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Key Points:
- Human activities have drastically decreased Yellow River flow over the past decades
- Recent Yellow River flow should have reached the highest level of the past 1,200 years if there were no human disruption
- Anthropogenic flow reduction is estimated to be about 44.5% during 1969-2010

Supporting Information:
- Supporting Information S1

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Deciphering Human Contributions to Yellow River Flow Reductions and Downstream Drying Using Centuries-Long Tree Ring Records

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Abstract The Yellow River flow has decreased substantially in recent decades, and the river often dried up in the lower reach and failed to reach the sea. Climate change and human disruption have been suggested as major causes of the flow reduction, but quantification of their relative contribution is challenging due to limited instrumental records and disturbance by dams. Here we use a basin-wide tree ring network to reconstruct the Yellow River flow for the past 1,200 years and show that the flow exhibits marked amplitude variations that are closely coupled to the hydrological mean state swings at multidecadal to centennial timescales. Recent flow should have increased to the highest level of the past 1,200 years if there were no human disruption. However, human activities have caused a loss of nearly half of natural flow since the late 1960s and are the main culprit for recent downstream flow reduction.

Plain Language Summary Recent Yellow River flow reductions have had major impacts on China's economy and water policy. The short and heavily human-modified gauge records are unable to reveal natural flow variability now and in the past. Here we use tree rings to reconstruct long-term Yellow River flow, which enables an assessment of natural flow variability and the detection of human contributions to recent flow reductions. Our 1,200-year reconstruction reveals that under natural conditions the Yellow River flow should have increased markedly since the early twentieth century. However, the observed flow decreased since the late 1960s and such a decrease must be predominately caused by human interventions instead of climate change.

1. Introduction

The Yellow River originates from the Tibetan Plateau (TP) and wanders 5,464 km through the dry northern region of China from west to east before emptying into the Bohai Sea (Figure 1a). It is the second-longest river in China and the sixth-longest in the world. The river basin is a core birthplace of ancient Chinese civilizations (Gernet, 1996; Pietz, 2015). Nowadays, it supplies water to over 150 million people and 15% of China's cropland (Chen et al., 2012; Immerzeel et al., 2010). The Yellow River is extremely prone to natural and human disturbances, as the watershed is characterized by low and highly variable precipitation and fine-grained loess soil that is subject to easy erosion (Chen et al., 2012; Hassan et al., 2008; Xu & Cheng, 2002). Historical records indicate that the river flooded more than 1,500 times and shifted its course 26 times noticeably and seven times drastically in the middle and lower basin during the past three millennia, with at least five major floods that caused the death of more than half a million people each (Chen et al., 2012; Yellow River Conservancy Commission, YRCC, 1982, 2001; Xu, 1993). However, the river flow decreased substantially in recent decades and the flow reduction led to frequent downstream drying-up events that were not recorded before the twentieth century (Fu et al., 2004; Liu & Zhang, 2002; YRCC, 1982, 2001; Xu, 1993). Climate change and human disruption have been suggested as the causes of recent flow

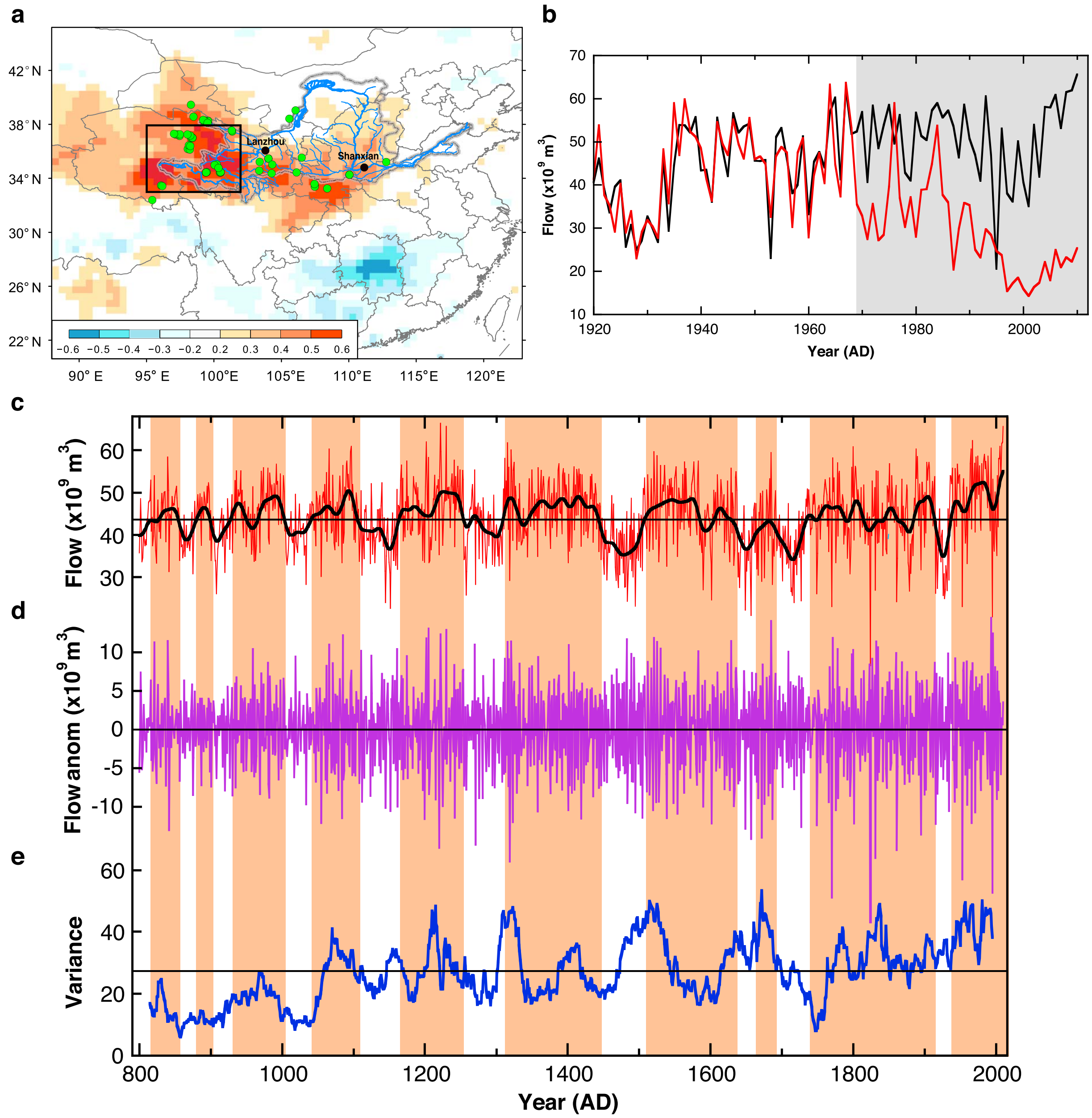

Figure 1. The Yellow River flow reconstruction. (a) Spatial correlation field of the reconstructed Yellow River flow with annual (July–June) precipitation during 1951–2010. The correlation coefficient at the 0.05 significance level is about 0.25, based on a two-tailed Student's *t* test. Other symbols are as follows: tree ring sample sites (green dots), gauge stations (black dots), the region over which headwater precipitation is averaged (black box), the Yellow River mainstream and its tributaries (blue lines), and the watershed boundary (gray line). (b) Comparison of the gauged (red) and reconstructed (black) flow records at Shanxian station during 1920–2010. Shading denotes the dam construction era. (c) The reconstructed flow (red) and its 31-year low-pass filter (bold) during 800–2010. Horizontal line denotes mean of the reconstruction. (d) Interannual variability of the reconstructed flow processed using a 9-year high-pass filter. (e) The 31-year running biweight variance for the 9-year high-pass-filtered flow. The unshaded vertical bars in (c)–(e) denotes periods of low flow.

reduction, but their relative contribution is poorly constrained (Miao et al., 2011; Piao et al., 2010; Wang et al., 2006; Zhao et al., 2014). Another major uncertainty is how the river flow may change under future warming, with some models projecting an increase and others a decrease in river flow in the 21st century (Nijssen et al., 2001; Piao et al., 2010; Su et al., 2016).

A solid understanding of river flow variability and relative contribution of various forcing requires long hydrometric records. However, modern Yellow River gauge records did not start until after 1919, with most observations from the 1950s onward. The brief hydrometric records are incapable of revealing recent natural flow trend and variability due to the construction of dozens of dams and reservoirs in the upper and middle reaches of the river since the 1960s (Wang et al., 2006). On the other hand, proxy-based flow reconstructions targeted the headwater (Gou et al., 2007, 2010), not the mainstream in the middle and lower reaches of the river. In this study, we develop a basin-wide tree ring network to reconstruct the middle Yellow River flow for the past 1,200 years and assess its long-term fluctuations, recent anomalies, major forcing, and possible future change.

2. Data and Methods

2.1. Gauge Records

The Yellow River flow records were obtained from the Shanxian and Lanzhou gauge stations (Figure 1a). Shanxian is the first modern hydrometric station on the Yellow River, which was set up near the end of the middle reach of the river in May 1919. The Shanxian station (34°49′N, 111°09′E) was relocated to Sanmenxia (34°49′N, 111°22′E) in June 1959 due to the construction of the Sanmenxia dam. Data from the two stations are often merged for long-term hydrological studies due to their proximity (19 km in-between). The Lanzhou gauge station was set up in the upstream of the river in August 1934. Considering that the first major dam (i.e., Liujiaxia Dam) on the upstream of the river was completed in October 1968, we only used the Shanxian gauge records from 1919 to 1968 for the dendrohydrological regression model development. Missing values from the Shanxian station record for four years (1944, 1945, 1947, and 1948) were linearly interpolated with the Lanzhou flow records, based on their relationship during 1934–1968 ($r = 0.83$, $p < 0.001$).

2.2. Flow Reconstruction

We aim to reconstruct the middle Yellow River flow recorded at the Shanxian station for a hydrological year from the prior October to the following September. We utilized 68 moisture sensitive tree ring chronologies from the upper and middle Yellow River watershed for the reconstruction (Figures 1a and S1 in the supporting information). The chronologies range from 204 to 2012 years, with a median length of 566 years (Figure S2). To account for the decrease in the number of predictor tree ring chronologies back in time, the flow reconstruction was developed with a commonly used iterative nesting procedure (Text S1). Of the 68 moisture-sensitive chronologies that are available for the study, only those that correlate significantly (at 0.01 level) with the gauged Shanxian flow records during the full calibration period 1920–1968 were retained as actual predictors in the regression models. The initial nest spans the common period of all chronologies from 1800 to 1990. Other nests were produced by iteratively extending backward with a step of 100 years till A.D. 800 and forward with a step of 10 years till CE 2010, respectively. This procedure results in 13 nests in total. For each nest, principal components analysis was performed on the actual predictor chronologies, and the first few principal components, determined by the minimum Akaike criterion (Akaike, 1974), were used to develop the regression model. We performed rigorous cross-validation tests, and the resulting statistics indicate skillful regression for all the nests (Figure S2). Finally, the flow reconstruction was achieved by splicing all the regressions together, with their mean and variance adjusted to be the same as the 1800–1990 nest.

3. Results

Our middle Yellow River flow reconstruction spans a 1,200-year period of 800–2010 and accounts for 40.6–76.0% (R^2_{adj} = 39.3–75.5%) of instrumental flow variance during the full calibration period 1920–1968 (Figure S2). Our reconstruction agrees well with the gauged Shanxian flow records at both high- and low-frequency components during 1920–1968 when the river ran freely (Figure 1b). The reconstructed and gauged records depart markedly thereafter when the flow was heavily disturbed by dams constructed on the upper and middle reach of the river. To validate the flow reconstruction independently, we considered the possible impacts by precipitation, temperature, and glacier meltwater. The reconstructed flow shows significant positive correlations with instrumental precipitation (Becker et al., 2013) in large areas of the upper and middle watershed (Figure 1a). The correlations are most significant in the headwater region, with the area averaged precipitation correlated with the reconstructed flow at 0.70 ($p < 0.001$) for 1951–2010 (Figures 1a and S3). The results indicate that precipitation in the headwater region contributes most to the gauged flow at the Shanxian station, in line with the fact that the upstream flow recorded at the

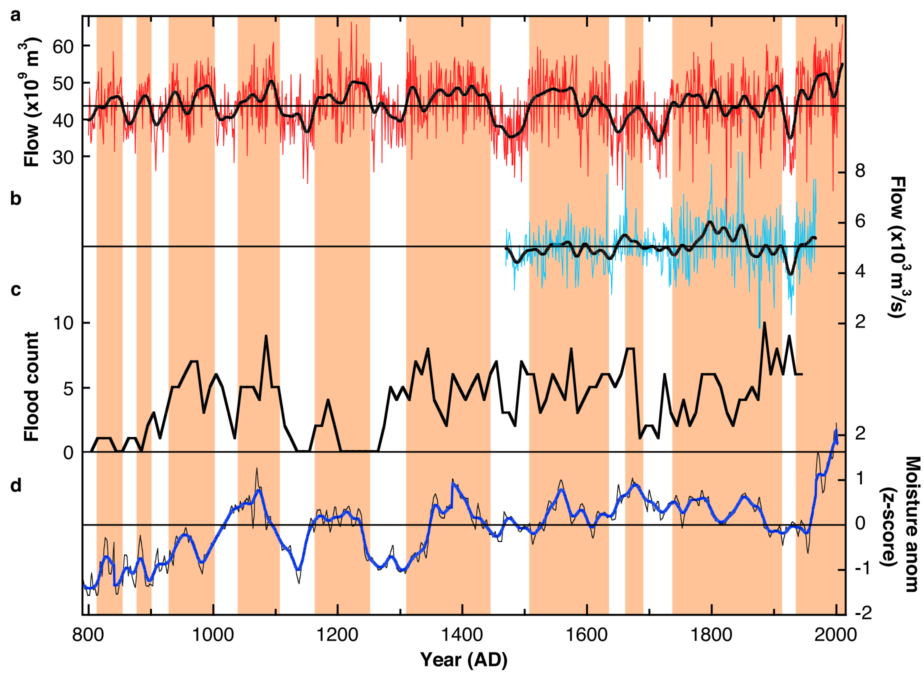

Figure 2. Verification of the reconstructed flow. (a) The reconstructed Yellow River flow during 800–2010, as in Figure 1c. (b) The document-based flooding season river flow (blue) and its 31-year low-pass filter (bold) during 1470-1968 (Pan et al., 2013; Wang et al., 1999). Horizontal line denotes mean of the record. (c) Frequency of river flooding per decade in the middle and lower reaches of the Yellow River during 800–1949 (Yellow River Conservancy Commission, 1982, 2001). (d) The average of four moisture sensitive lake and cave records in the upper and middle watershed (black) and its 31-year low-pass filter (blue) during 790–2002 (Table S1). Each series has been normalized before averaging. The unshaded vertical bars in a–d denotes periods of low flow.

Lanzhou station accounts for ~75% of the Shanxian flow records before the dam construction era (Figure S4). By considering precipitation in areas significantly correlated with the gauged flow before the dam construction era, recent flow can be estimated with a linear regression (Text S2). The estimated flow from precipitation data is correlated with the tree ring-based reconstruction at 0.73 (p < 0.001) for 1951–2010 (Figure S5), reaffirming that precipitation is the most critical factor for natural flow variability. In contrast, spatial correlations of the reconstructed flow with basin-wide temperature are largely insignificant to marginally significant (Figure S6), suggestive of a weak influence of temperature on the river flow with an exception of the TP region that is discussed below. Moreover, the glacierized area is only 0.11% of the Yellow River basin and the contribution of glacier meltwater to the Yellow River flow is estimated to be less than 2% (Su et al., 2016; Zhang et al., 2013). Glacier meltwater is thus a negligible factor affecting the Yellow River flow and its reconstruction.

Paleorecords from historical documents, lake and cave sediments in the watershed are employed to verify our flow reconstruction from a long-term perspective. The Yellow River water level during the flooding season (i.e., April–October) was recorded at the Shanxian station since 1766, and the records were used to derive the yearly flooding season river flow (Pan et al., 2013). Historical documents were further used to extend the flow records back to 1470 (Wang et al., 1999). Our reconstruction is correlated with the document-based flow records at 0.20 (p < 0.001) during 1470–1968 (Figures 2a and 2b), and their variations are coherent at multidecadal timescales (Figure S7a). Because of catastrophic impacts of river flooding, China has precise records of the Yellow River levee breach and flooding during the past two millennia (YRCC, 1982, 2001). With the records we calculated the frequency of river flooding in the middle and lower reaches of the river during 800–1949 (Figure 2c) and found that it is largely coherent with our flow reconstruction at multidecadal timescales (Figure S7b). The only major disparity occurred during the 1130s–1260s, a wartime period during which the river shifted its main course southward and was not embanked (Chen et al., 2012). In addition, our reconstruction varied coherently with moisture sensitive lake and cave records in the upper and middle watershed (Figure S8 and Table S1), with high flow coincident with wet periods in the watershed and vice versa for a reduction (Figures 2d and S7c). The above agreements are remarkable in light of the independent nature of the proxies, lending fidelity of our tree ring-based flow reconstruction.

4. Discussion and Conclusions

Our reconstruction captures the middle Yellow River flow variability over the past 12 centuries. The reconstructed flow displays marked interannual variability superimposed on multidecadal to centennial mean state swings (Figure 1c). A visual inspection suggests a low-frequency modulation of flow amplitude (Figure 1d). Here we calculated a 31-year running biweight variance to measure changes in flow amplitude, a technique that highlights multidecadal amplitude modulation of a time series while reducing bias that might be introduced by extreme outliers in a 31-year window (Li et al., 2011, 2013). As shown in Figure 1e, superimposed on a general rising trend are large fluctuations in flow variance on multidecadal to centennial timescales. Flow variance was generally reduced from the ninth to the early eleventh century and varied around a normal state from the late eleventh century to the eighteenth century. Then the variance showed a persistent increasing trend, with the late twentieth century variance being the highest of the past 12 centuries. In general, the variance fluctuations matched well with the hydrological mean state swings on multidecadal to centennial timescales, with strong variance in periods of high flow and vice versa for weak variance (Figures 1e and S7d). Therefore, the Yellow River flow amplitude is closely coupled to its hydrological mean state, and extreme flow tends to occur during wet periods of the river.

The reconstructed flow exhibits marked multidecadal to centennial variations over the past 12 centuries (Figure 1c). Spectral analysis reveals two significant quasi-regular cycles at 50- to 60- and 130- to 220-year band, respectively (Figure S9). The 50- to 60-year cycle is pronounced during the ninth to the tenth century and since the seventeenth century, while the 130- to 220-year cycle has persisted since the eleventh century. We found that the multidecadal to centennial flow fluctuations varied coherently with the proxy-based TP and Northern Hemisphere (NH) temperature anomalies over the past 12 centuries (Tables S1 and S2), with increased flow during warm periods in the NH and on the TP and vice versa for a reduction (Figures 3a–3c, S7e, and S7f). The above records generally show a good coherency with solar radiation record (Delaygue & Bard, 2011) during most of the past 12 centuries (Figures 3a–3d and S7g), suggesting that changes in solar radiation may have largely set the pace for the temperature and flow anomalies.

The reconstructed Yellow River flow has increased since the early twentieth century, coincident with a warming trend in the NH and on the TP (all significant at 0.01 level based on a Mann-Kendall trend test (Kendall, 1975; Mann, 1945); Figures 3a–3c). The flow increase is corroborated by the observed increase in headwater precipitation (significant at 0.01 level) that contributes most to the gauged flow records at the Shanxian station (Figure S3). Increasing temperature may affect the river flow as temperature increases, the runoff efficiency (i.e., ratio of runoff to precipitation) may decrease (Lehner et al., 2017; Woodhouse & Pederson, 2018). Although there is a lack of relationship in the headwater region, temperature in other parts of the TP appears to be an important controlling factor on the river flow (Figure S6). Regression analysis using the ERA-Interim reanalysis data (Dee et al., 2011) was performed in order to understand the atmospheric process. Associated with positive headwater precipitation anomalies in May–September are negative anomalies of 500-hPa geopotential height in central Asia and positive anomalies in northern China, and the anomalous pressure gradient in-between induces southerly wind over the northeastern TP (Figure 4a). The orographic blocking of the southerly wind by the Amne Machin Mountain (6,282 m above sea level) causes ascending air motion and convective precipitation that lead to moisture increase in the Yellow River headwater region (Figure 4b). Similar atmospheric circulation anomalies are identified when regressed against the TP surface temperature (Figures 4c and 4d), suggesting that the former may be a response to the latter, and recent moisture increase in the headwater region is a result of TP warming. The above dynamic perspective is in line with the long-term association between the TP temperature and the Yellow River flow during the past 12 centuries (Figures 3a and 3c). Together, they suggest that the TP temperature is a major factor affecting the natural Yellow River flow variability.

Our reconstruction of 1,200 years of the Yellow River flow provides a long-term background to assess its recent anomalies. Although previous studies underlined the importance of human interventions, they generally considered climate change and drought occurrence as a major cause of recent flow reduction (Miao

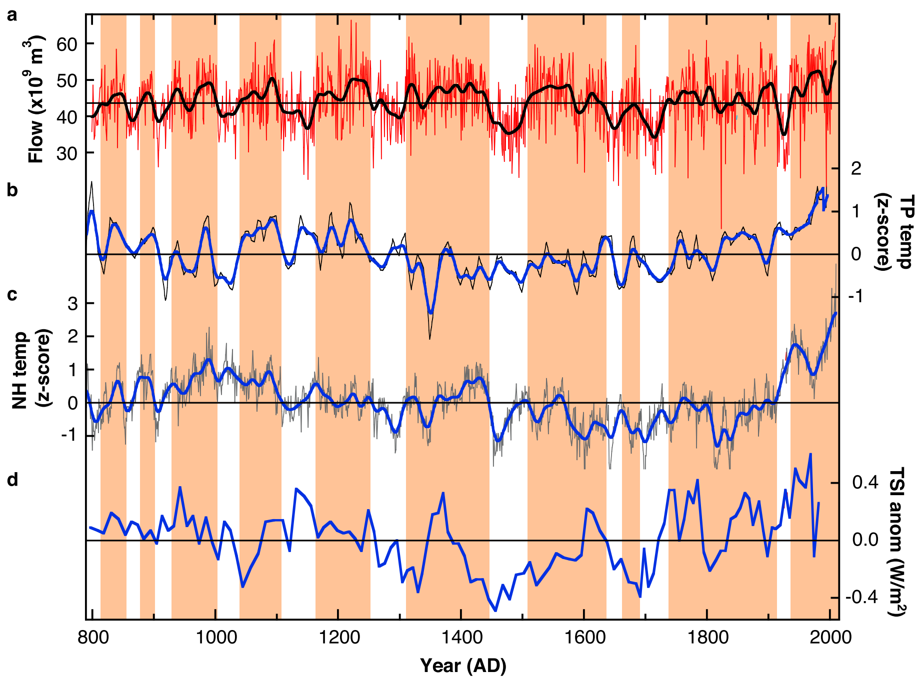

Figure 3. Comparison of the reconstructed flow with temperature and solar records. (a) The reconstructed Yellow River flow during 800–2010, as in Figure 1c. (b) The TP temperature anomalies as represented by the average of four temperature sensitive lake and ice core records in the northern TP (Table S1). (c) The NH temperature anomalies as represented by the average of ten temperature reconstructions covering the past 12 centuries (Table S2). Each series in (b) and (c) has been normalized before averaging. Bold line in (a)–(c) denotes a 31-year low-pass filter. (d) A total solar irradiance (TSI) record (Delaygue & Bard, 2011). The unshaded vertical bars in (a)–(d) denotes periods of low flow. TP = Tibetan Plateau; NH = Northern Hemisphere.

et al., 2011; Piao et al., 2010; Wang et al., 2006; Zhao et al., 2014). Admittedly, drought occurrence remains an important cause of the flow reduction in certain recent periods, in particular in the 1990s during which a marked flow reduction was observed in both gauged and reconstructed flow (Figure 1b). Regardless, our reconstruction reveals that the middle Yellow River flow should have increased in recent decades and reached the highest level of the past 1,200 years if there were no human disruption (Figure 1c). This contradiction is probably because previous studies paid less attention to precipitation in the headwater region that actually contributes most to the middle Yellow River flow (Figure S5).

The gauged flow at the Shanxian station is 44.5% less than the reconstruction since 1969, and the flow reduction amounts to 56.7% during the dry epoch of 1991–2010 (Figure 1b). Excluding uncertainties due to the model estimate, the deviation of the gauged flow from the reconstruction is mainly caused by human disruption, in particular water withdrawal for agricultural, industrial, and domestic purposes and the enhanced evaporative loss resulting from dam constructions. Water withdrawal is a direct human factor that is most responsible for recent flow reduction (Kong et al., 2016; Wang et al., 2012). Evaporative loss is indirect and currently accounts for ~6.0% of the water loss, but it is being exacerbated by basin-wide warming (Gao et al., 2011; Xu et al., 2007). Observations indicate that the highest water loss occurred in the middle reach, as the upstream flow recorded at the Lanzhou station accounted for ~75% of the Shanxian flow records before 1969, but it amounted to ~150% during the recent two decades (Figure S4). The above empirical assessment of human contributions to the Yellow River flow reduction supplements the model based estimates (Hu et al., 2015; Kong et al., 2016; Wang et al., 2012) and provides a crucial target for constraining the models as the latter still bear large uncertainties and require undisturbed flow records for calibration (Huang et al., 2016).

Our study implies that the Yellow River flow will likely increase in a future warmer climate, consistent with the most up-to-date model projection (Su et al., 2016). Nevertheless, decadal flow reduction due to natural forcing will inevitably reemerge, as it represents an inherent feature of the river flow variability

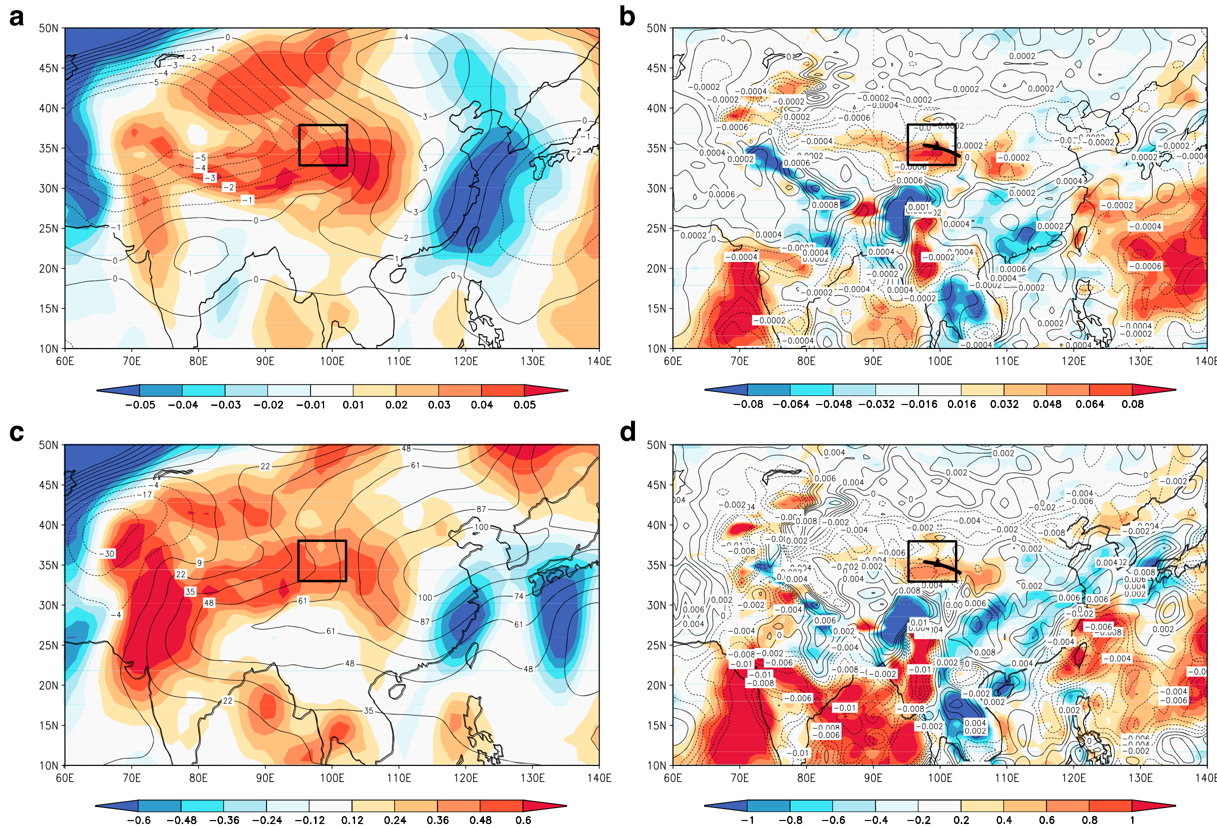

Figure 4. Spatial regression patterns for the period of 1979–2015. (a) The 500-hPa geopotential height (m^2/s^2; contour) and 500-hPa meridional wind (m/s; shading) regressed on the headwater precipitation. Positive wind anomalies indicate enhanced southerly wind. (b) The 300-hPa vertical wind (Pa/s; contour) and surface effective precipitation (P-E, mm/day; shading) regressed on the headwater precipitation. Positive (negative) vertical velocity anomalies indicate descending (ascending) motion. Black triangle and curve denote the peak and orientation of the Amne Machin Mountain. (c) Same as in (a) but regressed on the Tibetan Plateau (TP) surface temperature. (d) Same as in (b) but regressed on the TP surface temperature. The headwater precipitation and the TP surface temperature were averaged over a region as denoted in Figures 1a and S8. All regressions were performed for May–September. Black box in (a)–(d) denotes the headwater region of the Yellow River.

(Figure 1c). Future studies need to look into details of the flow response to various internal forcing such as the TP boundary conditions and the tropical climate mean state swings. Regardless, our study underlines the dire need of sustainable water management in the Yellow River basin. Given that frequent drying-up events occurred in the 1970s–1990s when the flow reduction was far less pronounced than many dry epochs over the past 1,200 years, future water shortage due to natural flow reduction could be more devastating than what happened recently in terms of duration and severity. Likewise, flow extremes may occur more frequently in the future, as flow variability generally increases during wet periods of the river. Mitigation strategies need to account for the joint risks of extreme droughts and floods, an escalated challenge for water management in the populous Yellow River basin and northern China.

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