Potential risks and challenges of climate change in the arid region of northwestern China

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Potential risks and challenges of climate change in the arid region of northwestern China

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ABSTRACT

In the arid region of northwestern China (ARNC), water resources are the most critical factor restricting socioeconomic development and influencing the stability of the area's ecological systems. The region's complex water system and unique hydrological cycle show distinctive characteristics. Moreover, the intensified hydrological cycle and extreme climatic and hydrological events resulting from global warming have led to increased uncertainty around water resources as well as heightened conflict between water supply and water demand. All of these factors are exerting growing pressures on the socioeconomic development and vulnerable ecological environment in the region. This research evaluates the impacts of climate change on water resources, hydrological processes, agricultural system, and desert ecosystems in the ARNC, and addresses some associated risks and challenges specific to this area. The temperature is rising at a rate of 0.31 °C per decade during 1961–2017 and hydrological processes are being significantly influenced by changes in glaciers, snow cover, and precipitation form, especially in the rivers recharged primarily by melt water. Ecosystems are also largely influenced by climate change, with the Normalized Difference Vegetation Index (NDVI) of natural vegetation exhibited an increasing trend prior to 1998, and then reversed in Xinjiang while the Hexi Corridor of Gansu showed the opposite trends. Furthermore, the desert-oasis transition zone showed a reduction in area due to the warming trend and the recent rapid expansion of irrigated area. Both the warming and intensified drought are threatening agriculture security. The present study could shed light on sustainable development in this region under climate change and provides scientific basis to the construction of the “Silk Road Economic Belt”.

1. Introduction

The intensification of the water cycle under global warming and controversies around changes in dryness and wetness in arid areas have become a hot research topic in recent years (Trenberth, 2011; Durack et al., 2012; Li et al., 2019), especially in data-scarce arid
regions. Studies based on observations or model simulations suggest that the global drought has increased since 1950 and may continue until the end of the 21st century (Huang et al., 2016), and responses of drought to climate change vary among regions (Li et al., 2019).

The arid region of northwestern China (ARNC) is located in the hinterland of Eurasian continent. This region is extremely important for the construction of the “Silk Road Economic Belt” and the future economic and social development of China. At the same time, the ARNC is characterized by rich natural resources and a vulnerable ecological environment. Although it is slated to provide energy to China throughout the 21st century, the area faces some serious issues, ranging from desertification to economic poverty.

Since 1961, the temperature in the ARNC has risen at a rate of 0.31 °C per decade, which is a fairly significant increase. Precipitation has also increased at an average rate of 4.86 mm per decade; in mountainous areas, the average rate could be as high as 10.00 mm per decade (Li et al., 2013; Yao et al., 2016a). Meanwhile, water vapor pressure is also on the rise (Yao et al., 2016b). From 1960 to 1986, the Standardized Precipitation Evapotranspiration Index (SPEI) was low and drought events occurred frequently. Since then, the SPEI has increased substantially, showing a warming and humidification trend. However, the SPEI started declining in 2003, indicating that the degree of drought has increased (Wang et al., 2015a, b; Wang et al., 2017; Yao et al., 2018). Other studies have pointed out that the Standardized Precipitation Index (SPI) has shown a similar tendency with SPEI since 1997 by starting to decrease (i.e., indicating a drying phase) (Yao et al., 2018). The annual aridity index decreased significantly (P < 0.05), indicating that the ARNC became wetter from 1960 to 2010 due to increasing precipitation (Liu et al., 2013). Seasonally, there were a drying trend in spring and a wetting trend in summer (pronounces in eastern Xinjiang and western Gansu) during 1958–2001, whereas in much of the ARNC, autumn and winter were getting wetter (Jin et al., 2004). The recent and ongoing changes in dryness and wetness in the ARNC are making this area the latest research hotspot (Li et al., 2019).

Climate change has led to changes in hydrological processes and water resources in the ARNC. Increased temperature and precipitation have accelerated the snow and glacier melt, leading to increased runoff in alpine glacierized catchments. For example, the Urumqi River, which is located in the eastern part of the Tianshan Mountains, experienced a 10.0% increase in runoff from 1950 to 2009 (Kong et al., 2012). Of this increase, 69.7% was caused by the increase in snow and glacier melt, with the proportion of snow and glacier meltwater jumping from 62.8% to 72.1% based on a water balance model (Sun et al., 2013). For the Tekes River, which has its source to the west of the Tianshan Mountains, rising temperature has accelerated the retreat of glaciers and altered the recharge processes, resulting in a reduction in the proportion of rainfall runoff from 9.8% in 1966–1975 to 7.8% in 2000–2008 based on the Soil and Water Assessment Tool (SWAT) (Xu et al., 2015). In addition, the increase in temperature also changed the form of precipitation falling in the mountainous areas (e.g., a decreased ratio of snowfall to rainfall in the Tianshan Mountains) using the threshold temperature method in combination with multi-source datasets (APHRODITE, Climate Prediction Center (CPC), and meteorological stations) (Li et al., 2020a).

The impacts of changes in the form of precipitation on water cycle are mainly reflected in variations of average runoff and seasonal distribution (Barnett et al., 2005; Regonda et al., 2005). The decreased ratio of snowfall to rainfall may lead to a reduction in river runoff, as demonstrated by an analysis of 420 watersheds in the United States through the Budyko hypothesis (Berghuijs et al., 2014). However, the mechanism for the reduction in river runoff remains unclear.

The ecosystems in the ARNC are generally thought to be highly susceptible to degradation caused by unfavorable climate change, resulting in possible desertification, deforestation, or woody encroachment (Williams and Albertson, 2006). Several researchers have analyzed the response of desert ecosystems to climate change in this region. For the Tarim River Basin, the Normalized Difference Vegetation Index (NDVI) has decreased at a rate of 0.005 per decade since 1999 and the bare land area of the border of the Taklimakan Desert has expanded by 7.8% (Chen et al., 2016a). From 1982 to 2006, the overall vegetation vitality and coverage of the Tarim River Basin have generally improved. However, drought and water shortage have put pressures on the vulnerable ecological areas, including the desert-oasis transition zone on the edge of the oasis and the riparian zone along the northeastern Kunlun Mountains. The vegetation vitality and coverage in these areas tend to decrease (Wang et al., 2013). Moreover, from 2000 to 2014, the vegetation productivity

![Fig. 1. Geographic location and topographic features of the arid region of northwestern China (ARNC).](image-url)
increased on the northern slopes of the Tianshan Mountains, the southern border of the Tarim River Basin, and the Hexi Corridor.

This paper addresses the plausible impacts of global climate change on water resources, hydrological processes, ecological systems, and oasis agriculture in the ARNC, and analyzes the future risk and challenges concerning climate change. The aim of this study is to shed light on the status of climate change impacts in the ARNC and provide a scientific basis to support decision-making for the construction of the “Silk Road Economic Belt”.

2. Study area

The ARNC, located in the hinterland of Eurasia, covers an area of about $2.50 \times 10^6$ km². It is comprised with many deserts, including the world’s second largest mobile sandy desert (i.e., the Taklimakan Desert), along with the Kumtag Desert, the Gurbantunggut Desert, the Badain Jaran Desert, and others. These deserts are the primary sources of dust storms in the region. The ARNC is far from any ocean and characterized by severe water shortage. It is composed of mountain-oasis–desert ecosystems. Spatially, the region is mainly composed of Xinjiang and Hexi Corridor in Gansu (Fig. 1). Xinjiang features a sprawling mountain-basin system and its climate is strongly affected by the uplift of the Tibetan Plateau and influenced by the westerly circulation. In contrast, most of the Hexi Corridor area is piedmont plains, with the western part dominated by the westerly circulation, the eastern part affected by the southwestern and southeastern summer monsoons, and the center portion serving as the intersection of the two diverse circulation systems. In general, the study area features an arid and windy climate and is covered with sparse vegetation. The annual precipitation is below 100.00 mm in the plain area, and potential evaporation could be up to 2500.00–3000.00 mm. Overall, the climate system in the ARNC is best described as complex with heterogeneity.

2.1. Water-scarce area with limited water resources

The ARNC is the driest region in China. The total amount of water resources in the study area is approximately $1.979 \times 10^{11}$ m³, accounting for 5.8% of China’s total water resources. The amount of available water resources is approximately $1.364 \times 10^{11}$ m³, with the per capita water resources totaling around $1.573 \times 10^3$ m³, 68.0% of the national average (Chen et al., 2012). In addition, the spatial and temporal distribution of water resources in the ARNC is uneven, with more water in the west and less in the east, and more in the mountains and less in the plains, which reduces the effectiveness of water resources and exacerbates water shortage. The formation and development of oases and the desert ecosystems mainly depend on the precipitation and meltwater from the mountains. Water resources are the key factor restricting the economic and social development of this region.

2.2. Oases as key shelter of life

The oases are distributed along the region’s rivers and are surrounded by deserts. These narrow strips of oasis area account for less than 10.0% of the region’s land. However, they represent the main source of life there, supporting 98.0% of the population and 95.0% of the gross domestic product (GDP). The population density of the oases is double that of the national average. The areas with the greatest population density are the Hotan Oasis and the Kashgar Oasis, formed by the Hotan River, the Yarkant River, and the Kashgar River basins in southern Xinjiang. Moreover, poverty is prevalent here, with the proportions of people living in poor and extreme poor accounting for 70.0% and 84.0% of those in Xinjiang, respectively.

The shortage of water resources has limited the development of the vast land area in southern Xinjiang, seriously restricting the pace of poverty reduction in the region and leaving nearly $1.2 \times 10^{13}$ ha of land area underused. At the same time, due to the lack of adequate irrigation in existing farmlands, land productivity has declined, forcing farmers to resort to extensive chemical fertilization, which has led to the compaction of soil and the increasing of planting costs.

3. Impacts of climate change on the ARNC

In the past half-century, the linear increasing rate of temperature in the ARNC is 0.31 °C per decade, which is much higher than either the national average or the global average based on the Climatic Research Unit (CRU) gridded Time Series TS3.26 (Harris et al., 2019). Of special note is that the temperature experienced a particularly sharp increase in 1998, with the annual average temperature since that year being 0.93 °C higher than the previous 30 years (Chen et al., 2017). However, as of 1998, temperatures have been in a state of high variability (Li et al., 2015). The warming has broken the original energy balance, altered the snow and glacier melt processes (Chen et al., 2017), accelerated the regional water cycle, and reversed the potential evaporation trends (Li et al., 2013). As a result, the water system recharged by mountainous precipitation and snow and glacier meltwater is becoming more vulnerable, the stability of ecological systems dominated by desert ecosystems is reducing, and the oasis irrigation system may suffer from a more severe risk.

3.1. Impacts of climate change on hydrological processes and water resources

The majority of the ARNC’s rivers are recharged by a combination of snow and glacier meltwater in the high mountains, precipitation in the mid-mountain forests, and fissure water in the low mountains. The hydrological components are complex in the mountainous areas, where the majority of the surface water resources originate (Chen, 2014). The water cycle in the arid area is significantly affected by climate changes. With the increase in air temperature, the elements of the water cycle have changed, and the responses of
precipitation, glaciers, and snow to warming and their subsequent impacts on hydrological processes are becoming more complex (Barnett et al., 2005). The complexity further increases the uncertainty around meltwater-dominated runoff (Regonda et al., 2005) and exacerbates the hydrological fluctuations and water resources concerns.

3.1.1. Shrinkage of glaciers and snow cover in the mountainous areas

The recent warming has accelerated the shrinkage of glaciers in the ARNC, which increased the glacial meltwater in the short term and weakened water system stability. The glacier area has been shrinking rapidly since 1975. Spatially, researchers found that the glacier retreat rate in the Tianshan Mountains is the fastest, with a retreat rate of about 10.0%–32.0%, followed by the northern slopes of the Karakorum-Kunlun Mountains (a retreat rate of 15.0%) and the northern Altay Mountains (mainly the Irtys River Basin, with a shrinking rate of about 5.0%) based on the remote sensing data and in situ observations (Li et al., 2010). Meanwhile, changes in snow cover area in the Tianshan Mountains has also measured with the maximum and minimum snow cover areas in the middle Tianshan Mountains, which decreased with the decreasing rates of 672 and 60 km² yr⁻¹, respectively (Chen et al., 2016b). From 2003 to 2016, terrestrial water storage derived from the GRACE data of terrestrial total water storage showed a decreasing trend as well, with the average decline rate in the ARNC being 3.00 mm yr⁻¹ and the loss rate of terrestrial water storage in the Tianshan Mountains being 2.23 × 10⁹ m³ yr⁻¹ (Chen et al., 2016b). In contrast, terrestrial water storage in the Altay and Kunlun Mountains exhibited an increasing trend (Deng and Chen, 2017).

3.1.2. Accelerated extreme climatic and hydrological events

Global warming has intensified the water cycle and increased the frequency and intensity of extreme climatic and hydrological events. The CRU TS3.26 dataset showed that the range of precipitation anomaly in the ARNC enlarged from about ±30.00 mm before 1986 to ±40.00 mm after that year (Fig. 2), with the standard deviation increased from 17.50 to 19.00 mm. Extreme precipitation events, along with decreased glacier melt recharge in some catchments (caused by glacier shrinkage), have together led to enlarged hydrological volatility (Swain et al., 2018). For example, the runoff in the Tarim River, the largest inland river in China, was 1.40 × 10⁹ m³ in 2009 and 7.20 × 10⁹ m³ in 2010. Historically, the year 2009 had the lowest runoff on record while the year 2010 had the highest runoff, more than five times that of 2009. The frequency of extreme hydrological events increased from 40 times per decade prior to the 1980s to 78 times per decade since the late 1980s (Wang et al., 2015c). River runoff in the study area is also strongly influenced by precipitation, glacier, and snow cover changes. With the retreat of glaciers, the recharge from glacier meltwater will eventually decrease, leading to an overall reduction in the glacier melt regulation function. Moreover, as the hydrological variability increases, the hydrological processes of the rivers will become more complicated.

3.1.3. Changes in hydrological processes

The recharge ratio of glacier meltwater to runoff could be as high as 50.0% in the ARNC (Yang, 1991; Zhou, 1999; Fang et al., 2018a) (Fig. 3). Glaciers play an important role in water resource composition and river runoff regulation, and glacier dynamics directly affect the future trend of water resources. Temperature increases would lead to changes in precipitation form, seasonal distribution, ice accumulation, and melting process, all of which affect the water cycle processes (Barnett et al., 2005). Hydrological processes are extremely sensitive to changes in temperature, especially in rivers dominated by meltwater recharge. For example, warming could lead to changes in the onset day and the end day of snowfall, and thus altered the snow cover duration (Li et al., 2020b). Warming could also lead to a decreased ratio of snowfall to rainfall, which could then affect the processes of water generation and confluence in the mountainous areas (Barnett et al., 2005; Li et al., 2020a).

Recent studies on runoff trends indicate complex responses to climate change. Catchments with a higher fraction of glacier/snow-

![Fig. 2. Precipitation anomaly of the ARNC and Northern Hemisphere based on Climatic Research Unit (CRU) gridded Time Series TS3.26 during 1961–2017.](image)
dominated areas that feature a high ratio of snowfall to rainfall have shown mainly increasing runoff trends in the past, while catchments with less or no glacierization and snow exhibited large variations in runoff changes (Li et al., 2020a). Increasing temperatures have led to an earlier spring peak flow and an increase in runoff during the flood season (Berghuijs et al., 2014). For example, according to the runoff data provided by the Xinjiang Tarim River Management Bureau, we found that since the early 1990s, the observed runoff of the source rivers (Kaidu, Qingshui, and Huangshuigou) of the Bosten Lake, China’s largest inland freshwater lake, increased significantly by 25.0%, 37.9%, and 47.9%, respectively, compared to the period 1960–1992 (Fig. 4). In general, rivers dominated by snowmelt runoff, such as those sourced from the northern slopes of the Tianshan Mountains and the Altay Mountains, have experienced seasonal shifts in the timing of maximum runoff. Specifically, the peak flow has moved to the late spring season instead of the water-demanding summer season, as the snow and glacier melt period has been pushed forward.

3.2. Impacts of climate change on desert ecosystems

The ARNC is composed of three major ecosystems: mountains, oases and deserts. The desert ecosystems provide the oases with essential protection from sandstorms. However, the recent shortage of water resources and the high degree of heterogeneity in their spatial and temporal distributions have made the ecosystems very vulnerable. Continued warming and worsening drought will lead to systemic changes and mutations in the ecosystems’ properties (Berdugo et al., 2020). These changes will result in the degradation and desertification of the already vulnerable terrestrial ecosystems in the arid desert regions due to the impacts of climate fluctuations (Williams and Albertson, 2006).

3.2.1. Ecological response to warming

In the desert areas, rising temperatures accelerate evaporation demand, leading to variations in soil moisture, groundwater depth,
and vegetation volatility. Under global warming, we examined the natural vegetation condition based on Global Inventory Modeling and Mapping Studies (GIMMS) NDVI3g V1.0 dataset. Generally, the vegetation coverage in the ARNC generally showed an increasing trend and then an abrupt decline during 1982–2015 (Fig. 5). Spatially, the northern slopes of the Tianshan Mountains and the margin areas of the Tarim River Basin showed an increasing trend in NDVI from 1982 to 1998. However, the vegetation index and vegetation coverage reversed to a decreasing trend after 1998 (Fig. 5), with shrub encroachment on grasslands being detected (Li et al., 2015). In contrast, the NDVI in the Hexi Corridor showed a decreasing trend from 1982 to 1998 and then reversed to increase during 1998–2015.

At the same time, the bare land area, namely desert area (defined as NDVI<0.01) at the edge of the Taklimakan Desert also showed a decreasing trend, followed by a slight increase. From 1982 to 1998, the area of bare land decreased at a rate of 0.25% yr⁻¹, but since 1999 it expanded at a modest rate of 0.03% yr⁻¹. The Taklimakan Desert has expanded 7.8% in the past decade (Chen et al., 2016a).

From these changes, we can see that the impact of warming on ecosystems is much greater than that of increased precipitation. The abrupt increase in temperature after 1998 has caused substantial negative effects on regional ecological systems despite the increased precipitation in this area (Li et al., 2015).

3.2.2. Shrinkage of the desert-oasis transition zone

The desert-oasis transition zone, located between oases and deserts, plays a critical role in maintaining the stability of oasis ecosystems and is also highly sensitive to climate change. We extracted the desert-oasis transition zone with the NDVI values between 0.05 and 0.35 and then further trimmed by visual interpretation. Fig. 6 shows the interdecadal dynamics of the desert-oasis transition zone in the Tarim River Basin over the past 26 years (1990–2015). It can be seen that the transition zone demonstrated a continuous shrinkage, with a declining rate of 12.4% per decade (Sun et al., 2020). Meanwhile, the NDVI in the same desert-oasis transition zone also decreased from 0.142 in 1990 to 0.127 in 2015. The shrinkage of natural vegetation coverage was mainly caused by the continuous expansion of cultivated land area, which increased from $2.45 \times 10^4$ km² in 1990 to $4.01 \times 10^4$ km² in 2015. As more water was extracted for irrigation, a sharp decrease in groundwater levels was observed, which caused some shallow roots of desert plants to die under the joint effects of continuous warming and intensified drought. This process has reduced biodiversity and vegetation coverage in

![Fig. 5. Spatial variations in Normalized Difference Vegetation Index (NDVI) change trends of natural vegetation in the ARNC during the period (a) 1982–1998 and (b) 1999–2015. NX, SX, and HC represent the northern Xinjiang, southern Xinjiang, and Hexi Corridor, respectively.](image-url)
the affected desert-oasis transition zone, and thus influenced the ecosystem function of the desert-oasis transition zone as ecological barriers.

3.3. Impacts of climate change on oasis agriculture

In the ARNC, oasis agriculture relies on irrigation. Where there is no irrigation, there is no agriculture. The vulnerability of oasis agriculture to climate change is magnified by high population pressure and water shortage across the oasis region. The high temperature fluctuations and intensification of extreme climatic and hydrological events not only aggravate the hydrological fluctuation, but also
change the natural factors of agricultural production and increase the instability of the oasis agricultural economy.

### 3.3.1. Intensifying competition for water resources

The unique characteristics of the water resources management in the ARNC are to maintain the sustainable development of the vulnerable ecosystems as well as the social and economic systems. The contradiction between ecological protection and economic development regarding the utilization of water resources is the core problem of water resources management in the arid areas. In the oases, the high demand on the water resources in the economic systems often occupies ecological water, which should be used to maintain the natural vegetation systems. The result, as has been seen to date, is the damage of desert ecosystems and a significant decrease in the oasis security.

The expanding irrigated area in the oases increased the water consumption for agriculture. This resulted in an intensification of water demand and water supply contradiction between production and ecological protection. A previous study shows that, from 1990 to 2015, the irrigation water demand in the Tarim River Basin increased from $1.93 \times 10^{10}$ to $4.719 \times 10^{10}$ m$^3$ (Fang et al., 2018b; Wang et al., 2019). Note that the irrigation water consumption in the Tarim River Basin accounts for 95.0% of the total water consumption in the oasis region. Due to the excessive crowding out of ecological water by agriculture, rivers are leeched of life-giving water, lakes are dried up, and the surrounding ecological environment is deteriorated. Moreover, future climate change is expected to make the mismatch between water resources and productivity more prominent, further intensifying the contradiction between water supply and water demand in the arid areas (Li et al., 2020a).

### 3.3.2. Food security under global warming

The extreme climatic events caused by warming have increased the fluctuation of agricultural production, which brings great challenges to oasis agriculture in the arid areas (Piao et al., 2010). In the past 50 years, the annual average, maximum, and minimum temperatures in the ARNC showed significant warming trends, with the ranges of warming rates being of 0.029 °C yr$^{-1}$–0.039 °C yr$^{-1}$, 0.043 °C yr$^{-1}$–0.056 °C yr$^{-1}$, and 0.025 °C yr$^{-1}$–0.031 °C yr$^{-1}$, respectively (Chen et al., 2014). As a result of warming, some crop yields will decrease. For example, if the temperature increases by 1.0 °C, the wheat yield will drop by 6.0%–20.0% and the rice yield by 4.5%–14.6% (Piao et al., 2010). By 2030, it is estimated that China’s crop production will reduce 5.0%–10.0% due to rising temperatures (Qin et al., 2002).

The significant increase in average annual temperature is attributed largely by the rise in the extreme minimum temperature in winter (Li et al., 2012). The rising winter temperatures are allowing some pests and diseases to survive through the winter and expand their survival area, putting further pressures on agricultural production. A previous research has shown that the number of days with temperatures equal to or below 0 °C in winter decreased and the 0 °C isotherm has migrated northwards by about 1.0 ° latitude (−100 km), leading to an extended overwintering space for myxomycetes and pests (Zhang et al., 1997). The overwintering pests affected crop growth, resulting in an increase in pesticides use, which subsequently boosted planting costs and threatened food security.

### 3.3.3. Drought risk

In the arid areas, rising temperatures not only boost soil evaporation in farmlands, but also accelerate the airflow exchange, thus increasing sand dust, floating dust and sandstorm weather, aggravating the process of desertification, and heightening the drought risk (Xiao et al., 2007; Deng et al., 2009). In recent years, global climate change and the intensification of human activities have increased the frequency of drought, prolonged its duration, and enlarged its influence scope (Li et al., 2017). Deng et al. (2019) pointed out that, under drought conditions, the start time for crop growth was 0.66–3.45 d later than that of previous years. In southern Xinjiang, an investigation on agricultural production showed that the spring drought causes a delay in cotton sowing time and a relative decrease in effective accumulated temperature during the growth period. Warming and droughts could result in a delay in each growth stage and lead to a drop in the cotton quality (Liu et al., 2010).

Hot-dry winds frequently occur in summer in the ARNC due to the specific climate and topography. Oasis areas are generally easily damaged by hot-dry winds than mountainous areas. In the arid environments characterized by high temperatures, these types of winds develop easily, which can cause physiological drought of crops and lead to production loss (Zhu et al., 2020). Across the ARNC, increases in temperature have intensified the occurrence intensity of hot-dry winds and aggregated the degree of harm to oasis agriculture. According to the results of Deng et al. (2019), the wheat yield was reduced by 5.0%–10.0% in years with mild dry-hot wind and 10.0%–20.0% in years with severe wind.

### 4. Future climate change risks

#### 4.1. Increased risk of water resources

River runoff in the ARNC depends heavily on glaciers and/or snow cover. However, with most glaciers in retreat and the glacier water supply changing, there has been a subsequent decline in glacier regulation function. Furthermore, as the variation rate in the river runoff increases due to the influence of extreme climatic and hydrological events, the hydrological processes of the rivers will become more complex. At the same time, rising temperatures are causing seasonal changes in snow and glacier meltwater, leading to increases in the frequency and intensity of extreme hydrological events. These changes resulted in reductions of water resource reproducibility and weakened the overall stability of the water system in the arid areas.

Moreover, as most of the water supply in the ARNC comes from precipitation and snow/glacier meltwater in the mountainous areas and these water resources are highly sensitive to global climate change, the rivers mainly supplied by meltwater will reach their...
inflection points of glacier melting, due to glacier retreat and glacier water storage reduction. At that time, the amount of surface available water resources will decrease sharply, or there will be an increase in the runoff variation due to the influence of precipitation anomalies, which further increases the risk of water resources (Table 1).

4.2. Increased risk of oasis economic sustainability

Climate change-induced alternations in water resources in terms of quantity and spatial/temporal distribution will make the contradiction between ecological protection and economic development more prominent in the utilization of water resources in the ARNC. As mentioned previously, the oasis and desert ecosystems in the region are highly subject to the mountainous hydrological processes and are extremely sensitive to changes in water conditions. The heavy demand for water resources in an oasis economic system often ‘squeezes up’ the ecological water use, leading to the shrinkage, drying up, and degradation of desert ecosystems in the lower reaches of the rivers. The increase in extreme hydrological events caused by climate change directly affects the water supply ability in the arid regions and increases the risk of the safe operation of major projects. Furthermore, continuous high temperature events will increase the frequency and intensity of hot-dry winds. The increase in extreme minimum temperatures in winter will lead to the aggravation of agricultural pests and diseases, which will bring serious challenges to the development of the oasis agricultural economy (Li et al., 2012). Accordingly, an in-depth analysis of regional extreme events and possible socioeconomic risks under future temperature rise scenarios is urgently needed to improve the comprehensive response to climate change, and to ensure the healthy and sustainable development of the agricultural economy in the oases.

4.3. Risks of “water-energy-food-ecology” system

The “water-energy-food-ecology” bond in the ARNC is tightly interrelated. However, climate warming has complicated the interdependencies of water resources security, energy security, food security, and ecological security, which greatly increased the uncertainty and risk levels of economic and social sustainable development in the arid regions. At the same time, with the construction of the “Silk Road Economic Belt”, China is building the crucial oil and gas extraction and processing supply base, the coal development reserve, the coal bed methane development and utilization base, the strategic mineral resource development base, and the specific agricultural production base in Xinjiang. Xinjiang is designed to become a key fulcrum supporting China’s economic development and plays an important role in the national resource security system, all of which requires greater demands for the coordinated development of the “water-energy-food-ecology” system.

At present, however, only a few studies have investigated the increasingly complex “water-energy-food-ecology” system in the ARNC. The impact of “warm-wet” or “warm-dry” process on ecological environment and economic and social development remains unclear. Therefore, an in-depth study of the “water-food-energy-ecology” system in the region is urgently required as a scientific basis to propose a sustainable development model and green development path for “water-energy-food-ecology” based on the most efficient use of water resources.

4.4. Implications on water resources research in Central Asia

Central Asia is regarded as a key hub for the construction of the “Silk Road Economic Belt”. However, water resources security has been a constant focus of strategic constraints and conflicts among countries along the “Silk Road Economic Belt”. The impacts of climate change and human activities on regional water cycle processes and patterns are exacerbating the water security problems of cross-border rivers in Central Asia. As a result, it has increasingly become a hot topic in international water research (Zeitoun et al., 2013; Best, 2019; Immerzeel et al., 2020). The Shanghai Cooperation Organisation has referenced mutual trust in water resources and ecology as one of the main contents of previous meetings and bilateral talks.

There are about 32 cross-border rivers between the ARNC and Central Asia. As mentioned, the development and utilization of cross-border river water resources are closely related to the construction of the “Silk Road Economic Belt” Initiative. Since the collapse of the

<table>
<thead>
<tr>
<th>Region</th>
<th>Climate change risk to water resources</th>
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<tbody>
<tr>
<td>Eastern Xinjiang</td>
<td>Glaciers here are small and show a distinct receding. With the disappearance of glaciers, some rivers will present a “tipping point of glacier melting” in the near future. River runoff will decrease rapidly due to the lack of glacier meltwater supply, which is at great risk.</td>
</tr>
<tr>
<td>Northern slopes of the Tianshan Mountains</td>
<td>Runoff of the Manas River will increase or remain at normal levels. However, hydrological fluctuations in some small- and medium-sized rivers will increase, raising the risk of extreme hydrological events from rapidly shrinking glaciers.</td>
</tr>
<tr>
<td>Southern Xinjiang</td>
<td>Large-scale glaciers are well-developed in the upper reaches of the Aksu River, the Yarkand River, the Hotan River, the Kaidu River, and the other large rivers. The runoff will maintain at a high level with fluctuations in the future. Also, the risk of glacier lake outburst floods in the Aksu River, the Yarkant River and the Keliya River will increase.</td>
</tr>
<tr>
<td>Hexi Corridor</td>
<td>The Heihe River and the Shule River will maintain a basically stable runoff level. However, the runoff that is at great risk.</td>
</tr>
<tr>
<td>Ili River Basin and Irtysh River Basin</td>
<td>Due to increased precipitation in the mountainous areas, runoff will continue to maintain a high level of fluctuation.</td>
</tr>
</tbody>
</table>
Soviet Union in the late 20th century, cross-border water resources management in Central Asian countries was not based on the river basin as a whole but instead on the individual interests of each country, leading to a predatory development pattern. This approach has made all the water resources security issues more complicated.

The increase in extreme climatic and hydrological events caused by global warming is changing water cycle processes, reducing the stability of the water system, exacerbating hydrological fluctuations and uncertainties in water resources, causing changes in the amount and availability of water resources, and increasing the contradiction between water supply and water demand of the oasis economic systems and desert ecological systems, all of which will trigger water crisis and threaten regional stability. There is little prior research on climate change and ecological environment in Central Asia due to a lack of reliable observations in the alpine regions and a lack of quantitative research on the distribution characteristics and evolution laws of water resources in the cross-border basins. It is necessary to strengthen the research on water problems in Central Asia as well as the ARNC, to evaluate the evolution trend of water resources and the key ecological and hydrological processes under climate change, and to assess the impacts of climate change and water utilization projects on water cycle and water resources. The aim is to provide scientific and technological support in terms of water security for the smooth implementation of the “Silk Road Economic Belt” Initiative.

5. Conclusions

In this study, we stressed the climatic and hydrological characteristics of the ARNC considering the mountain-oasis-desert ecosystem and systematically depicted the risks and challenges of climate change impacts on hydrological processes and water resources in the mountainous region, the agricultural systems in the oases, and the desert ecosystems in the ARNC.

Warming has caused a retreat of mountainous glaciers and snow cover, and in turn affected the hydrological processes by intensifying water cycle and aggravating extreme hydrological events. The hydrological timing and magnitude have also changed. Global warming has led to increased uncertainty around water resources, which resulted in tightened contradictions between water supply and water demand.

The “warm-wet” pattern is prevailing in the Hexi Corridor. However, the condition is not optimism in Xinjiang especially since 1998. The vegetation condition reflected by NDVI has reversed to a decreasing trend, with shrub encroachment on grasslands and shrinkage of the desert-oasis transition zone. By in-depth analysis of water issues in the ARNC, we also need to strengthen research on the evolution of water resources and key processes of hydrological and ecological processes in Central Asia under climate change, and assess the impacts of climate change and water utilization projects on water cycle and water resources. The security of water resources and ecological conditions guarantees scientific and technological support for the smooth implementation of the “Silk Road Economic Belt” Initiative, ultimately benefiting not only China, but also the other countries in the world.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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