

Climatic causes of ecological and environmental variations in the source regions of the Yangtze and Yellow Rivers of China

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Abstract In the source regions of the Yangtze and Yellow Rivers of China, glaciers, frozen ground, the hydrological system, and alpine vegetation have changed over the past decades years. Climatic causes of these variations have been analyzed using mean monthly air temperature and monthly precipitation between 1956 and 2000, and monthly evaporation from $\phi 20$ evaporation pans between 1961 and 1996. In the source region of the Yangtze River, lower temperature and plentiful precipitation during the 1960s and continuing into the early 1980s triggered a glacier advance that culminated in the early 1990s, while a robust temperature increase and precipitation decrease since 1986 has forced glaciers to retreat rapidly since 1995. Permafrost degradation is another consequence of the climatic warming. The variations in the hydrological system and alpine vegetation are controlled mainly by the climate during the warm season. Warmer and drier summer climate is the major cause of a degradation of the vegetation, desiccation of the high-cold marshland, a decrease in the areas and numbers of lakes and rivers in the middle and north source regions of the Yangtze and Yellow Rivers, and a reduction in surface runoff in the source region of the Yangtze River for the last 20 years. The causes of eco-environmental change in Dari area, near the outlet from the source area of the Yellow River, are different from those elsewhere in the study area. A noticeable reduction in runoff in the source region of

the Yellow River and degradation of alpine vegetation in Dari area are closely related to the permafrost degradation resulting from climate warming.

Keywords Source regions of the Yangtze and Yellow Rivers · Climate change · Eco-environment variations · Cause · China

Introduction

The source regions of the Yangtze and Yellow Rivers are located in the hinterland of the Tibetan Plateau. The mean height above sea level is $>4,000$ m in this area. The lofty topography results in a very cold climate. Mean annual air temperature ranges from -1.0°C to -6.0°C . Annual precipitation decreases from ~ 550 mm in the southeast to ~ 200 mm in the northwest. As a result, permanently frozen ground (permafrost) is extensive and glaciers have formed in the Mountains (Fig. 1). Rivers and lakes are numerous owing to precipitation and to the supply of meltwater from glaciers and snow cover (Fig. 2). Dominant vegetation types in the area are high-cold grassland dominated by *Stipa purpurea*, *Carex moorcroftii*, and *Littledalea racemosa* species, and alpine meadow dominated by *Kobresia pygmaea*, *Kobresia humilis*, *Kobresia tibetica*. The cryospheric environment, including the high-cold terrestrial hydrological and alpine vegetation systems, has changed greatly in the past 50 years, and especially in the past 20 years. Glaciers have receded (Lu et al. 2002; Yang et al. 2003), permafrost has warmed and even degraded (Wang et al. 2001a; Yang et al. 2004a), lakes and rivers have decreased in size and number (Wang et al. 2004;

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Fig. 1 Map of the source regions of the Yangtze and Yellow Rivers, showing the distribution of glaciers and frozen ground, and the meteorological stations used in our study

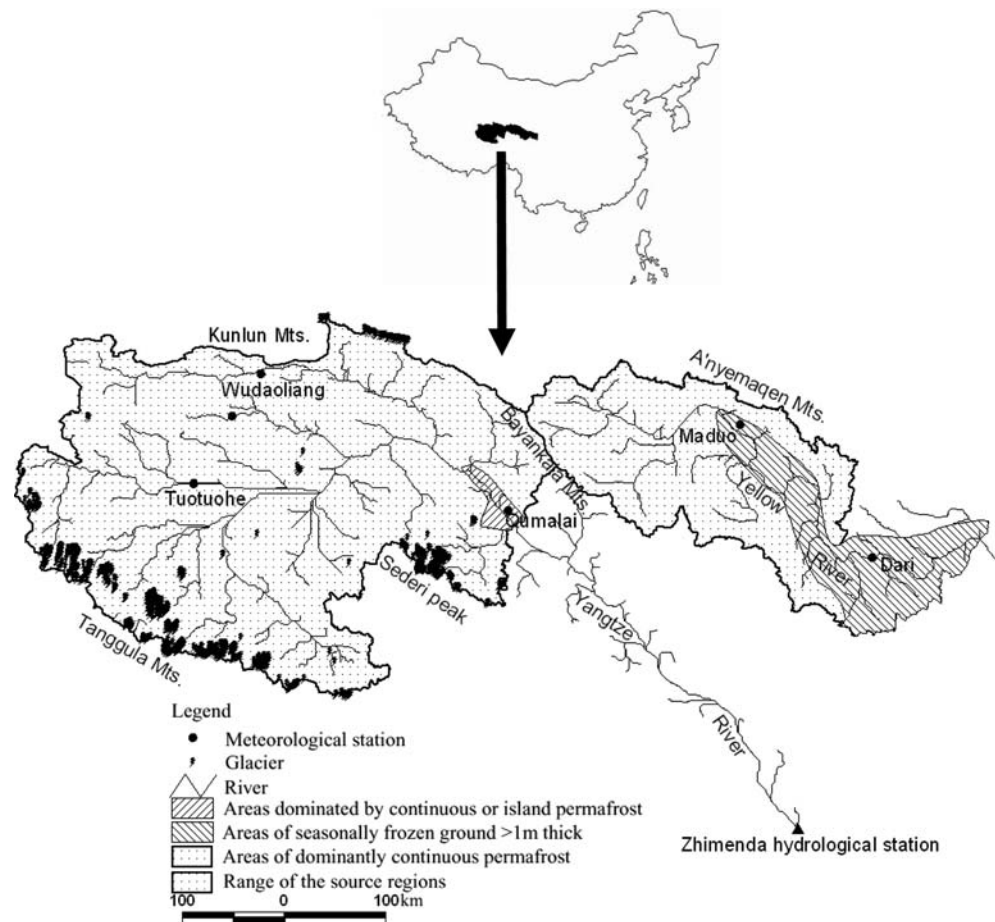
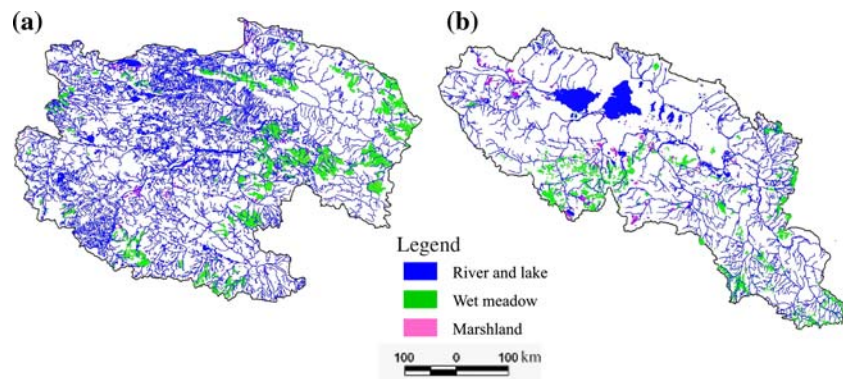


Fig. 2 Map showing various types of high-cold wetlands in the source regions of the Yangtze and Yellow Rivers. **a** Source region of the Yangtze River; **b** source region of the Yellow River



Yang 2006), the area of high-cold marshland has decreased sharply (Yang 2006), surface runoff in rivers has dropped markedly (Yang 2006), alpine vegetation has been heavily degraded locally, and soil loss and desertification have been severe (Wu 2000; Zheng 2000; Sha et al. 2001). These changes have made the ecological environment worse, consequently reduced the carrying capacity of pasture land by about 70–80% (Zhang et al. 1999). More importantly, the changes

affect not only the source regions themselves, but also the middle and lower reaches of the two river systems. For example, along the lower Yellow River there are water shortages, the water supply is frequently cut-off, and the water environment has deteriorated (Liu and Zhang 2004), and along the middle and lower Yangtze River floods have increased (Jiang and Shi 2003) and soil moisture loss has been aggravated (Wang et al. 2001b). All of these are directly related to the poor

eco-environmental health in these areas since the late 1980s. The ecological environment of the source regions is so important that these changes have attracted the attention of the Chinese government and the entire country. Completion of Qinghai-Xizang Railway and its opening to traffic have made the economic potential of the source regions more evident.

For these reasons, studies of ecological and environmental change in the source regions of the Yangtze and Yellow Rivers have been a focus of environmental change research in western China during the past 10 years. Comprehensive studies of variations in climate, glaciers, frozen ground, alpine vegetation, and surface runoff have been carried out (Wang and Cheng 2001; Wang et al. 1998, 2001a, b, c, 2004; Yang et al. 2003, 2004a, b, 2006; Liu et al. 2002; Lu et al. 2002; Yang 2006; Xie et al. 2003). The major purpose of the present study is to determine the role of climate in controlling variations in the cryospheric environment, hydrological system and alpine vegetation by analyzing the variations in air temperature, precipitation, evaporation from $\phi 20$ evaporation pans in the source regions of the Yangtze and Yellow Rivers for the past 50 years, and especially for the past 20 years.

The study region and data sources

Description of the study region

The headwaters of the Yangtze River are between 32°30' and 35°40'N and between 90°30' and 96°00'E. The watershed area is 12.24×10^4 km². The headwater region of the Yellow River is between 33°00' and 35°35'N and between 96°00' and 99°40'E. Its watershed covers 4.49×10^4 km² (Ding et al. 2003). Both areas are on the Tibetan Plateau (Fig. 1).

Data used

Meteorological stations are sparse; there are only five stations, Wudaoliang, Tuotuohe, Qumalai, Maduo, and Dari in the study region. Moreover, these stations are located in the relatively lower altitudes (Fig. 1). Owing to good agreement among the five stations, variations in air temperature at these stations are believed to be representative of its changes in the region as a whole. Precipitation at the five stations is less representative of higher altitudes owing to strong local variability. The meteorological data used in this study are mean monthly air temperature and monthly precipitation between 1956 and 2000, and monthly evaporation from $\phi 20$ evaporation pans between 1961 and 1996.

Evaporation data from 1997 to 2000 are not available. Thus evaporation during the 1990s is the averaged from 1991 to 1996. Evaporation data from Qumalai station are excluded in the following analysis because of extended periods of missing data.

The Dari hydrological station is near the Dari meteorological station. The time series of measured runoff at Dari runs from 1959 to 1999. There is no hydrological station on the Yangtze River near the outlet from the study area. Thus measured runoff data from 1961 to 2000 at Zhimenda hydrological station (Fig. 1) are used.

Details of the ecological environment in the study region

Glaciers

Glacierization is a phenomenon resulting from a certain combination of air temperature and precipitation. Glacier advances when accumulation of snow exceeds melting, whereas glacier retreats when the converse is true. There are no glaciers in the source region of the Yellow River because no mountains reach 5,300 m height above sea level, the height of the local snowline. Thus the analyses of glacier changes and their causes are only possible for the source region of the Yangtze River. Glaciers are concentrated principally in the Tanggula Mountains, the Kunlun Mountains, and the Sederi peak (Fig. 1). Glaciers on the Tibetan Plateau are divided into three types: maritime, subcontinental, and continental (Shi and Liu 2000). Glaciers in the Tanggula Mountains and the Kunlun Mountains are continental, characterized by a high altitude snowline, little accumulation, low ablation, low budget gradient, low temperature, and sluggish movement (Pu 1994). Glaciers in the Sederi peak are subcontinental, a transitional type between maritime and continental. However, they are generally closer to the continental endmember in some physical characteristics (Pu 1994).

Glaciers have generally retreated in the source region of the Yangtze River during the past 40 years. For example, southern Jianggudiru Glacier, which is located in the western Tanggula Mountains, retreated 1,288 m between 1969 and 2000, a mean rate of 41.5 m/year (Yang et al. 2003). Though glaciers generally receded between 1969 and 2000, the trend was interrupted by short intervals of stagnation or advance. Advancing glaciers dominated before 1995 and most glaciers have retreated since then. For example, Dongkemadi Glacier, which is located in the middle Tanggula Mountains, advanced 9.4 m between 1969

and 1989 (Jiao and Yan 1993), and ~15 m from 1989 to 1994 (Yang et al. 2003). Since 1994, the glacier has been retreating steadily. Glaciers in many parts of the world behaved similarly (Dyurgerov et al. 2000; Meier et al. 2003; Bogen et al. 1989; Patzelt 1985; Porter 1986; Stingl and Garleff 1985; Leiva et al. 1986, 1989; Ding 1995; Zhang et al. 1981; Su et al. 1999; Li et al. 1999). Owing to this retreat glacier water reserves have decreased $\sim 65 \times 10^6 \text{ m}^3/\text{year}$ in the source region of the Yangtze River (Yang et al. 2003). Although this decrease results in an increase in runoff of glacial meltwater, the effect on the discharge of the Yangtze River is not particularly significant (Yang et al. 2003).

Frozen ground

The spatial distribution of frozen ground in the study regions was shown in Fig. 1. The majority of frozen ground is continuous permafrost, interrupted only by local large rivers and local area of high geothermal heat flux. In the past 20 years, the ground temperature at depths of 0 to 40 cm has increased by about 0.3–0.7°C in areas of predominantly continuous and island permafrost, and by 0.4–0.6°C in areas of seasonally frozen ground of intermediate thickness (>1 m). Ground temperatures increased by 0.2–0.3°C at depths of 15 to 20 m, and by 0.1–0.2°C at depths of 25 to 35 m in borehole No.1 at Fenghoushan Mountains. In a borehole at the Kunlun Pass they increased by 0.2–0.4°C at depths of 6 to 15 m (Jin et al. 2000). The permafrost table has dropped at the rate of 2–10 cm/year, and the active layer has thickened in the source region of the Yangtze River since the 1980s (Tong and Wu 1996). A thawing interlayer is widely distributed along the margins of the predominantly continuous permafrost area of the source region of the Yellow River. According to a large number of studies, the permafrost table was at the depths of 4–7 m below the surface, while seasonally freezing depth was only 2–3 m. The thawing interlayer reached the depths of 1–4 m.

Hydrological system

The river, lake and marshland (including high-cold wet meadows), components of terrestrial hydrological system (including three types of high-cold wetlands) are found mainly in the source region of the Yangtze River, where they account for 69.6, 71.8, and 74.5% of the total rivers, lakes, and marshlands, respectively, in the combined study areas. In the source region of the Yellow River there are relatively few of these components, and they are found largely in the western part

of the region (Fig. 2). Landsat TM images taken in 1986 and 2000 show a ~18.1% decrease in the number of lakes and a ~10.6% decrease in lake surface area in the source region of the Yangtze River between those two dates. Similarly, the number of rivers decreased by ~15.8% and their area decreased by ~9.0% in area in the source region of the Yellow River. The marshlands decreased sharply by ~24.4% in the combined study areas. In the source region of the Yangtze River they decreased by ~28.1%, accounting for ~86.0% of the total reduction area in the combined areas. In the source region of the Yellow River they decreased by ~13.4%, accounting for ~14.0% of the total. Surface runoff in rivers also decreased in both drainages (Fig. 3). The heavy solid line in the Fig. 3 is the differential mass curve. The runoff at Zhimenda hydrological station was close to the multi-annual average in the 1960s, higher than average in the 1970s and 1980s, and lower in the 1990s (Fig. 3a). The runoff at Dari hydrological station increased gradually over the 1960s to the 1980s and then dropped in the 1990s (Fig. 3b). The averaged runoff of the 1990s decreased by ~17.4% at Zhimenda, by ~22.7% at Dari compared to the mean runoff of the 1960s to the 1980s.

Alpine vegetation

Alpine vegetation in the study regions degraded noticeably over the past 20 years. Degradation occurs as vegetation cover is reduced, soil is uncovered in local areas, and above-ground biomass decreases in grasslands. High-cold grasslands and alpine meadows with higher vegetation coverage (>30%) have decreased by ~15.8 and ~5.2% over the 1986 to 2000 period, respectively (Wang et al. 2004). According to field studies of alpine meadows in the Tanggula Mountain area, the above-ground biomass of degraded alpine meadows has dropped by ~21.9–59.6% compared to that of undegraded alpine meadows. Vegetation cover is reduced from >90% in the undegraded to ~38–77% in the degraded areas.

The climate change in the study regions

Variations in the regionally averaged time series for mean annual air temperature and annual precipitation in the study regions are presented in Fig. 4. Mean annual air temperature had a robust increasing trend, rising 0.8°C in the source region of the Yangtze River and 0.7°C in the source region of the Yellow River between 1961 and 2000. Air temperature was lower

Fig. 3 Variations in measured annual runoff at Zhimenda (a) and Dari (b) hydrological stations in the source regions of the Yangtze and Yellow Rivers

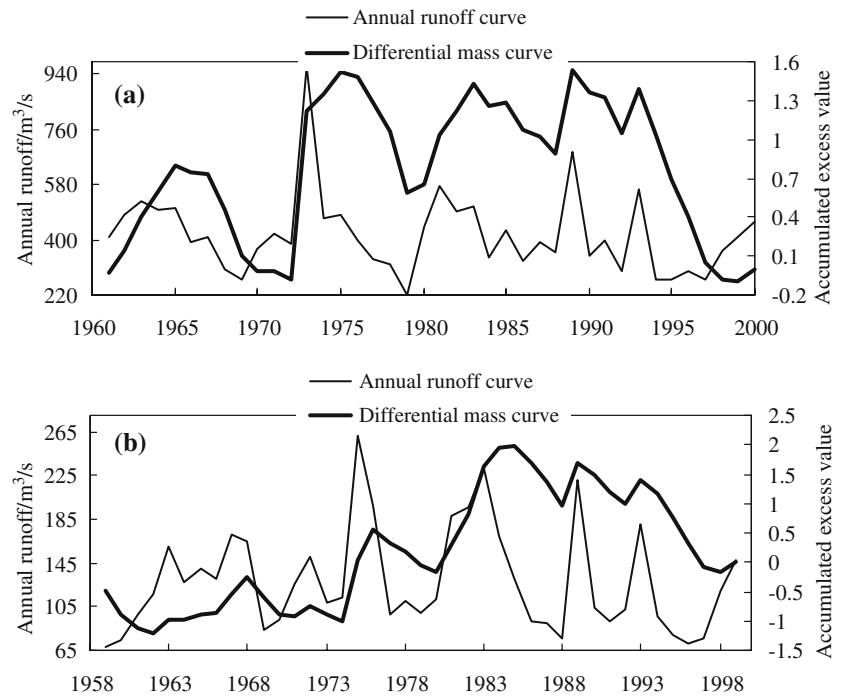
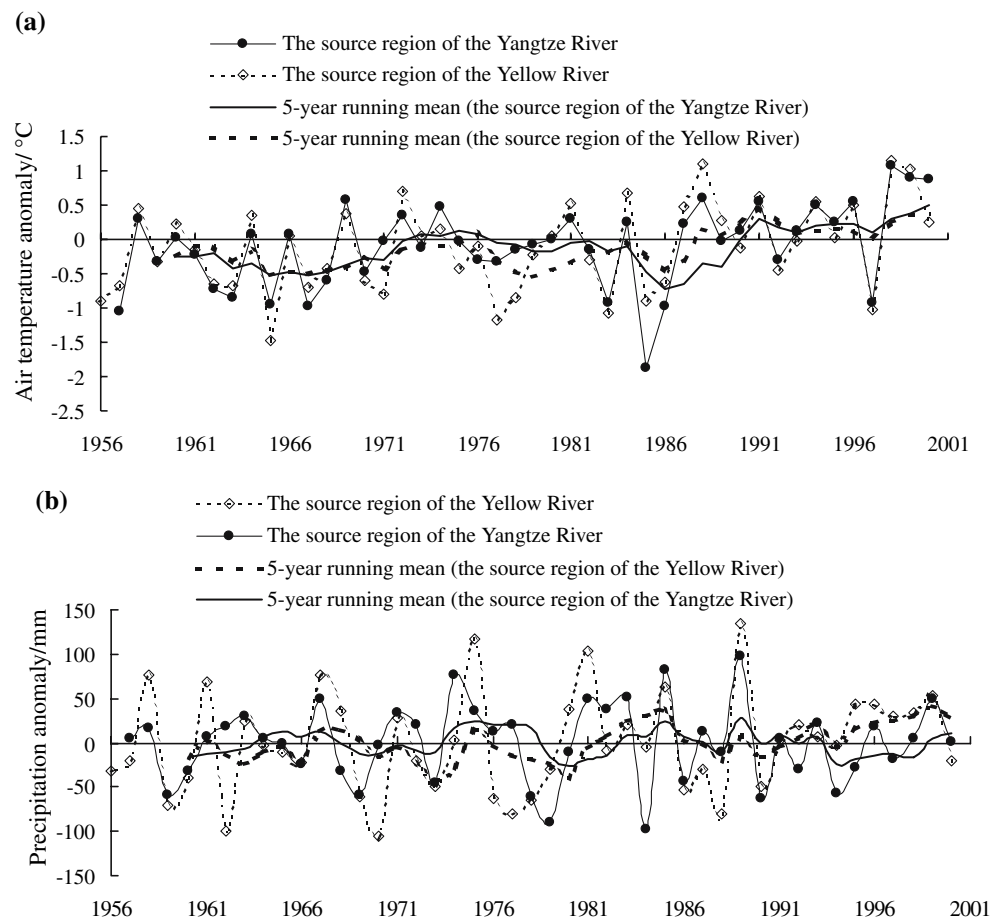


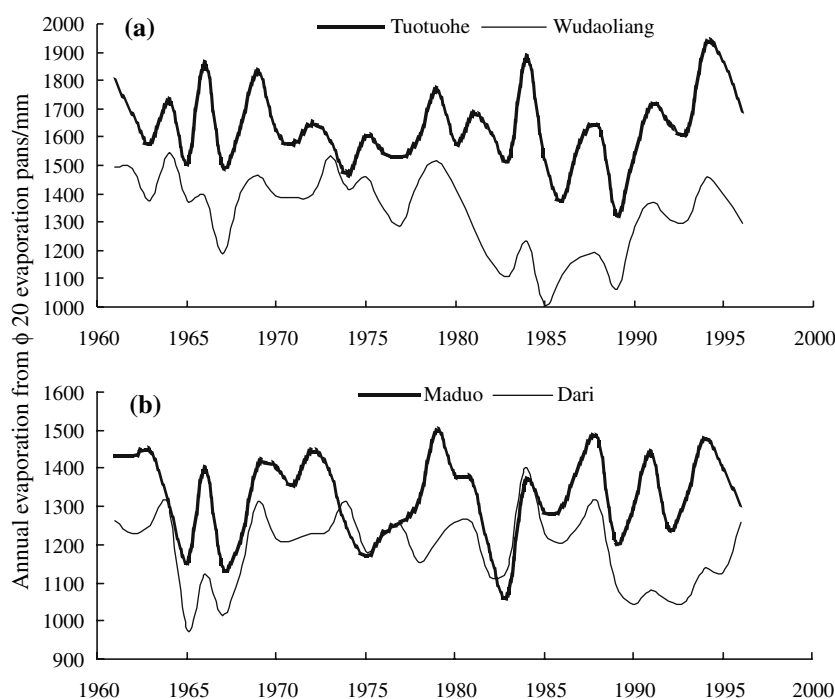
Fig. 4 Variations in annual average air temperature (a) and annual precipitation (b) in the source regions of the Yangtze and Yellow Rivers between 1956 and 2001. Variations are shown as deviations from the long term (1961–2000) mean



between the late 1950s and the early 1980s and has warmed significantly since 1986 in both areas. In the source region of the Yellow River, precipitation was scant from the 1960s to 1970s and plentiful in the 1980s and 1990s. It has increased by $\sim 7.4\%$ over the past 40 years. In the source region of the Yangtze River, as a whole, precipitation had no visible change trend. It was close to multi-annual average during the 1960s and 1970s, high in the 1980s, and low in the 1990s.

Though the mean annual air temperature is cold, ranging from -1.0 to -6.0°C , evaporation is high, ranging from 1189.9 to 1631.5 mm. This is due to strong winds in both areas. Figure 5 shows the time series of annual evaporation from $\phi 20$ evaporation pans at Tuotuohe, Wudaoliang, Maduo, and Dari meteorological stations. Evaporation decreased irregularly before the middle 1980s, and has generally increased quickly since then at Tuotuohe, Wudaoliang, and Maduo stations. Average evaporation during the 1990s was ~ 174.8 mm above that of the 1980s at Tuotuohe, ~ 195.2 mm at Wudaoliang, and ~ 66.4 mm at Maduo. In contrast, at Dari, annual evaporation increased before the middle 1980s (Fig. 5b) and has diminished rapidly since then; in the 1990s it was ~ 87.2 mm lower than in the 1980s. Overall, evaporation at Dari has decreased over the past 40 years, and the regionally averaged evaporation in the source region of the Yellow River decreased by $\sim 3.0\%$.

Fig. 5 Variations in annual evaporation from $\phi 20$ evaporation pans between 1961 and 1996. **a** Source region of the Yangtze River; **b** Source region of the Yellow River



Interpretation of eco-environmental change causes

Glacier and frozen ground

Variations in glaciers are a consequence of climate change. Temperature was lower and precipitation increased from the 1960s to the middle 1980s in the source region of the Yangtze River. Lower temperatures decreased ablation, whereas above average precipitation increased accumulation. Together these changes led to glacier advance. Because changes in glaciers lag climate change, most glaciers advanced continually until the early 1990s (Ding 1995). In the 1990s, precipitation decreased while air temperature increased $\sim 0.6^\circ\text{C}$ compared with the 1980s. This robust increase in temperature resulted in strong ablation, while the precipitation decrease gave rise to low accumulation. As a result, the glaciers retreated rapidly. As for frozen ground, warming temperatures clearly played a decisive role in its degradation.

Hydrological system and alpine vegetation

Precipitation and evaporation are two major components of the hydrological cycle, the third being runoff. The difference between precipitation and evaporation determines whether runoff is high or low and whether climate is humid or dry. In the study regions, 80–92% of annual precipitation falls during the warm season (May to September). In addition to precipitation,

meltwater from glaciers and snow pack are also an important source of runoff. However, this melting occurs principally during the warm season, especially between June and August. Thus, the climate during the warm season plays an important role in the changes of hydrological system and alpine vegetation. Herein, we therefore focus on variations in air temperature, precipitation, and evaporation during the warm season (Table 1). In Table 1 we see that air temperature turned significantly warmer during the 1990s. It warmed 0.5°C in the middle and northern part of the Yangtze River drainage, and 0.6°C at Maduo and 0.3°C at Dari in the Yellow River drainage. Precipitation during the 1990s was slightly above that of the 1980s at Tuotuohe and Maduo, but increased 41.7 mm at Wudaoliang. In the Dari area, precipitation was plentiful—above average in the 1980s and 1990s. However, the warm season precipitation of the 1990s was ~6.6 mm below that of the 1980s. The warm season evaporation of the 1990s increased by ~133.2, ~101.9 and ~42.8 mm at Tuotuohe, Wudaoliang, and Maduo areas, respectively, and decreased by ~36.7 mm in Dari area. Furthermore, the decrease in annual evaporation in the Dari area occurred primarily in the spring and summer; it was not noticeable in the autumn and winter (Qiu et al. 2003). The evaporation increase resulted from warming far exceeded the precipitation increase during the warm season at Tuotuohe, Wudaoliang, and Maduo. As a result, the climate during the 1990s has turned both warmer and drier in these areas. This climate has given rise to degradation of the vegetation, desiccation of the high-cold marshlands, decreases in the number and surface areas of rivers and lakes in the study area in the last 20 years.

In the Dari area in the eastern part of the source region of the Yellow River, the warm season climate was warmer and wetter, and evaporation was lower during the 1980s and 1990s. Thus, the same conclusion does not apply to eco-environmental changes in this area.

In the source region of the Yangtze River the sources of runoff are precipitation, melting of glaciers and snow, and groundwater. Heretofore, research on groundwater has not been carried out. Thus, the groundwater contribution to runoff is unclear. Though retreat of glaciers has increased runoff, the increase is small and has not had a particularly significant effect on total runoff in the source region of the Yangtze River (Yang et al. 2003). Thus, we think that the warmer and drier climate, resulting in higher evaporation, is the major cause of the surface runoff reduction in the 1990s in this area.

In the source region of the Yellow River, where there are no glaciers, runoff is mainly from precipitation, accounting for ~64.1% of all sources (Lan et al. 1999; Li et al. 1999), and is generated largely during the warm season, accounting for ~76% of annual runoff. The warm season precipitation increased by ~3.7% and the warm season evaporation decreased by ~1.9% in the source region of the Yellow River over the past 30 years. Thus, we think the noticeable reduction in runoff in the Yellow River and the degradation of the alpine vegetation in the Dari area are not closely related to variations in precipitation and evaporation since the 1980s. We suspect that it is related to the permafrost degradation resulting from warming. This idea has not been tested by field study or indoor model in China.

Conclusion and discussion

Between 1961 and 2000 robust increases in mean annual air temperature of 0.8°C in the source region of the Yangtze River and 0.7°C in the source region of the Yellow River have been recorded. Precipitation increased by ~7.4% in the source region of the Yellow River, but did not change significantly in the source region of the Yangtze River.

Table 1 Inter-decadal variations in air temperature, precipitation, and evaporation in both regions between May and September

Decade	Tuotuohe			Wudaoliang			Maduo			Dari		
	Air temp. (°C)	Prec. (mm)	Evap. (mm)	Air temp. (°C)	Prec. (mm)	Evap. (mm)	Air temp. (°C)	Prec. (mm)	Evap. (mm)	Air temp. (°C)	Prec. (mm)	Evap. (mm)
1960s	4.7	261.4	988.9	2.7	249.5	753.6	4.9	243.6	789.2	6.7	482.2	663.5
1970s	4.7	266.3	916.6	2.8	236.3	785.2	4.8	272.7	807.2	6.6	434.7	686.2
1980s	4.8	248.5	912.4	2.7	238.6	694.2	4.7	266.1	783.3	6.9	467.2	674.8
1990s	5.3	250.7	1045.6	3.2	280.3	796.1	5.3	273.1	827.1	7.2	460.6	638.1
Annual mean	4.8	254.8	957.0	2.8	250.1	753.2	4.9	264.1	798.9	6.8	457.4	668.7
1990s minus 1980s	+0.5	+2.2	+133.2	+0.5	+41.7	+101.9	+0.6	+7.0	+43.8	+0.3	-6.6	-36.7

Annual evaporation from $\phi 20$ evaporation pans decreased irregularly before the middle 1980s and increased quickly since then in the middle and northern source regions of the Yangtze and Yellow Rivers. As compared to that of the 1980s, the evaporation of the 1990s increased by ~ 174.8 mm at Tuotuohe, ~ 195.2 mm at Wudaoliang, and ~ 66.4 mm at Maduo. In Dari area of the source region of the Yellow River, annual evaporation variations were the reverse of those at other stations, namely, it increased before the middle 1980s and has diminished rapidly since then. Overall, evaporation at Dari has decreased over the past 40 years.

The glacier variations are a consequence of climate change. Lower temperature and plentiful precipitation triggered a glacier advance before 1995, while the robust temperature increase and precipitation decrease during the 1990s forced the glaciers to retreat rapidly after 1995 in the source region of the Yangtze River. Permafrost degradation was also a response to the warming.

Changes in the hydrological system and alpine vegetation are controlled mainly by the climate during the warm season in the study regions. The strong evaporation increase resulting from the warming far exceeded the precipitation increase in the middle and north source regions of the Yangtze and Yellow Rivers during the warm season. As a result, the climate became warmer and drier in these areas in the 1990s. This is the major reason for degradation of the vegetation, desiccation of the high-cold marshland, and decrease in the numbers and surface areas of rivers and lakes in these areas in the last 20 years.

In the Dari area in the eastern part of the source region of the Yellow River, the warm season temperature has been higher, precipitation more plentiful, and evaporation lower since the 1980s. Thus, we believe that the main causes of eco-environment changes in the Dari area are different from those in the middle and northern parts of the source regions of the Yangtze and Yellow Rivers.

In the source region of the Yangtze River, the warmer and drier climate is the dominant cause of a reduction in surface runoff since the late 1980s. We suggest that the noticeable reduction of the runoff in the source region of the Yellow River and the degradation of alpine vegetation in Dari area are closely related to permafrost degradation resulting from climate warming. But at present this idea has not been tested by field investigation or indoor model simulation.

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