
(3)
where \( I_{AI} \) is the dryness index; \( E_{TO} \) is potential evaporation in mm, which is derived from the Penman–Monteith model (Paredes et al., 2018); and \( P_{RE} \) is precipitation in mm. This index has been tested in the ARNC and demonstrates a good applicability.

Following Li et al. (2008), we define the westerly index \( (W_I) \) as the difference between the zonally averaged \((70^\circ–110^\circ)\) 500-hPa geopotential height fields along latitudes 35° and 50°N. It is expressed as

\[ W_I = \frac{1}{17} \sum_{\lambda=1}^{17} H(\lambda, 35^\circN) - \frac{1}{17} \sum_{\lambda=1}^{17} H(\lambda, 50^\circN), \]  
(4)
where \( W_I \) is the westerly index in gpm; \( H \) is the average geopotential height field at 500 hPa, in gpm; and \( \lambda \) is the longitudinal interval of 2.5° along the specified latitude.

2.3.2 Ensemble Empirical Mode Decomposition (EEMD)

The principle of EEMD is to average the measured values of multiple decompositions (i.e., add white noise of an appropriate size to the original data to simulate

Fig. 2. Correlations of (a) temperature and (b) precipitation between the CMIP6 multi-model ensemble results and the observed values.
multiple observations; and then average the dataset after iterative calculations). EEMD is the improvement of the empirical mode decomposition (EMD). The EMD method is suitable for processing non-stationary data sequences. It can obtain the intrinsic mode function (IMF) components, which are a series of data sequences with different characteristic timescales, through decomposing the fluctuations and trends of various scales in the original signal. In signal analysis, although the EMD method has obvious advantages, it also has defects such as edge effects and scale mixing. Using a new noise-assisted data analysis method (i.e., EEMD) can effectively solve the scale mixing problem in EMD. In order to avoid scale mixing and obtain physically unique IMF components, EEMD uses Gaussian white noise to average the dataset. Each IMF component needs the following two premises. (1) In the entire analysis period, the number of local extreme points and the number of zero-crossing points must be the same; if the two numbers are different, the difference must not exceed 1. (2) At any time, the average value of the envelope line determined by the local maximum and minimum must be equal to 0. Currently, the EEMD method has been widely used (Huang and Shen, 2005; Wu and Huang, 2009; Bi et al., 2018).

3. Characteristics of climatic warming and humidification in the ARNC

Many studies have analyzed the trends of climatic warming and humidification in the ARNC and a relatively consistent understanding of the trends has emerged (Liu et al., 2011; Ren et al., 2016). Here, we focus on a further examination of these phenomena, and analyze the processes involved and multi-scale characteristics of climatic warming and humidification and their spatial distribution patterns in the ARNC.

3.1 Processes and distributions of climatic warming and humidification in the ARNC

The variations in temperature, precipitation, and dryness index in the ARNC during 1961–2018 are plotted to examine the specific processes of warming and humidification in this region (Fig. 3). Temperature and precipitation have shown consistently increasing trends over the past 60 years. The rate of temperature increase is 0.34°C (10 yr)^{-1}, and the precipitation increase rate is 7.7 mm (10 yr)^{-1}, which in general agree with other studies (Ren et al., 2016). The dryness index decreases continuously over the past 60 years, indicating a climatic warming and humidification trend. The evapotranspiration increase caused by temperature increase behaves to offset the effect of precipitation increases. However, the precipitation increase alone is not sufficient to explain the trend of humidification. The overall change in climate is better expressed by the dryness index, which combines the effects of temperature and precipitation to demonstrate the overall trend of climatic warming and humidification in the ARNC.

It is worth noting that the changes in precipitation and dryness index are not linear. The precipitation increase is relatively constant during 1961–1986 with a rate of about 3.5 mm (10 yr)^{-1}, but accelerates significantly after 1986 with a rate of about 10.2 mm (10 yr)^{-1}. The dryness index only slightly decreases during 1961–1986, but starts to decrease significantly after 1986. There is a similar characteristic in the decadal changes of precipitation and the dryness index (Fig. 3).

Because a 30-yr period is the standard timescale for calculating climate averages, we divide the approximately 60 years of data into two sets: 1) 1961–1990 and 2) 1991–2018. This results in a more precise analysis of the increasing and decreasing trends of changing character-

![Fig. 3. Changes in (a) temperature, (b) precipitation, and (c) the dryness index during 1961–2018.](image-url)
The rates of precipitation and temperature increases during 1991–2018 are 10.5 mm (10 yr)$^{-1}$ and 0.3°C (10 yr)$^{-1}$, respectively; while those during 1961–1990 are only 5.6 mm (10 yr)$^{-1}$ and 0.19°C (10 yr)$^{-1}$. The rates of both precipitation and temperature increases during 1991–2018 are almost twice those during 1961–1990. The rate of the dryness index change during 1991–2018 is −0.014 (10 yr)$^{-1}$, which, compared with the rate of −0.011 (10 yr)$^{-1}$ during 1961–1990, indicates an accelerating decrease in the dryness index.

The changes in precipitation, temperature, and the dryness index in the ARNC indicate not only the current trend of climatic warming and humidification, but also an acceleration of this trend. The acceleration of precipitation increase is more significant than that of temperature increase. All of these observations point to the need of great vigilance regarding the impact of climatic humidification in the ARNC both for now and in the future.

It is also essential to understand whether the increasing trends of temperature and precipitation in the ARNC are spatially widespread, which reflects the extent of climatic warming and humidification in this region. Our results show that temperature tends to increase over the entire ARNC during 1961–2018 at a rate of 0.0–0.8°C (10 yr)$^{-1}$ (Fig. 5a). More details are revealed by examining the probability distribution of temperature variation rate, which indicates that 61.8% of the area experiences temperature increase at the rate of 0.2–0.4°C (10 yr)$^{-1}$; 25.8% of the area has a temperature increase rate of 0.4–0.6°C (10 yr)$^{-1}$; 10.1% has a temperature increase rate of 0.0–0.2°C (10 yr)$^{-1}$; and 2.3% has a temperature increase rate of 0.6–0.8°C (10 yr)$^{-1}$ (Fig. 6a). Therefore, most of the region has a temperature increase rate of 0.2–0.6°C (10 yr)$^{-1}$. Compared with that in other areas, the climatic warming is more significant in northern Xinjiang, the Qaidam basin, and the Alxa Plateau of Inner Mongolia.

The rate of precipitation variation (the ratio of precipitation change rate to multi-year average precipitation) during the last 60 years is within the range of −5% to 15% (10 yr)$^{-1}$. Note that 93.4% of the area experiences precipitation increase, while only a few parts of the Helan Mountain experiences precipitation decrease (Fig. 5b). Areas with the rate of precipitation increase within the range of 0%–5% (10 yr)$^{-1}$ and 5%–10% (10 yr)$^{-1}$ account for 38.5% and 40.6% of the entire ARNC, respectively; while areas with the increase rate within the range of 10%–15% (10 yr)$^{-1}$ account for 14.3% of the entire area. Precipitation decrease with the rate within the range of −5% to 0% (10 yr)$^{-1}$ is found in 6.6% of the entire region (Fig. 6b). Overall, precipitation increase is more pronounced over Xinjiang, the Qaidam basin of Qinghai, and the Hexi Corridor. The spatial distributions of temperature and precipitation variation rates indicate that the trends of warming and humidification are generally very consistent throughout the ARNC.

### 3.2 Multi-timescale contributions to climatic warming and humidification

Because climate change always shows multi-scale
characteristics, it can be assumed that climatic warming and humidification in the ARNC are also affected by factors on multiple timescales. The changes in temperature and precipitation in the ARNC over the past 60 years show a consistent long-term increasing trend. However, the two elements also present distinct interannual and interdecadal variations. To reveal the contributions of different change processes at different timescales to the overall variations of temperature and precipitation, we use the EEMD method to generate annual average temperature and annual precipitation series. Multi-timescale oscillation components/IMF of different timescales and long-term trend signals are extracted. To better understand the multi-scale characteristics of temperature and precipitation changes in the ARNC during the past 60 years, we use IMF1, IMF2, IMF3, IMF4, and ST to represent the trends at four timescales from interannual to multidecadal, and the overall long-term trend.

Analysis of the temperature changes using the EEMD method reveals the following results. (1) The long-term trend of temperature makes the largest contribution and accounts for 63.9% of temperature changes. (2) The variations at quasi-interannual scale of 2.2 and 8.9 yr account for 18.9% and 12.1% of the temperature changes, respectively. (3) The contributions of variations at 17 and 37 yr are relatively low and together they only account for 5.1% of the temperature changes (Table 1). The characteristics of scale contribution to precipitation changes are different. The quasi-annual scale of 3.1 yr makes the largest contribution of 51.5%, followed by the contribution of the long-term trend that accounts for 32.1% of the precipitation changes; and the variation at quasi-interdecadal scale of 7.2 yr accounts for 12.9% of the precipitation changes. The contributions of variations at quasi-multidecadal scales of 16.6 and 38.7 yr are relatively low, and the two together only account for 3.5% of the precipitation changes (Table 2).

It can be further inferred from the results of the EEMD decomposition that the continuous significant warming since 1961 (Fig. 7) is mainly related to the significant increase in the contribution of the long-term trend. The weak trend of precipitation increases before 1986 is related to not only the relatively stable change in the long-term trend, but also the quasi-multidecadal scale IMF4 (38.7 yr) in the drying phase. The significant increase in precipitation can be attributed to the trend increase and the quasi-multidecadal scale of IMF3 (16.6 yr), which is in the wet phase.

Based on the characteristics of the scale contributions of temperature and precipitation variations, it can be hypothesized that global warming, caused by continuous increase of atmospheric greenhouse gases, is the main contributor to the mid- and long-term trends that dominate the characteristics of temperature variation. The contribution of interannual precipitation variation dominates the precipitation changes, which is attributed to the prevailing effect of the El Niño–Southern Oscillation (ENSO) on precipitation. The effect of the Pacific Decadal Oscillation (PDO) leads to precipitation variation on quasi-decadal scale, which also contributes to the precipitation changes. Due to significant precipitation changes in re-

Table 1. Contributions of temperature changes at different timescales decomposed by using the EEMD method

|          | IMF1 | IMF2 | IMF3 | IMF4 | Long-term trend |
|----------|------|------|------|------|-----------------|
| Contribution (%) | 18.9 | 12.1 | 2.3  | 2.8  | 63.9            |
| Period (yr)   | 3.2  | 8.9  | 17.3 | 37.5 | /               |

Table 2. Contributions of precipitation changes at different timescales decomposed by using the EEMD method

|          | IMF1 | IMF2 | IMF3 | IMF4 | Long-term trend |
|----------|------|------|------|------|-----------------|
| Contribution (%) | 51.5 | 12.9 | 1.8  | 1.7  | 32.1            |
| Period (yr)   | 3.1  | 7.3  | 16.6 | 38.7 | /               |
response to temperature changes, precipitation variations at mid- and long-term scales also make significant contributions to precipitation changes. The response of temperature to precipitation changes is apparently related to the contributions of temperature variations at quasi-annual and quasi-decadal scales.

4. Impact of climatic warming and humidification on ecological vegetation

The ecological vegetation is of great importance in the ARNC, as desert covers most of the region. The NDVI index (standardized vegetation index) in the Nanjiang basin, the Qaidam basin, the Hetao region of Gansu, and the Alashan Plateau of Inner Mongolia is less than 0.3. The NDVI index is above 0.4 only in a few parts of the ARNC, which are mainly located in the high-altitude areas such as Tianshan, Altai, Kunlun, the Helan Mountains, and the margins of oases and deserts (Fig. 8). It can be inferred from the vegetation distribution pattern that the region’s ecological vegetation acts as frontal barriers, preventing the expansion of deserts, which is critical to the ecological safety of the ARNC.

Moreover, like other natural entities, the ecological vegetation of the ARNC is fairly sensitive to climate change. Climatic warming and humidification in this region will inevitably cause changes in the distribution pattern of vegetation, and thereby affect its role as an ecological barrier. Currently, the vegetation index in about 82.4% of the ARNC region has been increasing since 1981. Areas with an NDVI increase within the ranges of 0.0–0.015 (10 yr)$^{-1}$ and 0.015–0.030 (10 yr)$^{-1}$ account for 39% and 30% of the total area in the ARNC region, respectively. Only 17.6% of area in this region experiences a decreasing NDVI (Fig. 9). The above results reflect the effects of climatic warming and humidification and their significant impacts on ecological vegetation growth in the ARNC, especially the effects of increased precipitation. It should also be noted that areas with increasing vegetation index are mainly located in high mountain areas, where the general condition is relatively good for plant growth. The NDVI has been decreasing in areas with relatively poor plant growth conditions, such as the Taklimakan Desert, the Kumtag Desert, and the Badain Green Desert. Clearly, the impacts of climatic warming and humidification on the ecological vegetation of the ARNC.
are greatest in areas with climatic and environmental conditions favorable for plant growth. In areas with poor climatic and environmental conditions, it is still difficult for vegetation index to increase, even if precipitation has increased.

Although many climatic factors affect ecological vegetation, temperature and precipitation are the key factors, which directly determine the water and temperature conditions necessary for plant growth. The NDVI in the ARNC is highly positively correlated with temperature and precipitation in the current year and the previous year (Table 3). This positive correlation indicates that vegetation growth in the ARNC severely depends on warm and moist conditions.

However, the correlation between the vegetation index NDVI and temperature is slightly higher than that between NDVI and precipitation. The correlation of NDVI with the temperature in the previous year is higher than that with the temperature in the current year. Therefore, it can be inferred that over the mountains, where the vegetation is mainly distributed, plant growth is more restricted by lack of heat, and the effect of available heat during the previous year is more critical than that of the current year. These characteristics of climatic impacts are more indicative of the long-term trend of climate change in the ARNC, which contributes to the improvement of the ecological vegetation. These results are important for implementing ecological and environmental protection projects, which are designed to return farmland to forest and grassland.

Temperature, precipitation, and the NDVI index are detrended to further study the details of the ecological vegetation response to interannual fluctuations of climate. The correlations of NDVI with temperature and precipitation after the detrending are significantly lower than before detrending. This indicates that the improvement of the growth status of most ecological vegetation depends more on the long-term stability of climatic conditions. There is a significant positive correlation between NDVI and precipitation in the current year, and a smaller but positive correlation of NDVI with temperature and precipitation in the previous year. This means that the response of ecological vegetation growth to climate variability is generally significantly related to interannual fluctuation of precipitation.

The NVDI values in desert, grassland, cultivated land, and urban areas all have positive correlations with temperature and precipitation (Fig. 10), indicating the overall effect of precipitation on vegetation under the arid climate condition. Moreover, in desert and urban areas, the correlation between NDVI and precipitation in the current year is significantly higher than that with precipitation in the previous year. In contrast, in grassland and cultivated areas, the correlation of NDVI with precipitation in the current year is equivalent to that with precipitation in the previous year. The relatively low NDVI in desert areas can be attributed to the rapid evaporation of water. In contrast, the relatively low NDVI in urban areas can be related to paved and asphalted ground, which blocks the infiltration and upward movement of water. The groundwater formed by the infiltration of precipitation in grassland and cultivated areas

![Fig. 9.](image)

Table 3. Correlation coefficients of temperature and precipitation with the NDVI index in the ARNC before and after detrending, respectively.

|                     | Before detrending | After detrending |
|---------------------|-------------------|------------------|
|                     | Precipitation in   | Temperature in    | Precipitation in | Temperature in    | Precipitation in | Temperature in |
|                     | previous year      | previous year     | previous year    | current year      | previous year    | current year   |
| NDVI                | 0.38**             | 0.51***           | 0.62***          | 0.56***           | 0.19             | 0.37**         |

Note: **, *, and * indicate that the correlation is significant at the confidence levels above 90%, 95%, and 99%, respectively.
plays a vital role in vegetation growth.

Compared with the correlation between precipitation and vegetation, the correlations between temperature and regional vegetation in different land-use types are higher and more complex. The vegetation index is weakly negatively correlated with temperature of both the current year and the previous year in desert areas. Although it is also weakly negatively correlated with the temperature in the current year in grassland and urban areas, it is significantly positively correlated with the temperature in the previous year. The temperatures in both the current year and the previous year are positively correlated with the regional vegetation, while the correlation with the previous year temperature is significantly higher than that with the current year temperature. These differences in correlation can be explained by the fact that desert areas have sufficient heat resources, which increase evaporation and reduce water availability for vegetation growth. Cultivated agricultural areas are generally irrigated and contains oases. Therefore, as water is always provided, any increase in temperature can improve the condition for plant growth.

In order to further analyze the synergistic effects of temperature and precipitation on vegetation, the matching relationship between temperature and precipitation is divided into four typical climate types: cold–dry, cold–wet, warm–dry, and warm–cold. The criteria for identifying typical dry, wet, cold, and warm years are: 1) the absolute value of the single-element anomaly must be greater than 0.5; and 2) the sum of the absolute values of the two-element anomalies must be greater than 1.5. Based on the above criteria, the years 1982, 1986, and 1997 are identified as typical cold–dry years; the years 1991, 2000, and 2008 are identified as typical warm–dry years; and the years 2002, 2007, and 2010 are identified as typical warm–wet years. The warm–wet climate in the ARNC is the most favorable for vegetation growth and the average regional NDVI is 0.359 in these years, while the cold–dry climate is the worst, when the average regional NDVI is 0.327. Compared with the cold–wet climate, vegetation cover is slightly better under the warm–dry climate (Fig. 11). These results may also indicate that in cold areas and oases, where precipitation levels are quite stable, poor thermal conditions may be more restrictive for ecological vegetation growth than the moisture condition. Low precipitation might restrict vegetation growth only in desert edges, where vegetation is sparsely distributed and scattered.

In summary, the trend of climate warming and humidification in the ARNC is favorable for the improvement of ecological vegetation. The significant continuous warming and humidification since the 1960s has led to better vegetation growth. However, improvements in vegetation have occurred more in areas that already have sufficient precipitation rather than over desert areas that are dry and rainless.

5. Discussion

Due to the complexity of the mechanisms that drive warming and humidification trends in the ARNC and the uncertainty of the predicted results of future climate scenarios, it is currently difficult to conduct clear, systematic analysis and provide conclusions regarding the two issues. Here, we attempt to make some discussion on the above issues from a few specific perspectives.
Previous studies have come to various conclusions regarding the mechanisms driving the trend of warming and humidification in the ARNC (Guan et al., 2015; Huang et al., 2017b). However, the essential influencing factors appear to be the sources of atmospheric water vapor transport and the precipitation conversion rate in the region. The atmospheric circulations in the ARNC indicate that water vapor in this area is mainly transported by the westerly winds (Wang et al., 2005). The precipitation index (standardized precipitation anomaly) and westerly index show a synchronous increasing trend. The correlation coefficient between them is 0.36 at the 99% confidence level (Fig. 12). Therefore, the increase in water vapor transport caused by the intensified westerly wind circulation may contribute to the increase in precipitation. However, the increasing trend of the westerly index is not as great as that of the precipitation index, which implies that the enhanced transport of water vapor caused by the westerly wind circulation may not be the only reason for the significant precipitation increase. Other factors, such as precipitation efficiency, may also have an impact on the humidification trend.

Theoretically, the net flux of regional water vapor is the net input or output of regional water vapor. If it is a net input, water vapor is converted into precipitation; and if it is a net output, water vapor is lost by evapotranspiration. Ren et al. (2016) analyzed recent changes in the water vapor flux over the ARNC during 1979–2012 (Fig. 13a). They found that the net water vapor flux in the ARNC has been increasing significantly, which clearly indicates an increase in the conversion efficiency of water vapor into precipitation. There is also a good correlation between the net water vapor flux in the ARNC and the precipitation index, which is significant at the 90% confidence level (Fig. 13b).

Considering the physics of precipitation, vertical air motions are the most critical factor affecting the efficiency of precipitation, given a constant water vapor in-

![Fig. 12.](image1.png)  
(a) Variations of the westerly index and precipitation index. (b) Scatter plot of the correlation between the westerly index and precipitation index.

![Fig. 13.](image2.png)  
(a) Variation curves and (b) scatter plot of vertical velocity, net water vapor flux, and precipitation index.
put. The vertical velocity and the net water vapor flux in the layer between 700 and 200 hPa have increased significantly at the same time (Fig. 13a), and they are highly correlated. The correlating coefficient can be up to 0.51 and statistically significant at the 99.5% confidence level (Fig. 13b).

The trend of precipitation increase in the ARNC is probably related to the westerly wind circulation and the increase in vertical air motions. The increase in vertical air motions may be related to the weakening of the compensating sinking airflow around the plateau caused by the increase of precipitation over the Tibetan Plateau in recent years. However, their relationship with global climate change remains unclear (Zhang et al., 2007).

It is essential to understand how climatic warming and humidification in the ARNC will affect the regional climate. The ARNC can be classified into different sub-areas according to temperature: 1) cold temperate zone with average annual temperature below 4.5°C; 2) medium temperate zone with average annual temperature in the range of 4.5–9.3°C; and 3) warm temperate zone with average annual temperature above 9.3°C. Sub-areas can also be classified according to precipitation: 1) extreme arid zone with average annual precipitation below 100 mm; 2) arid area with average annual precipitation in the range of 100–250 mm; and 3) semi-arid area with average annual precipitation above 250 mm (Huang et al., 2017a; Ma et al., 2017). Regarding the current situation, climatic warming and humidification over the past 60 years have resulted in remarkable increases in temperature and precipitation with the values of 1.97°C and 44.7 mm, respectively. The spatial distributions of temperature and precipitation in the ARNC during 1961–2018 (Fig. 14) show that the cold temperate zones have contracted slightly and the warm temperate zones have become more extensive, yet the overall temperature zones remain largely unchanged. Although the extreme arid zone has contracted slightly and the semi-arid zone expanded slightly, the distribution of the precipitation zones has also remained unchanged. In summary, the continuous trends of warming and humidification over the past 60 years have not changed the basic climate distribution pattern in the ARNC, and any change in climatic condition is local and weak.

We now use the latest data from the CMIP6 ensemble models to make qualitative predictions of the future climate in the ARNC. In the present study, the CMIP6 multi-model ensemble simulation under the revised medium emission scenario (SSP2-4.5) is used for analysis. The results show that the rate of temperature change during 2019–2099 would be 0.32°C (10 yr)^−1, which is slightly lower than that over the past 60 years (Fig. 15). In 2040, the average annual temperature would reach 9.3°C, making the entire region a warm temperate zone. By 2099, the average annual temperature of the ARNC would be 11°C, 2.5°C higher than it is now. The rate of precipitation changes from 2019 to 2099 would be 3.0 mm (10 yr)^−1, which is less than half of that over the past 60 years. By 2099, annual precipitation would increase by 24 mm and reach 200 mm. It can be concluded that the ARNC will broadly retain its current climate state for the next 20 years, and that changes by 2099 will be limited. However, in the future, compared with precipitation changes, perhaps it is more important to monitor temperature changes.

It is remarkable that, although climatic warming and humidification in the ARNC over the past 60 years have generally promoted the improvement of ecological vegetation, the predicted greater temperature increases in the future would become detrimental to plant growth. Temperature increase has a negative effect on water loss by increasing evapotranspiration, which may offset its positive effects on heat availability and even on increased precipitation. Therefore, even if the trends of warming and humidification continue in the ARNC in the future, their impact on ecological vegetation remains uncertain. It is
likely that such trends may be unfavorable for the improvement of vegetation growth in the long run.

6. Conclusions

Over the past 60 years, not only have the temperature and precipitation in the ARNC increased, but the precipitation increase has also accelerated significantly. Meanwhile, the dryness index has decreased. Climatic warming and humidification have clearly occurred in the ARNC, a situation that deserves further study.

The trend of temperature increase is consistent over the entire region, with an increase in the range of 0.2–0.4°C (10 yr)$^{-1}$. The increasing trend of precipitation affects 93.4% of the region, with an increase in the range of 5–10 mm (10 yr)$^{-1}$. The trends of warming and humidification in the ARNC are consistent and systematic.

The contributions of the long-term trends and interannual-scale trends have dominated climatic warming and humidification in the ARNC, and the contributions of the long-term trends prevail in the process. The contributions of variations at quasi-annual and quasi-decadal timescales to temperature increase cannot be ignored either. Precipitation variation at the quasi-annual timescale makes the most significant contribution to changes in precipitation, followed by the long-term variation. It can be inferred that mid- and long-term trends of temperature changes, which are attributed to global warming caused by continuous increase of atmospheric greenhouse gases, make the dominant contributions to temperature changes in the ARNC region. The contribution of interannual precipitation variation dominates precipitation changes, which is attributed to the prevailing effect of ENSO on precipitation. The effect of PDO leads to precipitation variation on quasi-decadal scale, which also contributes to the precipitation changes. The contributions of temperature and precipitation variations at various timescales can also to a certain extent reflect the mutual feedback effects between temperature and precipitation.

The current trends of climatic warming and humidification in the ARNC have resulted in a general improvement of vegetation growth. Since the 1980s, 82.4% of the regional vegetation has thrived. Over the long term, the NDVI vegetation index has been significantly positively correlated with precipitation and temperature. Regarding interannual fluctuations, the vegetation index responds more significantly to precipitation. Moreover, the vegetation index is positively correlated with precipitation in the current year and the previous year, which is true for all land-use types. The vegetation index is more closely related to current year precipitation in urban and desert areas. In grassland and cultivated areas, the vegetation index is similarly related to precipitation in the current year and the previous year. The correlation between the vegetation index and temperature in the previous year seems to be better than that with the current year temperature in most land-use types. Except in desert areas, where vegetation index and temperature in the previous year are weakly negatively correlated, the correlations between the vegetation index and temperature in the previous year are significantly positive in grassland, cultivated land, and urban areas. Regarding the synergy between climatic factors, the warm–wet climate is most conducive to vegetation growth, while the cold–dry climate is the least favorable. The vegetation growth in the ARNC is significantly dependent on moisture and temperature conditions. The degree of dependence varies

Fig. 15. Variations of (a) temperature and (b) precipitation observed in the ARNC over the past 60 years and predicted by the CMIP6 ensemble model over the next 80 years.
between vegetation types and climate conditions.

The trends of climatic warming and humidification in the ARNC are probably related to the intensification of westerly wind circulation and ascending air motions. The intensified westerly wind circulation increases water vapor transport over the ARNC. The ascending air motions trap more water vapor and result in more precipitation in the area. The increased ascending air movement may be related to the weakening of the compensating descending airflow around the Tibetan Plateau caused by increased precipitation.

The trends of climate warming and humidification over the past 60 years have not changed the climate distribution patterns within the ARNC. The arid region in Northwest China still has a mid-temperate arid climate. The trend towards a warm and humid climate in the ARNC is likely to continue until 2099 at least, but the rate of change will be slow. Over the next 20 years, the current dry–cool climate will persist. In the future, changes in temperature should be more carefully monitored than changes in precipitation.

This paper provides statistical analyses of the reasons behind the significant increase in precipitation in the ARNC. Without systematic numerical simulation experiments, predictions of the future climate in the area would involve considerable uncertainties. More systematic analyses based on new and improved datasets are required to further refine the conclusions presented here.

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