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Recent and future climate change in northwest China

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Abstract As a consequence of global warming and an enhanced water cycle, the climate changed in northwest China, most notably in the Xinjiang area in the year 1987. Precipitation, glacial melt water and river runoff and air temperature increased continuously during the last decades, as did also the water level of inland lakes and the frequency of flood disasters. As a result, the vegetation cover is improved, number of days with sand-dust storms reduced. From the end of the 19th century to the 1970s, the climate was warm and dry, and then changed to warm and wet. The effects on northwest China can be classified into three classes by using the relation between precipitation and evaporation increase. If precipitation increases more than evaporation, runoff increases and lake water levels rise. We identify regions with: (1) notable change, (2) slight change and (3) no change. The future climate for doubled CO_2 concentration is simulated in a nested approach with the regional climate model-RegCM2. The annual temperature will increase by 2.7 °C and annual precipitation by 25%. The cooling effect of aerosols and natural factors will reduce this increase to 2.0 °C and 19% of precipitation. As a consequence, annual runoff may increase by more than 10%.

1. Introduction

Northwest China is located in the innermost center (31°∼50°N, 73°∼111°E) of the Eurasia continent. The long distance to the surrounding oceans causes a more or less dry climate.

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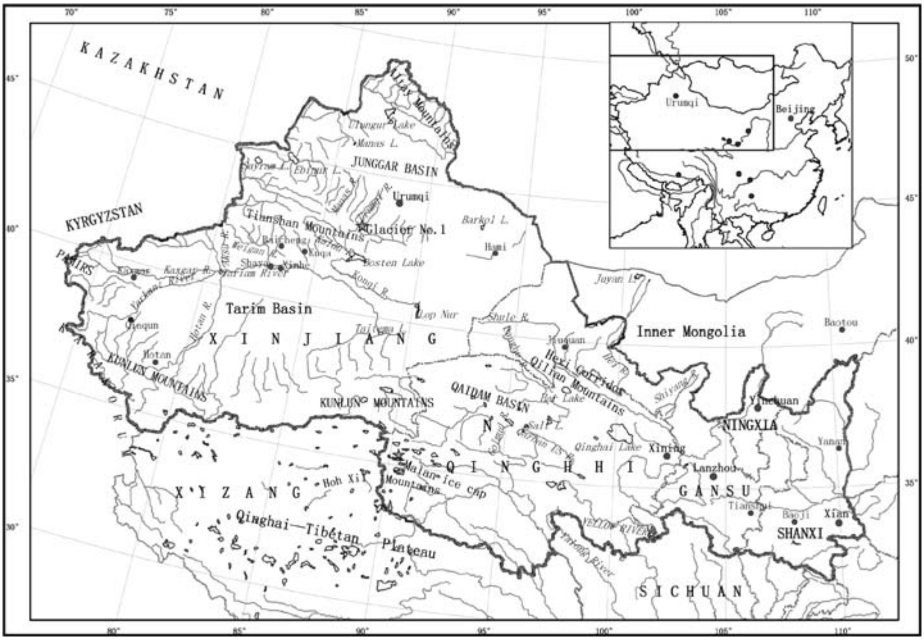

Fig. 1 Sketch map of northwest China

The high mountains with high orograhic precipitation like Tianshan Mountains, Kunlun Mountains and Qilian Mountains block atmospheric circulation and create thus vast desert basins in the rainshadow, such as the Tarim Basin, the Junggar Basin and the Qaidam basin. Both arid basins and humid mountains are sensitive to climate change (Figure 1).

From the end of the Little Ice Age to about 1980, the climate in northwest China has been warm-dry. During the past twenty years it has changed to warm-wet. Research in glaciology, dendrochronology and meteorology has shown for the period from the end of the Little Ice Age to the 1980s, that the air temperature increased by 1.3 and 1.0 °C and the precipitation in the central Tianshan Mountains and in the east Qilian Mountains decreased by 50 to 65 and 70 to 85 mm respectively (Wang, 1991). From 1920 to 1932, the mean annual precipitation in North Xinjiang has decreased by 11.8% compared to the last 350 years (Yuan et al., 2001). After many years of continuous precipitation deficit, an extreme drought occurred in Northwest China during 1928 to 1929. It caused two to three million deaths and was also the reason for continuously low water levels of the Yellow River for 11 years from 1922 to 1932 (Xu et al., 1997). From 1950 to 1987, the runoff from 53 mountain rivers in Northwest China had a generally decreasing trend (Lai and Ye, 1995). These results lead Shi and Ren (1990) to the conclusion that the climate of Northwest China is becoming more warm-dry. We also thought that this trend would continue for the first half of 21st century. However, recent research on climate variation has shown that the water level of the Bosten Lake (42°N, 86°36′E) in central Xinjiang has been rising since 1987 and that the surface area of the Ebinur Lake is also growing (Hu et al., 2002). This facts indicate the increase of precipitation and runoff and lead Shi et al. (2002) to the hypothesis that climate in Northwest China change from warm-dry to warm-wet. The practical consequences of this trend for ecology and economy of west China would be dramatic. However, there remain some important open questions: (1) whether the change is supported by sufficient evidence, (2) whether the time scale for the change is decadal or centennial, and (3) what is the spatial extent of the present climate change. To address these issues, the Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences organized a workshop in Lanzhou in September 2002 with participation of scientists from ten institutes of the Chinese Academy of Sciences, the China Meteorological Administration and the Ministry of Water Resources. The aim of the workshop was to collect all available information about climate and environmental change in Northwest China up to the summer of 2002. This paper presents the results of this workshop.

2. Indicators of climate change in northwest China

The following findings support the thesis, that climate in Northwest China started to change from the year 1987 on from warm-dry to warm-wet.

1. Increasing air temperature
   Temperature data of the last 50 years indicate that the air temperature has a positive trend of 0.2 °C per decade, with a steep increase from the 1980s to the 1990s. The 1990s are considered the warmest decade of the last 1000 years (Wang and Dong, 2002). Compared to the period from 1961 to 1986, average annual air temperature from 1987 to 2000 increased by 0.7 °C for 128 meteorological stations in Northwest China. The same analysis showed an increase by 1.7 °C in the north of Xinjiang with the highest increase in winter. However, outside northwest China, ice core data from the Malan ice cap (35°50′N, 90°42′E) in the Hoh Xil Mountains at the central north Tibetan Plateau show a decrease of 0.6 °C during late 1970s to 1990s (Wang et al., 2003).
2. Increase of precipitation
   From 1980 to 2000 precipitation increased in west and central northwest China as in most regions of the middle and high latitudes. Compared to the years from 1961 to 1986, average annual precipitation from 1987 to 2000 was 22% higher, it increased by 36.0 mm in north Xinjiang; by 33%, 17.4 mm in south Xinjiang and by 10% to 20% in west and middle Hexi Corridor and in some parts of Qinghai Province. A seasonal analysis showed that precipitation increment was highest in winter, followed by rainfall in summer. In the Tianshan Mountains, Qilian Mountains and Altai Mountains, precipitation depends on altitude, the high mountains provide a high amount of the water consumed in northwest China. Although precipitation measurements are very sparse in the high mountains, the increasing runoff of rivers coming from the mountains indicates a substantial increase of precipitation.
3. Melting of glaciers and increase of glacial melt water
   According to the Chinese Glacier Inventory, 22 240 glaciers exist in the mountain drainage basins of northwest China covering an area of 27 974 km^2 with an ice storage of about 2814.81 km^3 (Liu et al., 2000). In a warmer climate, glaciers are retreating and thinning. It is estimated that the glacier area was reduced by 1400 km^2 from 1960 to 1995 with a corresponding increase of glacial melt (Liu et al., 2002). Glacier No.1 (42°30′N, 86°26′E) at the source area of the Ürümqi River, Tianshan, is taken as an example (Figure 2). The average annual runoff of glacial melt water from 1985 to 2001 accounts for 936.6 mm per year, which is 84.2% more than runoff 508.4 mm from 1958 to 1985 (Li et al., 2003).
4. Increase of river runoff
   Actually there are only few meteorological stations for temperature and precipitation measurements in the middle and high mountains in Northwest China, but time series of runoff

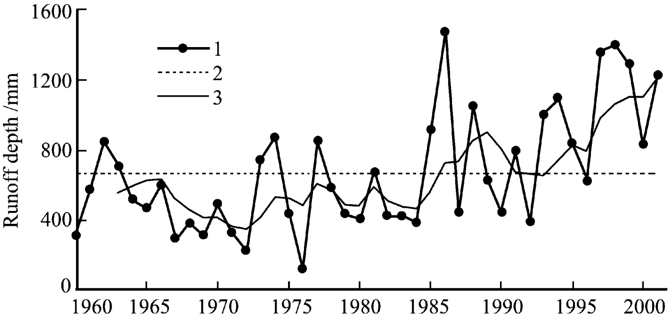

Fig. 2 Variation of melt water runoff of glacier no.1 at the source area of the Ürümqi River from 1960 to 2001 (1. Runoff depth; 2. Mean annual runoff depth; 3. 5-year moving average of runoff depth), (adopted from Li et al. 2003)

of mountain rivers can also give valuable information about climatic and environmental changes in the mountains. Compared to the years 1956 to 1986, 18 of 26 rivers in the Xinjiang area showed an increase of average annual runoff from 5 to 40%. The rivers are originating from Altai Mountains, Tianshan Mountains, and the Karakorum. The highest increase was observed along the south flank of the west Tianshan. However, in the same period, river runoff originating from the central West Kunlun Mountains was reduced by 1.6 to 9.2%. This can be attributed to the decreasing temperature in the northwest part of Tibetan Plateau as fore mentioned ice core data from Malan Ice Cap. The annual total runoff of the Xinjiang area increased from 1987 to 2000 by 6.21 × 10^9 m^3 (7%) compared to 1956–1986. The rivers of the Hexi Corridor of Gansu Province such as the Heihe River, the Shule River and the Dan River originate from the central and west part of the Qilian Mountains. Their runoff increased from 6.34 to 24%. On the other hand, the runoff of the Shiyang River in the east and other eastern rivers showed a decreasing trend in the same period. Runoff of the rivers located at the southeast Qaidam Basin in the Qinghai Province and originating from the east Kunlun Mountains, such as the Qahan Us River and the Golmud River, increased from 6.57 to 26.1%. Other rivers in the Qinghai Province also showed a decrease of runoff. Among them are the upper reaches of the Yellow River whose runoff decreased by 16.75%. This is an important reason for the drying at the downstream of the Yellow River (Yan and Jia, 2003).

5. Water level rise and area expansion of the inland lakes

The water level of the Bosten Lake (42°N, 86°30′E) in the central Tianshan Mountains had a falling trend from start of the measurements in the year 1955 until 1986 (Figure 3). Its surface area was reduced by 13%. The trend reversed in 1987. Until 2002, the water level increased by 4.5 m, arriving at a level 1 m higher than the highest during the 1950s. The lake area grew by more than 1000 km^2. Additionally, the amount of water used for irrigation in the upstream of the lake has increased and 0.45 × 10^9 m^3 water were redirected from the lake per year to aliment the Konqi River and Tarim River at the downstream of the lake. It is therefore evident that the lake water balance and the related climatic conditions must have changed essentially. Obviously, inflow and precipitation into the lake exceed the sum of evaporation, outflow and irrigation water from the lake since 1987. The annual discharge at the Dashankou Hydrological Station of the Kaidu River, which is the main feeding river of the Bosten Lake, increased from 2.47 × 10^9 m^3 in 1986 to 4.97 × 10^9 m^3 in 2000 (Zhang et al., 2003). This indicates a large increase

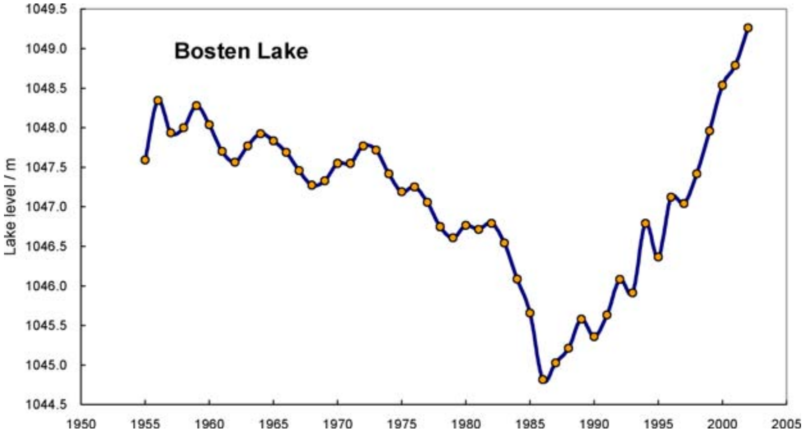

Fig. 3 Water level variation of the Bosten Lake in the Central Tianshan Mountains, Xinjiang from 1955 to 2002 (adopted from Hu et al., 2002)

of precipitation and glacial melt water in the Tianshan Mountains. We assume that this water balance change of the Bosten Lake is a signal and indicator of climate change from warm-dry to warm-wet in northwest China.

The Ebinur Lake (44°30′N, 82°25′E) in the lower northern region of the west Tianshan Mountains is characterized by its wide area and shallow depth, thus its area is extremely sensitive to climate change. Because of the warm-dry climate and a large increase of water consumption, the lake area decreased from 1070 in 1957 to 499 km^2 in 1987. After 1987 inflow increased rapidly and the lake area enlarged to 1064 km^2, thus recovering to the water level of 1957. Without agricultural water use, the lake area would reach 1300 km^2 at the beginning of 20th century (Wang et al., 2003).

The terminal lakes of the inland rivers often dried up because the stream water was used for agriculture and consumption before reaching the lake. The Lake Manas (45°30′N, 86°E), a terminal lake of the Manas River at north flank of the Tianshan Mountains, dried up in 1962. South of the Tianshan Mountains, the Lop Nur Lake and Taitema Lake downstream of the Tarim River dried up in 1972. In the west of Inner Mongolia, the Juyan Lakes consist of West Juyan Lake (Gaxun Nur) (42°30′N, 100°40′E) and East Juyan Lake (Sogu Nur) (42°20′N, 101°E) at the terminal of the Hei River originating from the north flank of the Qilian Mountains. These lakes dried up in 1961 and in 1994. In recent years, however, the Lake Manas and the Taitema Lake have partly recovered because of the increase of stream discharge. In July 2002, a large flood occurred at the upper stream of the Hei River and the discharge reached 931 m^3/s at the mountain outlet. Additional water diversion at the middle and upper streams was limited by administration, thus also contributing to the recovery of the river. The, water now reaches formerly dried up river channels at the downstream and finally the East Juyan Lake.

The areas of the Sayram Lake (2072 m a.s.l., 44°40′N, 87°E) at the west Tianshan Mountains and the Har Lake (4078 m a.s.l., 38° 10′N, 98°E) in the Qilian Mountains showed only small changes because of the high altitude and the lower evaporation rate of the lake water. However, in recent years, a rising water level and a larger surface area of the lakes was observed. An analysis of U.S. NOAA images showed an area of 630 km^2 for the Har Lake in 2001, about 40 km^2 more than 1994 (Guo et al., 2003).

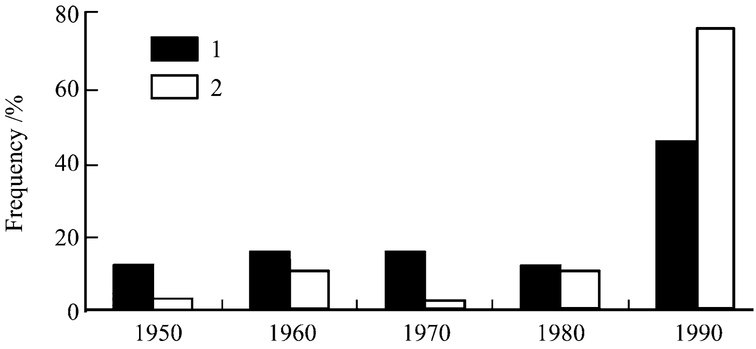

Fig. 4 Frequency of extraordinary flood and deluge of 26 rivers in Xinjiang from 1950 to 1990 (1. Frequency of annual discharge with 20 year return period 2. Frequency of annual peak discharge with 50 year return period.), (adopted from Wu et al., 2003)

On the other hand, the water level of the famous Qinghai Lake still descends based on the water level record until 2001 because it lies outside the regions of the climate change to warm-wet. However, a 30 cm water level rise was observed in summer, 2002 (Xu and Wang, 2002).

6. Increasing frequency of flood disasters

The flood affected area of Xinjiang was only 4.28×10^3 to 5.22×10^3 ha during 1950s to 1970s, but it suddenly increased to 36.47×10^4 ha in 1987 (Jiang et al., 2002). This can be an effect of climate change. Large floods caused by heavy rainfalls and rapid glacier and snowmelt under the high air temperature conditions are climatic extreme events. The floods are classified according to their return period: a period $P \geq 50$ years is an "extraordinary flood", $20 \leq P \leq 50$ is defined as a deluge. Figure 4 shows that during the 45 years from 1956 to 2000 we counted 56 deluges, 27 occurring during the 14 years from 1987 to 2000, 21 out of 28 extraordinary floods from 1956 to 2000 happened from 1987 to 2000 (Wu et al., 2003). As pointed out in the IPCC Report (IPCC 2001), the total precipitation increases in various regions, while the increase of the large or extreme precipitation events is more obvious. Among all flood disasters in Xinjiang, the most serious was in 1996, when 8 rivers reached the highest level and 5 rivers the second highest. (Zhang and Shi, 2002). The direct economic loss the GDP in Xinjiang was 7% for that year. In 1999, 24 rivers in Xinjiang reached highest level and 7 rivers the second highest. The glacier dammed outburst flood at the Yarkant River from the Karakorum Mountains disappeared during late 1980s and 1990s, but it reappeared in 1999. The flood discharge reached 6070 m^3/s at the Qiaqun Hydrological Station that was the second highest level (Wu, 2002). In 2002, an extraordinary flood of over 100 years return period occurred for the Weigan River at the south flank of the Tianshan Mountains. The continuous heavy precipitation and the rapid glacier melting formed and enhanced the deluge from 19 to 23 of July, destroying two big reservoirs. The flood discharge reached 3540 m^3/s, causing the serious disasters in the Baicheng, Shaya, Xinhe, and Kuqa counties (Huang et al., 2003).

7. Increase of vegetation cover

The change of vegetation cover was examined by using the normalized difference vegetative index (NDVI) of NOAA/AVHRR images that were available for northwest China from 1981 to 2001. The degenerating vegetation (NDVI $0.225\sim-0.02$) covers 56%, the relatively stable vegetation (-0.02–0.02) accounts for 31%, 13% of formerly uncovered area is now covered by vegetation improvement (NDVI 0.02–0.339). The main area with

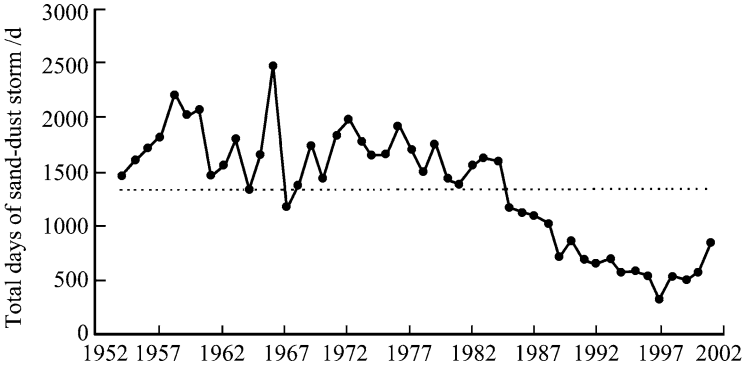

Fig. 5 Variation of the annual days with sand-dust storms from 1954 to 2001 in Northern China (adopted from Li et al., 2003)

additional vegetation is located in west Xinjiang and north Xinjiang. This corresponds to the precipitation increase found in this area. In oasis areas such as Hotan of south Xinjiang; the Hexi area of Gansu Province; the Yinchuan plain of Ningxia region, the vegetation cover also improved because of better water supply and management (Ma et al., 2003).

8. Reduction of sand-dust storm days

A sand-dust storm is defined as sand and dust weather with the visibility of less than 1 km. If the minimum visibility $\leq$200 m and the maximum wind speed $\geq$20 m/s, it is defined as the strong sand-dust storm; If the minimum visibility $\leq$50 m and the maximum wind speed $\geq$25 m/s, the sand and dust weather is defined as extraordinary strong sand-dust storm (Wang and Dong, 2002). Figure 5 shows the annual variation of total days with sand-dust storm over the whole northern of China from 1954 to 2001. It indicates that the sand-dust storms were most frequent from 1960s to 1970s; it was reduced in the middle of 1980s and reached a minimum in the 1990s. After 1997 the number of sand-dust storm days slightly increased, especially in the eastern part of northern China (Qian et al., 2002).

The number of strong and extraordinary sand-dust storm is 48, 68, 89, and 47 in 1950s, 1960s, 1970s and 1980s respectively. In the 1990s it is reduced to 36 (Qian et al., 2002). The decrease of the sand-dust storms may be attributed partly to the above-mentioned precipitation increase and improved vegetation cover. When the vegetation cover is larger than 60% there is only low wind abrasion. High wind abrasion appears only for vegetation cover of less than 20% (Wang et al., 2001). The decrease of the number of days with gale is the most important reason for the reduced sand-dust storms. Based on the statistical data from Xinjiang, the gale days were reduced from 14.3 in the 1960s–1970s to 11.2 in the 1980s–1990s in north Xinjiang. The corresponding mean gale speed was reduced from 16.90 to 14.11 m/s. There is a positive correlation between the days of sand-dust storms and the gale days on the basis of the statistics of the data from different regions and different decades in the Xinjiang area, and they are rapidly reduced from 1960s–1980s to the years of 1990s (Zhang and Shi, 2002). The gale wind forms mainly by the strong and cold air flows from north to south during winter and spring. Under the global warming, air temperature of the northern high latitudes increases more than in middle and low latitudes. Thus, the lower gradient of north-south atmospheric pressure causes a decrease of gale. However, the variation of weather situation may still cause large fluctuations of the pressure gradient.

3. Criteria, distribution, and possible reasons for climate change in northwest China

3.1. Criteria for climate change

The above-mentioned changes in air temperature, precipitation, glacial melt water, river runoff, lake water level, flood, vegetation and sand-dust storm days are indicators for a climate change from warm-dry to warm-wet in Northwest China. This global warming enhances the water cycle and increases both precipitation P and evaporation E. Through the balance of P and E, there will be the two situations as follows:

First situation:

$$\Delta P < \Delta E \tag{1}$$

If precipitation increases less than the evaporation (Equation (1)), the climate changes to warm-dry as for example from the end of the Little Ice Age to the 20th century in Northwest and North China. This trend of warm and dry continues up to now in the eastern part of Northwest China and North China.

Second situation:

$$\Delta P > \Delta E \tag{2}$$

If precipitation increases more than evaporation (Equation (2)), the climate changes to warm-wet as could be observed since 1987 in the central and west regions of northwest China.

The above two situations are theoretical. In reality the actual evaporation includes plant evapotranspiration, which is not easy to measure. Water balance equation for a river basin is as follows

$$R = P - E \pm \Delta S \tag{3}$$

Where R is runoff and ΔS is the water storage change including glaciers, ground water, lakes and reservoirs. When $\Delta P > \Delta E$, Equation (3) indicates that both runoff and glacial melt water increase, and the water levels of the inland lakes rise and their areas enlarge. A further increase of available water and temperature would enlarge vegetated area and reduce desertification. If such situation persists for a period of 10 years and more, the climate changes to warm-wet.

3.2. Spatial extent of the climate change

At present, the change of northwest China from warm-dry to warm-wet climate can be classified into three types as shown in Figure 6.

1. Notably changed region
   In this area, all of the above-mentioned eight aspects of change from warm-dry to warm-wet could be observed. This area covers north Xinjiang, the Tianshan Mountains and their slopes, the west Tarim Basin, the down stream area of the Yarkant River, the central-west part at the north flank of the Qilian Mountains, the area of southeast Qaidam Basin with

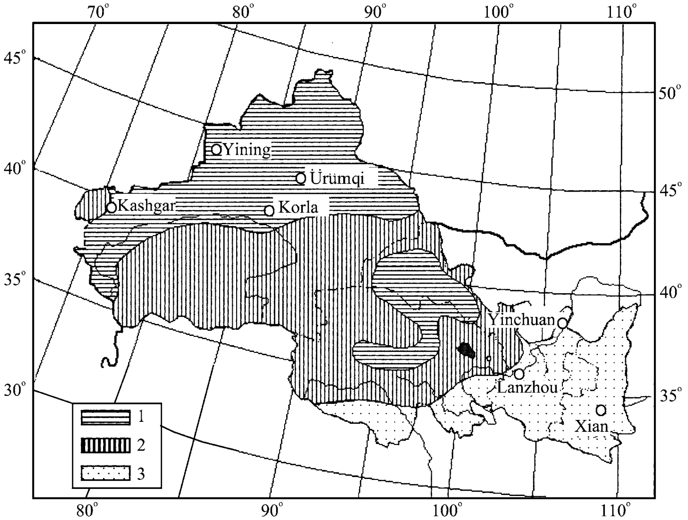

Fig. 6 Area of change from warm-dry to warm-wet climate in Northwest China (1: Notably changed region; 2: Slightly changed region; 3: Unchanged region)

the Golmud River and the Qarhan Us River. The region's western boundary could extend into the central Asian countries, including parts of Kazakhstan and Kyrghyzstan.

2. Slightly changed region
   In this class, precipitation increases are too small to generate additional surface runoff. The region's vegetation cover is not or only partially improved, but the days with sand-dust storms are reduced. This region covers in the Taklamakan Desert in the Tarim Basin, the Gobi desert in east Xinjiang and areas around the edge of Gansu and Qinghai province, and the interior Qaidam Basin. Because of the originally extremely dry environment, the evaporation from the land surface is very small and the local water cycle is unable to promote precipitation increase. Some parts of Gansu and Qinghai Province are also tentatively put into this class.
3. Unchanged region
   This region is mainly in the central and east Gansu, Ningxia, Shanxi and east part of Qinghai provinces. The region is characterized by the semi-arid to temperate climate and light southeast monsoon precipitation, which remained warm-dry in 1990s.

3.3. Possible causes of the climate change

Two possible causes of climate change are:

(1) Increase of atmospheric water vapor content and the favorable weather situation.
Precipitation is a function of water vapor content in the atmosphere. The NCEP/NCAR reanalysis (1958–2000) showed the atmospheric vapor content decreased in most parts of Northwest China during the 1960s and 1970s. This trend reversed in 1980s and changed to an increase in 1990s, especially in the western part of Northwest China (Figure 7). In many places, the water vapor increased from 0.07 to 1.6 mm in the 1990s. The source of atmospheric water vapor is the Indian Ocean, the south of the Arabian Sea, and partly the west and northern part of Atlantic Ocean and the Arctic Ocean. (Yu et al., 2003).

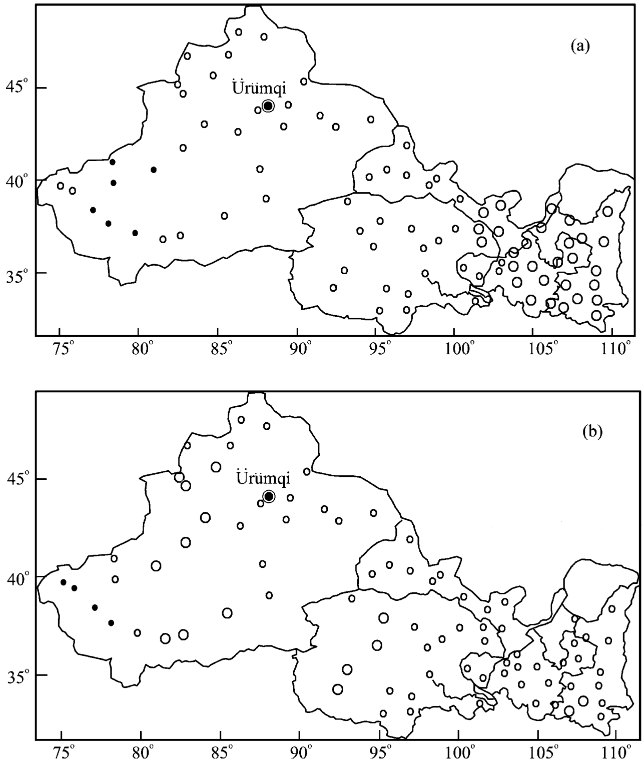

Fig. 7 Distributions of linear trend of annual water vapor content in the total air column in northwest China ((a) 1980s, (b) 1990s, *large circle*: 0.7–1.4 mm/10 yr in 1980s or 1.6 mm/10 yr in 1990s, *small circle*: 0–0.7 mm/10 yr, *black dot*: –0. 2~0 mm/10 yr), (adopted from Yu et al., 2003)

A comparison of the geopotential height and wind field of the 500 h Pa surface of 1987 to 1999 and 1961 to 1986 indicates that the pattern in the period of 1987 to 1999 was favorable to enhanced southern wind and water vapor transport to the north. Therefore, the atmospheric circulation during the years from 1987 to 1999 favours the precipitation in the Xinjiang region.

(2) Enhanced water cycle caused by global warming.

The recent climate change from warm-dry to warm-wet in the west and central parts of Northwest China is not an isolated phenomenon. From 1980s to 1990s, the water cycle is enhanced and accelerated by the notable global warming, causing an increase of precipitation. The trends of annual precipitation between 30°–55°N in 1990–1999 reached with 6.8% a higher value than the 0.3% increase from 1946 to 1975, especially in North America, western Russia and central Asia.(Salinger, 2005). The surface temperature of the Indian Ocean is usually higher than that of the Pacific Ocean and the Atlantic Ocean at the same latitude owing to their northern side closed by land masses. The 1990s was the warmest decade of the last 1000 years. The air temperature in the Indian Ocean region was the highest in 1998, the water temperature was 3 to 5 °C higher than the normal value measured by AVHRR images in the tropic Indian Ocean. The annual mean air temperature at Chogos islands in the center of the Indian Ocean rose 1 °C from 1963 to 1998 (Sheppard, 1999) causing a massive decline of coral reefs (Wilkinson et al., 1999).

Table 1 Climate change in Northwest China under doubling of CO_2 concentration, simulated with a regional climatic model RegCM2 based on CSIRO simulations

	Annual	Winter	Spring	Summer	Autumn
Temperature (°C)	2.7	3.0	3.0	2.7	2.6
Precipitation (%)	25	47	36	9	28

Therefore, the evaporation from the Indian Ocean should be higher, thus increasing water vapor transport from the Arabian Sea to the Northwest China. Bengtsson (1997) estimated that the increase of air temperature caused by doubling of the greenhouse gases would increase the vapor content of the atmosphere by 15%. It will increase the vapor transport from the ocean to the land by 11%, land surface evaporation by 5%, land precipitation by 8.5% and the runoff back to the ocean by 10.3%. As a consequence, the accelerating water cycle caused by global warming increases precipitation in the west and central parts of Northwest China.

4. Future projection of climate in northwest China

It is natural for different attitudes and suspicions to come forth as soon as the hypotheses is brought forward about the climate change from warm-dry to warm-wet in Northwest China. The key problem is with whether the time scale of the change is in decades or in centuries, and whether the spatial scale is only limited in the central and west parts or it can extend eastward to cover the entire Northwest China and even to whole Northern China. No matter which method is used to project the future, there are still many uncertainties. As previously mentioned, the authors recognize that precipitation increase induced by global warming and the speed up of the water cycle could be a reason for the climate change to warm and wet of major parts of northwest China since 1987. IPCC (2001) synthesized the simulation results of more than 20 GCMs and suggested that the global mean air temperature could increase by 1.4 to 5.8 °C in the 21st century because of the large increase of greenhouse gases (IPCC, 2001). Nevertheless, it is difficult to work out a correct prediction of future climate, because the intensification of the water cycle, variability of precipitation and increase of air temperature are all nonlinear processes. It is therefore very difficult to decide where the precipitation would increase because of the complexity of the circulation patterns. As Figure 7 indicates, the atmospheric vapor content increased in the eastern part area of northwest China during the 1980s and 1990s, yet the different circulation patterns brought drought in the east and excessive precipitation in the west.

Among the existing climate modeling studies in China with focus on Northwest China. Gao et al. (2001, 2003) e.g. apply a nested approach combining the regional climate model RegCM2 (Giorgi et al., 1993) and the global coupled ocean-atmosphere model CSIRO R21L9 (Gordon, 1997) to simulate the climate for double CO_2 content. Their results indicate that the annual air temperature would increase by 2.7 °C, and the annual precipitation would increase by 25% in Northwest China. Figure 8 shows the increase of simulated precipitation and air temperature increase in Northwest China. Table I shows the simulated climate change for different seasons in Northwest China.

If precipitation increase would reach the values in Figure 8a, then actual climate change in the Northwest China would continue as century scale. However, Gao et al. (2003) an-

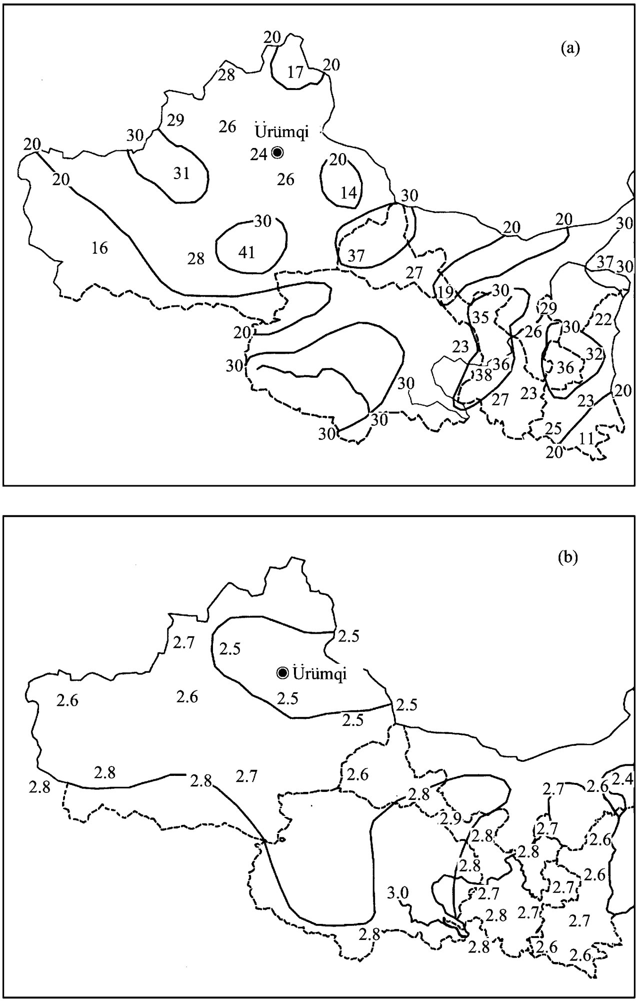

Fig. 8 Simulated climate change for double CO_2 content by a regional climate model in Northwest China ((a) Change of annual precipitation (%) (b) Change of annual air temperature (°C)), (adopted from Gao et al., 2003)

nounced that because of various uncertainties in the climate models, the results of numerical simulations could be very variable.

In addition to the man made increase of greenhouse gases, the non-human or natural factors also may have contributed to the recent climate change. There could be e.g. a solar activity change expressed by the solar spot cycle length (SCL). This solar spot cycle could be longer during the next 10 to 20 years, thus the air temperature could decrease as compared to the 1990s. On the other hand, a higher solar activity in the next 250 years could be favour a warm and wet climate (Tang et al., 2002). Considering both the warming effect of CO_2 and the cooling effect of aerosol from the simulation of 7 GCMs, Zhao et al. (2002) synthesize the influence of human activities on one side and and natural factors on the other side. They project that the possible warming would be about 2.0 °C and precipitation increase by 19%

in northwest China. Precipitation increase would be the highest with 23% in Gansu and the least with 14% in Inner Mongolia. The annual runoff would also increase by several to more than 10%. Zhao et al. (2002) also pointed out that the projection of air temperature change is relatively reliable, while that of precipitation change is highly variable (Zhao et al., 2002). Taking into account the natural effects, along with the spatial variation, some regions will become slightly wet or dry, or alternatively wet and dry.

5. Conclusion and discussion

Based on an analysis of the hydrological and meteorological data base, basic circulation patterns and modeling studies we think that climate change from warm-dry to warm-wet started in 1987 in northwest China. Eight facts support this thesis: (1) A continuously rising air temperature with an annual temperature 0.7 °C higher from 1987–2000 compared to 1961–1986. (2) A notable increase of precipitation with annual precipitation 10–30% higher from 1987–2000 compared to 1961–1986. (3) Glacier retreat and glacial melt water increased. Glacier area is reduced by 1400 km^2 from 1960 to 1995 and the annual runoff of glacial melt water was 84.2% higher in 1985–2001 than during 1958–1985 at Glacier No.1 of the Urumqi River, Tianshan. (4) Increased of river runoff. The annual total runoff of the Xinjiang area was 7% higher in 1987–2000 than in 1956–1986. (5) Water level rise and area expansion of the inland lakes. The Bosten Lake in the central Tianshan Mountains showed a descending trend from 1955 on which reversed to rise since 1977 and reached 4.5 m in 2002. The lake area grew by more than 1000 km^2. (6) Frequency of flood disasters largely increased. Extraordinary flood occurred 7 times during 1956–1986 and 21 times from 1982–2000 in Xinjiang area. (7) Vegetation cover increases in the west and north Xinjiang, linked with a notable increase in precipitation and with better management on water usage in several oasis (8) Less sand-dust storm days. In northern part of China, the 68 and 89 days with strong and extraordinary sand-dust storms in the 1960s and 1970s were reduced to 47 in the 1980s and 36 in the 1990s.

The climate change discussed above can be classified into three types shown in Figure 6: (1) The notably changed region covers largely northern part of Xinjiang and west part of Gansu, and small part of Qinghai. (2) The slightly changed region covers the Taklamakan Desert, the borderland of Xinjiang, Gansu and Qinghai and (3) the unchanged region covers mainly the east part of northwest China.

An analysis of moisture transport and atmospheric circulation showed an increase of moisture during 1980s and 1990s caused by the global warming which enhances the northward transport of moisture from the tropical Indian Ocean. A change of the upper air wind field over Northwest China indicates that the moist current from the south is strengthened in recent years especially in Xinjiang area. This is the main reason for the west to become wet and the east to be still dry.

Using a regional climate model RegCM2 nested with a global coupled ocean-atmospheric model from CSIRO to simulate the climate under doubling of CO_2 in northwest China, the results indicate that annual air temperature could increase 2.7 °C and annual precipitation by 25% as showed in Figure 8. Considering the cooling effect of aerosols and natural factors mainly solar activity change, here only give the variation of solar spot cycle length, temperature could increase by 2.0 °C and the precipitation by 19% in northwest China.

Owing to the complexity of climate change and large area of extensive deserts and high mountains without meteorological observations, the above projection contains large uncertainties. Further work is required to to detect, attribute and understand climate and to reduce uncertainties. The monitoring of alpine glaciers, climate, hydrology, lakes and ecology should be greatly extended. Adapting the climate change, we have to make use of water resources and energy more efficient. It is necessary to construct more reservoirs in the alpine area to regulate runoff and reduce the flood disasters and to improve the use of water power.

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