NOTES AND CORRESPONDENCE

Long-Term Changes in Ice Phenology of the Yellow River in the Past Decades

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ABSTRACT

The authors quantitatively describe the changes in the characteristics of ice phenology including the flow rate and freeze/breakup dates of the Yellow River based on observations of the past 50 yr. In both the upper and lower reaches of the Yellow River, increasing temperature delays the freeze date and advances the breakup date, thus decreasing the number of freeze days and the expanse of river freeze. From 1968 to 2001, the freeze duration has shortened significantly by 38 days at Bayangaole and 25 days at Sanhuehe, respectively. From the early 1950s to the early 2000s, the changes in freeze and breakup dates have shortened the freeze duration in the lower reach of the Yellow River by 12 days. The flow rate has reduced from 500 to 260 m$^3$/s$^{-1}$, and the expanse of river freeze has also decreased significantly by about 310 km. In addition, in the lower reach of the river, the location of earliest ice breakup has shifted downstream significantly in the last 50 yr, although the location of earliest freeze exhibits little change.

1. Introduction

The global temperature, measured by both direct observations and credible proxy data, has risen considerably in the recent decades. The fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) indicates that the rise in global-average surface temperature has been particularly pronounced since about 1950, with an updated trend of 0.74° ± 0.18°C during 1906–2005, which represents an increase from the trend of 0.6° ± 0.2°C for 1901–2000 reported in the third IPCC assessment report (Houghton et al. 2001, 194–238; Solomon et al. 2007). As reported by Ren et al. (2005), the mean annual surface air temperature in mainland China as a whole has increased by about 1.3°C from 1951 to 2004, with a warming rate of about 0.25°C decade$^{-1}$. The most significant warming has occurred in winter and spring in northern China and the Tibetan Plateau.

Global warming has been believed to exert considerable impacts on human beings, the environment, and economic and social developments and these impacts have urged the scientific and social communities to improve the understanding of the cause and consequence of the phenomenon. Responses of regional climate to global warming have received substantial research interests during recent years (e.g., Fu and Ye 1995; Ye and Fu 1995; Ye and Lin 1995; Josep and Iolanda 2001; Shen 2001; De Viron et al. 2002; Spagnoli et al. 2002). For example, many features related to the response of the regional climate over China to global warming have been identified (Fu et al. 2003), including the changes in climate belts, climatic seasons, and phenology. Ye et al.
(2003) showed that in eastern China the temperate extratropical belt, the warm extratropical belt, and the northern subtropical belt shifted northward significantly as a response of regional climate to global warming.

The increase in temperature over China is characterized by large spatial differences. For instance, the warming in northern China is more significant than that in southern China (Sha et al. 2002; Zheng et al. 2002; Ge et al. 2003; Ye et al. 2003). The Yellow River (YR), which is mainly located between 33° and 43°N, flows from south to north from Lanzhou of Gansu Province to Hekou of Inner Mongolia, and from Zhengzhou of Henan Province to the estuary. (Figure 1 shows the location of YR and several sites that are discussed in this study.) As a result, winter temperature is higher in the upper reach of the river but cooler in the lower reach, and freeze of the river proceeds from lower to upper reaches. Also, the ice cover is thicker in the lower reach than in the upper reach. In spring, ice thaw progresses from upper to lower reaches due to the higher temperature in the south. Since the lower reach may still be frozen when ice cover breaks up in the upper reach, clogging of water and ice often raises water level and causes ice-jam floods in the curved and narrow sections of the river.

The ice-jam floods of the Yellow River can lead to serious disasters as occurred in 1951, 1955, 1969, 1970, 1979, 1982, and 1985. For example, the floods in 1955 inundated 360 villages in Lijin county of Tianjin City and in Binxian and Zhanhua counties of Shandong province. They affected about 177,000 people and 59,000 ha of farmland, causing 80 deaths and damaging 5,355 houses. Therefore, it is of great importance to study the ice phenology and ice-jam floods of the YR and their socioeconomic impacts.

The ice phenology of different water bodies in the world including the mechanics of ice-jam flooding and the relationship between ice-jam flooding and climate change has received increasing research interest in recent years (e.g., Prowse and Culp 2003; Beltaos 2003; Beltaos and Prowse 2001; Beltaos and Burrell 2003). As pointed out by Magnuson et al. (2000), from 1846 to 1995, the freeze and breakup dates of lakes and rivers have shown consistent trends of delayed freeze (5.8 days century\(^{-1}\)) and earlier breakup (6.5 days century\(^{-1}\)) in the Northern Hemisphere. Although studies of the Yellow River have mostly focused on the technical issues related to disaster prevention and reduction, the negative effect of the Sanmen Gorge Reservoir (see Fig. 1) on the 1996 YR ice-jam floods and the cause of ice-jam flood formation in Shandong Province, Inner Mongolia, and other places have also been discussed (Chen and Ke 1994; Bi et al. 1996; Wang 1996; Wang and Shi 2000; Bai et al. 2002). Li and Gao have introduced a statistical method to forecast the breakup date of YR based on analysis of precipitation and temperature (Li and Gao 1998). Chen and Ji (2005) have later developed a fuzzy optimization neural network approach to forecast the freeze and breakup dates. They have argued that multiple factors should be considered to predict ice-jam floods and their case study.
for Inner Mongolia seemed to show that the proposed approach yielded useful results. Furthermore, Sui et al. (2005, 2006) have found that both the evolution of frazil ice jams and the associated variation in water level depended upon the interaction between hydraulic variables during the ice-jammed period. Sui et al. have also pointed out the importance of ice accumulations for the change in river channel geometry based on field investigation conducted at Hequ of the YR valley.

However, the long-term trends of the ice phenology of the Yellow River have seldom been analyzed and the relationships of these trends to global warming are unknown. In this study, we carry out an analysis of the characteristics of ice phenology of the YR under global warming. Specifically, we investigate the long-term changes in freeze and breakup dates, flow rate, and other parameters of the YR in the past 50 yr.

2. Data

The main ice phenology data analyzed in this study include two parts: the freeze and breakup days and other information for the lower reach of the Yellow River, and the freeze and breakup dates for the Inner Mongolia reach of the river. The former is available for the period of 1950–2001 and the latter only for 1968–2001. The data were obtained based on daily scientific observations by hydrological stations. The number of times of observations was increased during the freeze and breakup dates. The dataset was prepared and archived by the Hydrology Bureau of the Yellow River Conservancy Committee, Ministry of Water Resources of China, in accordance with the standards of the People’s Republic of China for hydrological observations. We also analyze the surface temperature data compiled by the China Meteorological Administration. The dataset contains observations of 4 times day$^{-1}$ over 612 Chinese stations, covering the time period of 1951–2000. We define the daily mean temperature as the averaged value of four observations of the day. A nine-point smoother is applied to remove the short-term perturbations of temperature.

The freeze and breakup dates are defined, respectively, as the maximum ice volume of the whole freeze expanse within the lower reach of YR and the average flow during the entire ice season. Ice volume was calculated as follows:

1) Estimate the quantity of blocked ice and averaged flow rate.
2) Determine the upstream and downstream locations of the blocked ice.
3) Divide the ice-blocked river reach into several sections and compute their combined roughness.
4) Deduce the stable water level and the stable ratio under the ice cover for each section.
5) Compute the level of blocked ice based on the stable ratio of each section.
6) Calculate the thickness of blocked ice based on the blocked ice level minus the stable water level under the ice cover.
7) Calculate the total ice volume based on the thickness of blocked ice for all sections.

3. Results

a. Upper reach

To analyze the changes in ice-run date, freeze and breakup dates, and freeze duration in the upper reach of the Yellow River, we focus on Bayangaole and Sanhuhe (see Fig. 1) of Inner Mongolia where most complete data records exist, although we also conduct a similar analysis for other sites. At Bayangaole (Figs. 2a–d), the mean ice-run date has become later by 11 days (from 16 to 27 November) and the mean freeze date has also become later by 19 days (from 6 to 25 December) from the end of the 1960s to the end of the 1990s. In contrast, the breakup date has advanced by 19 days, from 23 March in the 1960s to 4 March in the 1990s. Therefore, the duration of river freeze has shortened by 38 days on average, from 109 days in the end of the 1960s to 71 days in the end of the 1990s.

At Sanhuhe (Figs. 2e–h), the ice-run date has been postponed by only 4 days (from 15 November in the end of the 1960s to 19 November in the end of the 1990s) and the mean freeze date has been delayed by 14 days (from 29 November in the 1960s to 13 December in the 1990s). On the other hand, the mean breakup date has advanced by 11 days, from 27 March in the 1960s to 16 March in the 1990s. These changes correspond to a shortening of freeze duration by 25 days (from 116 to 91 days). Nonparametric test indicates that the changes in the ice-run date, freeze and breakup dates, and freeze duration at Bayangaole and the breakup date and freeze duration at Sanhuhe in the upper reach of YR are all significantly significant. (A trend is considered significant if the value presented by
letter S in Fig. 2 determined by the nonparametric test is below 0.05.) It should also be pointed out that our analysis of other sites of the river section also reveals similar trends.

b. Lower reach

The lower reach of the Yellow River is an unstable freeze section, where ice thawing and ice-jam flooding often occur. From 1950 to 1993, it froze up in 39 of 42 winters, and ice-jam floods occurred frequently. Since the completion of the Sanmen Gorge Reservoir in 1960, the upper-reach flow has been under better control to prevent ice jams in the spring breakup period. Furthermore, northern China has obviously become warmer in the recent years, which tends to reduce severe ice-jam floods resulted from levee breaks. However, ice-jam floods still occur due partially to the limitation of reservoir storage. More studies of the changes in ice slush characteristics in the lower reach of YR are important for further reducing the risk of the ice run.

In the last decades, the earliest freeze date of the lower reach of YR has changed only slightly, being postponed by 2 days from the early 1950s to the early 2000s (Fig. 3a). However, the breakup date has advanced significantly by 17 days (from 28 to 11 February; see Fig. 3b), and the freeze duration has shortened by 12 days (from 56 days in the early 1950s to 44 days in the early 2000s; see Fig. 3c). The flow rate has reduced from 500 m$^3$/s in the 1950s to 260 m$^3$/s in the 2000s (Fig. 3d), and the expanse of river freeze has also reduced significantly from 440 to 130 km, shortened by 310 km in 50 yr (Fig. 3e). In addition, the maximum ice volume of freeze expanse has decreased significantly from 55 000 000 m$^3$ in early 1950s to 15 000 000 m$^3$ in the end of 1990s, a reduction of 40 000 000 m$^3$ (see Fig. 3f).

It can be seen from Fig. 4 that, in the last decades, the site of earliest freeze in the lower reach of YR is confined to 118°–120°E and exhibits no apparent change in trend. However, the location of earliest breakup shows a trend of eastward (downstream) migration. More spe-
specifically, the location of earliest breakup moved from 114.5°E in the 1950s to 117°E in the 1990s, and the change is highly statistically significant.

The above-discussed features of ice phenology are closely linked to the changes in temperature. As seen from Fig. 5, temperatures have increased significantly in northern China in both winter and spring from 1951 to 2001. Compared to the 1950s, the winter temperature...
increased 1°–3°C along the YR valley in the 1990s, with an increase of 2°–3°C in the Inner Mongolia reach and the middle of the lower reach. Averaged over the whole YR valley, the spring temperature also exhibits a warming trend of 1°–2°C in the north. On the one hand, the increase in temperature to some extent causes a series of changes in YR including delayed freezing, earlier breakup, shorter expanse of river freeze, and decreased freeze duration. It also causes changes in maximum ice volume and flow rate. Because the increase in temperature is more obvious in the upper reach than in the lower reach, the changes in freeze and breakup dates are more significant at Bayangaole and Sanhuhe, which are located in the upper reach (see Figs. 2 and 3). Our results are similar to those by Beltaos (2002) who has conducted a study of the Saint John River in Canada and found that winter events had the most serious impacts, via major ice jams formed against the strong ice-cover segments. The incidence of such events in Canada is expected to increase under a warmer climate, as a result of more frequent ice thaws. On the other hand, changes in the precipitation along the YR valley and the flow regulations such as the effect of the Sanmen Gorge Reservoir should also play certain roles in the long-term changes in the ice phenology features revealed above. For example, the flow regulations related to the Sanmen Gorge Reservoir must affect the flow rate. However, Prowse and Conly (1998) indicated that in the Peace–Athabasca Delta flow regulation seemed to have only produced minor changes in ice thickness and strength but not reduced the ice flow at the time of breakup. Nevertheless, a full investigation into these additional effects is beyond the scope of this analysis. Further studies of the impacts of flow regulations and other climatic variability on ice-jam flooding of YR are necessary during the global warming era.

4. Summary

At Bayangaole and Sanhuhe of the Inner Mongolia section (upper reach) of the Yellow River, the ice-run dates have been postponed by 11 and 4 days, respectively, from 1968 to 2001. Correspondingly, the mean freeze dates have been delayed by 19 and 14 days at the two sites. In contrast, the breakup dates have advanced significantly by 19 and 11 days, respectively. As a result, the freeze duration has shortened significantly by 38 days at Bayangaole and 25 days at Sanhuhe. Analysis of other sites of the upper reach of YR also reveals similar trends.

The earliest freeze date of the lower reach of YR has undergone little change from 1950 to 2001, being postponed by only 2 days. However, the breakup date has advanced significantly by 17 days. These changes shorten the freeze duration by 12 days. From the early 1950s to the early 2000s, the flow rate has reduced from 500 to 260 m³ s⁻¹, and the expanse of river freeze has also decreased significantly by about 310 km. The maximum ice volume of the freeze expanse has reduced significantly by about 40 000 000 m³ as well. Like the...
FIG. 5. Differences in (a) winter, (b) spring, and (c) annual mean surface temperature between the 1950s and 1990s (1990s minus 1950s). Positive (negative) values represent an increase (decrease) in temperature. Unit: °C.
earliest freeze date, the site of earliest freeze in the lower reach of YR has changed only slightly. However, the site of earliest breakup has shifted downstream significantly during the recent years.

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