

Understanding and seasonal forecasting of hydrological drought in the anthropocene

Xing Yuan¹, Miao Zhang^{1,2}, Linying Wang^{1,2}, and Tian Zhou³

¹CAS Key Laboratory of Regional Climate-Environment for Temperate East Asia (RCE-TEA), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, 100029, China

²University of Chinese Academy of Sciences, Beijing, 100049, China

³Pacific Northwest National Laboratory, Richland, WA 99352, USA

Correspondence to: Xing Yuan (yuanxing@tea.ac.cn)

Abstract. Hydrological drought is not only caused by natural hydro-climate variability, but can also be directly altered by human interventions including reservoir operation, irrigation and groundwater exploitation, etc. Understanding and forecasting of hydrological drought in the anthropocene are grand challenges due to complicated interactions among climate, hydrology and human. In this paper, five decades (1961-2010) of naturalized and observed streamflow datasets are used to investigate hydrological drought characteristics in a heavily managed river basin, the Yellow River basin in North China. ~~It is found that h~~Human interventions decrease the correlation between hydrological and meteorological droughts, and make the hydrological drought respond to longer time scale of meteorological drought, ~~especially during rainy seasons.~~ Due to large water consumptions over the middle and lower reaches, there are ~~118%-262%~~ ~~two to four fold~~ increases in the hydrological drought frequency and up to ~~six~~~~eight~~-fold increases in the drought severity, the drought duration increases by ~~4221-8399%~~, and the drought onset becomes earlier. The non-stationarity due to anthropogenic climate change and human water use basically decreases the correlation between meteorological and hydrological droughts, reduces the effect of human interventions on hydrological drought frequency while increase the effect on drought duration and severity. A set of 29-year (1982-2010) hindcasts from an established seasonal hydrological forecasting system are used to assess the forecast skill of hydrological drought. In the naturalized condition, the climate-model-based approach outperforms the climatology method in predicting the 2001 severe hydrological drought event. Based on the 29-year hindcasts, the former method has a Brier Skill Score of 11%-26% against the latter for the probabilistic hydrological drought forecasting. In the anthropocene, the skill for both approaches increases due to dominant influence of human interventions that have been implicitly incorporated by the hydrological post-processing, while the difference between two predictions decreases. This suggests that human interventions can outweigh the climate variability for the hydrological drought forecasting in the anthropocene, and the predictability for human interventions needs more attention.

1. Introduction

Drought is a natural phenomenon occurring ~~recursively~~ due to climate variability that are associated with oceanic and/or terrestrial anomalies (Hong and Kalnay, 2000; Hoerling and Kumar, 2003). As the rainfall deficit reaches a certain threshold,

the meteorological drought occurs. If the meteorological drought persists for a period of time, it will decrease the soil moisture and river flow, resulting in agricultural and hydrological droughts. Although the rainfall deficit is a primary driver for the agricultural and hydrological droughts, terrestrial hydrological processes (e.g., snow melting, evapotranspiration), geological and topographic conditions also play a non-trivial role in the drought propagation (Van Loon et al., 2012; Rimkus et al., 2013; Teuling et al., 2013; Stoelzle et al., 2014; Staudinger et al., 2015). Therefore, monitoring and forecasting of agricultural and hydrological droughts not only provide more relevant guideline for the management of agricultural and water resources, but also raise challenging science questions on the mechanism and predictability of multi-scale drought processes (Pozzi et al., 2013; Yuan et al., 2013; Wood et al., 2015).

Given that rainfall deficit is a major cause for the hydrological drought, many studies focus on the understanding of the propagation from meteorological to hydrological drought. For instance, Vicente-Serrano and López-Moreno (2005) investigated the relationship between streamflow and antecedent rainfall by using a correlation analysis, and found that hydrological drought index series has the highest correlation with a two-month accumulated meteorological drought index series in a mountainous Mediterranean basin. Such correlation analysis method was then widely used to understand the time scale of hydrological drought (Rimkuset al., 2013; Haslingeret al., 2014; Bloomfield et al., 2015; Folland et al., 2015; Niu et al., 2015; Kumar et al., 2016). A recent study from Barker et al. (2016) comprehensively investigated the relationship between meteorological and hydrological droughts for 121 near-natural catchments in the United Kingdom, where the relationship was found to be associated with natural climate and catchment properties.

Besides natural climate and hydrological processes that affect the development of hydrological drought, human activities such as land use and land cover change, urbanization, irrigation, reservoir operation and groundwater exploitation can also influence hydrological drought significantly (AghaKouchak et al., 2015; Van Loon et al., 2016a). López-Moreno et al. (2009) found that the second largest reservoir in Europe increased the duration and severity of hydrological drought over downstream areas. Similar studies found that the reservoir regulation might reduce the drought severity over upstream areas but increase it over downstream areas over Australian and Chinese catchments (Wen et al., 2011; Zhang et al., 2015), because many reservoirs were built for meeting the irrigation demand more reliably. However, there is limited knowledge on the integrated impact of human activities on hydrological drought processes over a large river basin due to the lack of human water use data, which is one of the major issues that hinders the understanding of hydrological drought in the anthropocene (Van Loon et al., 2016b). An alternative approach is to use a land surface hydrological model (Wada et al., 2013; Zhou et al., 2016) or a less complicated water balance model to recover the naturalized streamflow by assimilating the reported water use data. The naturalized streamflow data can be used to calibrate hydrological model without the human component to investigate the natural response of hydrological processes to the climate variations (Yuan et al., 2016), it also can also be used to investigate the integral anthropogenic impact on the hydrological drought by comparing with the observed streamflow time series.

The ultimate goal of the understanding of drought processes is to facilitate the development of drought early warning systems for drought adaptation and mitigation, and the development of ocean-atmosphere-land coupled general circulation

models (CGCMs) provides an unprecedented opportunity to transfer the advances in seasonal forecasting research (Kirtman et al., 2014; Yuan et al., 2015a) into an integrated drought service. Besides the meteorological drought forecasts (Dutra et al., 2012; Yuan and Wood, 2013; Ma et al., 2015), the agricultural drought forecasts with dynamical seasonal climate forecast models have also been widely applied and evaluated (Luo and Wood, 2007; Mo et al., 2012; Sheffield et al., 2014; Yuan et al., 2015b; Thober et al., 2015). However, dynamical forecasting of hydrological drought based on the CGCM-hydrology coupled approach (Yuan et al., 2015a) has received less attentions (Trambauer et al., 2015; Sikder et al., 2016), although there are many statistical forecasting studies for low flows. The reasons are threefold: 1) a skilful seasonal forecasting of streamflow usually occurs over basins with large storages of snow, surface and/or subsurface water (Wood and Lettenmaier, 2008; Koster et al., 2010), and the strong control from initial hydrological conditions limits the added value from climate predictions (Wood et al., 2016; Yuan, 2016); 2) unlike the meteorological drought forecasts, both agricultural and hydrological drought forecasts are influenced by the uncertainty in hydrological model, and the hydrological drought forecasting tends to be more challenging since the errors from upstream areas can be transferred to or even amplified in downstream areas; and 3) many river basins are altered by human activities, where the management impacts are often neglected in most dynamical forecasting system. In fact, seasonal forecasting of hydrological drought in the anthropocene raises the questions of how to define the predictability of the anthropogenic processes within a coupled hydro-climate system, how to distinguish the uncertainty from each component, and how to assess the forecast skill of hydrological drought with natural and anthropogenic forcings.

This paper focuses on the understanding and seasonal forecasting of hydrological drought over a heavily managed river basin in North China, the Yellow River basin. Both the naturalized and observed streamflow along the mainstream of Yellow River will be used to investigate the relationship between meteorological and hydrological droughts under natural and anthropogenic conditions, to quantify the influence of human activities on the characteristic of hydrological drought (e.g., drought frequency, duration and severity, and the seasonality of hydrological drought onset), and to assess hydrological drought forecasting in the anthropocene with an experimental seasonal hydrological forecasting system established over the Yellow River basin (Yuan et al., 2016).

2. Data and Method

2.1 Study domain and hydroclimate observation data

Precipitation dataset at 0.25-degree resolution during 1961-2010 was interpolated from 324 meteorological stations within the Yellow River basin (Yuan et al., 2016). Figure 1 shows that regional mean annual precipitation decreases from southeast to the northwest. Most precipitation over Yellow River occurs in summer season due to the influence of East Asian monsoon, resulting in a strong seasonality of precipitation, with more than 80% of annual precipitation falls within May-September (Fig. 2). For each hydrological gauge, the sub-basin mean precipitation was calculated to investigate the relationship between meteorological and hydrological droughts.

Figure 1 shows the locations of 12 mainstream hydrological gauges used in this study, with Tangnaihai gauge in the headwater region and Lijin gauge at the outlet of the entire Yellow River basin that has a drainage area of $7.52 \times 10^5 \text{ km}^2$.

Details of the drainage areas for the 12 gauges can be found in Yuan et al. (2016). Both the natural and observed streamflow datasets at monthly time scale during 1961-2010 were ~~obtained from~~ provided by local authority of the Bulletin of Yellow River Water Resources (<http://www.yellowriver.gov.cn/>), where ~~the~~ naturalized streamflow (W_{nat}) was calculated as follows:

$$W_{nat} = W_{obs} + W_{irr} + W_{idu} + W_{civ} + W_{div} + W_{res}$$

where W_{obs} is the observed streamflow; W_{irr} is surface water consumed in irrigation, i.e., irrigated surface water that is transpired from crop, evaporated from bare ground and river/channel water surface, absorbed into soil (through infiltration, percolation and recharge to shallow groundwater), leaked from river/channel bed to groundwater during transportation, so the W_{irr} is not simply those withdrew from river, while it is actually the surface water consumption in the processes of irrigation that already considers the flow return to the river; similarly, W_{idu} and W_{civ} are surface by adding the water consumed by agricultural, industrial and civil sectors, by considering the waste water returned to the river; W_{div} is the interbasin water diversion, and W_{res} is the water regulated by reservoirs, back to the observed streamflow (Yuan et al., 2016). To account for the non-stationarity both from anthropogenic climate change (Milly et al., 2008, 2015) and land use/land cover changes (Villarini et al., 2009; Zhang et al., 2011), the variable runoff coefficient (annual runoff divided by annual precipitation) and more physically based methods that consider the soil conservation (e.g., Grain for Green project over Loess Plateau), effect of groundwater overdraft on surface water, and evaporation loss from reservoirs or channels, are used to correct the naturalized streamflow. Such correction is critical over Yellow River due to significant climate change and human interventions (Zhang et al., 2011). For example, small, medium and heavy rainy days decreased by 20-26% over the areas between Hekouzhen and Longmen gauges in 1980s as compared with those in 1950s and 1960s, with duration of extremely heavy rainfall decreased from 0.82 day to 0.38 day. The annual streamflow over the middle reaches of Yellow River could decrease by 19% with the same annual precipitation due to ecological conservation, and could decrease by 47% due to the riverbed leakage induced by groundwater overdraft. The corrections for the annual mean streamflow over the areas from Tangnaihai to Lanzhou, and down to Hekouzhen, Longmen, Sanmenxia, Huayuankou and Lijin are 3.16×10^8 , 0.80×10^8 , 6.17×10^8 , 10.99×10^8 , 9.23×10^8 and 2.61×10^8 m^3 , respectively. To our knowledge, this is the most comprehensive estimation of naturalized streamflow over Yellow River basin so far, based on abundant data from different sectors. Yuan et al. (2016) used the naturalized streamflow to calibrate the Variable Infiltration Capacity (VIC) land surface hydrological model (Liang et al. 1996) during 1961-1981, when the human interventions were supposed to be limited. The naturalized streamflow was then compared with VIC simulations during the validation period 1982-2010, and it is found that the naturalized streamflow agreed with VIC simulations quite well with Nash-Sutcliffe efficiency (NSE) varied between 0.71-0.91 (Figure 4 in Yuan et al., 2016).

Except for the Tangnaihai gauge in the headwater region, streamflow at the hydrological gauges used in this study were influenced by human interventions (Fig. 3). Therefore, the Yellow River is an ideally large river basin to investigate the hydrological drought processes and predictability in the anthropocene. In general, human interventions decrease streamflow over upper and middle reaches of Yellow River during rainy season while increase it during dry season (Figs. 3b-3h). This

带格式的: 下标

带格式的: 下标

带格式的: 居中

带格式的: 下标

带格式的: 下标

带格式的: 下标

带格式的: 下标

带格式的: 下标

带格式的: 下标

带格式的: 上标

带格式的: 上标

带格式的: 字体: (默认) Times New Roman, 10 磅, (中文) 中文(简体, 中国), (其他) 英语(英国)

suggests that reservoirs in the upper and middle reaches of Yellow River store rain water in wet season and distribute it in the remaining time of the year according to the need, which is similar to regulations in other parts of the world (Wada et al., 2014). Actually, Figure 4a shows that the annual mean observed streamflow at upper reaches can be higher than the naturalized streamflow during dry years due to the reservoir water release (e.g., years 2000, 2002, 2006 and 2010 for Lanzhou gauge). Over the lower reaches, the observed streamflow is significantly lower than the naturalized streamflow during wet season due to heavy water consumption, and riverbed leakages because of groundwater overdraft and possible geomorphology change caused by sediment accumulation (Figs. 3i-3l), ~~but~~ The observed streamflow former is close to the naturalized streamflow latter during dry season because of no significant water consumption or reservoir management. Figure 4 also shows that the magnitudes of reservoir storage changes are quite small as compared with streamflow. In fact, the mean absolute changes of reservoir storage during 1998-2010 are about 14%-38% and 12%-14% of observed and naturalized streamflow, respectively. This suggests that other human interventions, such as direct withdrawal of surface water for agricultural, industrial and civil consumptions, account for a large part of streamflow variations over Yellow River.

2.2 Definitions of drought indices and hydrological drought event

The Standardized Precipitation Index (SPI; McKee et al., 1993) was used as the meteorological drought index. The main advantage of SPI is its multiscale nature, i.e., it can be used to represent meteorological drought at different time scales. In this study, sub-basin mean precipitation datasets averaged over antecedent 1 to 24 months were used to calculate SPI-1 to SPI-24. To account for the seasonality, the SPI for each target month and for each time scale was calculated separately by using 50-year data. For example, SPI-6 at October 1982 was calculated by firstly fitting an empirical distribution based on the precipitation averaged between May and October during 1961-2010, and the May-October mean precipitation in 1982 was then used to determine the SPI6 value for October 1982.

Similarly, monthly naturalized streamflow datasets at 12 hydrological gauges during 1961-2010 were also standardized by using the same procedure, resulting in hydrological drought index named as Standardized Streamflow Index (SSI). Note that SSI was similar to the standardized runoff index (SRI) defined by Shukla and Wood (2008), except that streamflow was used here for a standardization. For the anthropogenic streamflow, the same parameters of probabilistic distributions fitted from the naturalized streamflow were used, and the SSI values were then calculated. Both the 50-year (1961-2010) data and a series of 30-year transient climatology (e.g., 1961-1990 climatology was used for year 1975, 1962-1991 climatology was used for 1976, and so on) were used to calculate the stationary and non-stationary SPI/SSI values respectively.

A threshold of -0.8 was used to represent a drought condition for both SPI and SSI. And a hydrological drought event was selected when the SSI was below -0.8 for at least 3 continuous months (Yuan and Wood, 2013), where the drought onset month was the first month that the SSI fell below -0.8. Once a hydrological drought event occurred, both the duration months and the severity ($\sum_{i=1}^n (-0.8 - SSI_i)$, where n is the number of month for the drought event) were calculated. And the number of drought events, mean drought duration and severity were obtained for both naturalized and observed SSI.

2.3 Seasonal hydrological ensemble hindcast datasets

A number of seasonal hydrological ensemble hindcast datasets created by Yuan (2016) were used in this study. To have this paper self-contained, the hindcast experiments were briefly described below. Firstly, a continuous offline hydrological simulation with the calibrated VIC model and river routing model driven by observed meteorological forcings from 1951 to 2010, was conducted to generate the initial hydrological conditions (ICs) for the hydrological hindcasts (Yuan et al., 2016).

5 The observed meteorological forcing datasets including daily precipitation, daily maximum and minimum surface air temperature, and surface wind were interpolated from 324 China Meteorological Administration stations. The VIC model version 4.0.5 was used to predict runoff in a water balance mode over the entire Yellow River basin with 1321 grid cells at 0.25-degree resolution, and a routing model was used to translate the runoff into streamflow at each 0.25-degree grid cell, and to route the flow into rivers and finally into the ocean (Yuan et al., 2016). Secondly, a set of 6-month Ensemble

10 Streamflow Prediction (ESP) experiments were carried out by using the VIC and routing models, where the hydrological models were initialized with the generated ICs and were forced by 28 ensemble forcing during 1982-2010 excluding the target year. It is named as ESP/VIC hereafter. Thirdly, a grand ensemble of 99 realizations from eight North American Multimodel Ensemble (NMME; Kirtman et al., 2014) models was used to force hydrological models to generate the NMME/VIC hindcast dataset (Yuan, 2016). Here, the 1-degree NMME global hindcasts of monthly precipitation and

15 temperature were bilinearly interpolated into 0.25-degree, the interpolated monthly hindcasts for each NMME model were then bias-corrected independently against observations by using the quantile-mapping method (Wood et al., 2002) in a cross-validation mode (i.e., dropping observation and forecast in the target year when generating the climatology), and these bias-corrected monthly hindcasts were finally temporally disaggregated to daily by historical sampling and rescaling (Yuan, 2016). The forecast streamflow can be directly compared with offline simulated streamflow. To compare with observed

20 streamflow, a hydrological post-processing procedure (Yuan, 2016) was applied to adjust the forecast streamflow statistically by using the Bayesian theory. To account for the non-stationarity, the hydrological post-processing was carried out by using observed streamflow during 1982-2010 in a cross-validation mode (Yuan, 2016), and the corresponding SSI was also calculated by using the concurrent hindcast period (i.e., 1982-2010). It should be pointed out that the non-stationarity could be reduced further in a real-time forecasting mode because of the gradual use of concurrent climate and hydrology information for the calibration and initialization of hydrological model for the (seasonal) hydrological forecasting in the next 3-6 months. While only the ensemble mean (deterministic) forecast skill for streamflow was evaluated in Yuan (2016), both deterministic and probabilistic forecast skill of streamflow (especially for the low flows) ~~are~~ were assessed in this paper.

3. Results

30 3.1 Relation between meteorological drought and hydrological drought

Figure 5 shows the Pearson correlation coefficients between SPI at different time scales and monthly SSI both for naturalized and observed streamflow. There is an increase in the correlation as the SPI time scale increases, suggesting that streamflow is not only influenced by concurrent precipitation, but also by antecedent precipitation up to a few months. Similar to Vicente-Serrano and López-Moreno (2005), the time scale with the maximum correlation is considered as the time

scale of SPI that streamflow responds to. For the naturalized streamflow, it responds to 6-12 months SPI over the upper and middle reaches of Yellow River, and to about 4 months SPI over the lower reaches. The correlations for observed streamflow are significantly lower than for naturalized streamflow for gauges from Xunhua down to Huayuankou, with p values less than 0.01 (Figs. 5b-5j). There is also a significant difference in correlation for Gaocun gauge with $p < 0.05$ (Fig. 5k), but the difference is not statistically significant for Lijin gauge with $p > 0.1$ (Fig. 5l). Except for the Tangnaihai gauge in headwater region, the SPI time scales with the maximum correlation are longer for the observed streamflow than the naturalized streamflow, suggesting that human interventions basically make the hydrological drought respond to longer time scale of meteorological drought. By considering the non-stationarity, the correlations decrease generally from Longmen gauge (Fig. 5h) to the downstream areas, and the decrease are more obvious for the observed streamflow and for the longer timescale of SPI. This suggests that the relation between meteorological drought and hydrological drought over lower reach of Yellow River is not stationary, anthropogenic climate change and human interventions add more nonlinearity to the propagation from meteorological to hydrological droughts.

In order to analyze the relation during different seasons, five gauges from upper to lower reaches are selected and the correlations between SPI at different time scales and monthly SSI for different target months are plotted in Figure 6. It is found that streamflow responds to shorter time scale of SPI in wet and warm seasons and longer time scale in dry and cold seasons. Again, the correlations for observed streamflow for different target months are lower than that for naturalized streamflow, except for the headwater region (i.e., Tangnaihai gauge) without significant human interventions (Fig. 6). The differences are larger during summer seasons than the winter seasons, which is consistent with the seasonality of human water use as shown by different streamflow in Figure 3. Again, non-stationarity basically weakens the relation between meteorological and hydrological droughts over the lower reaches, regardless of seasons.

3.2 Effect of human interventions on the hydrological drought characteristics

To demonstrate the effect of human interventions on the streamflow variations directly, both the time series of naturalized and observed SSIs calculated based on transient climatologies are plotted for the five selected gauges in Figure 7. It is found that human interventions sometimes have positive influence on hydrological drought over the upper reaches. For example, the observed SSI can be larger than the naturalized SSI at Lanzhou gauge (Fig. 7b). However, those increases mostly occur in winter seasons, while they do decrease in summer season when the water demand and water consumption are high. For the middle and lower reaches, observed SSIs are basically lower than the naturalized SSIs (Figs. 7d-e), indicating that human interventions exacerbate the hydrological drought conditions in the lower reaches of the Yellow River basin. The results based on the 50-year climatology generally have lower SSI in 1990s-2000s and higher SSI in 1960s-1970s (now shown), suggesting there are decreasing trends in streamflow over Yellow River basin that is consistent with previous studies (e.g., Piao et al., 2010).

By following the definition of hydrological drought event (it should last for at least 3 continuous months) in Section 2.2, the frequency, duration and severity of hydrological droughts under natural and anthropogenic conditions are calculated and shown in Figure 8. Under natural condition, seasonal hydrological drought occurs 8-16 times during the 50-year (1961-2010)

period, where the frequency of hydrological drought is not necessarily higher over lower reaches than that over upper reaches (Fig. 8a). This is partly because there is more precipitation over lower reaches, and the naturalized hydrological drought basically represents the response to the meteorological drought. In contrast, the observed hydrological drought frequency shows quite different characteristics, where the human interventions increase the drought frequency by ~~7%~~^{up} to ~~80~~~~65~~% from the upper gauges down to the Xiaheyan gauge (the 5th gauge in Fig. 8a), but they increase the drought frequency by ~~200~~~~118~~% or even ~~400~~~~262~~% over the lower reaches (e.g., Lijin gauge at the outlet).

For the drought duration in natural conditions, it is generally longer over upper reaches which is again due to a drier climate (Fig. 8b). With human interventions, there is a slight decrease in drought duration for the upper gauges down to Xiaheyan gauge. This suggests that human interventions reduce the persistency of drought over the upper reaches of the Yellow River basin. From Shizuishan gauge (the 6th gauge in Fig. 8b) down to the outlet, the duration of hydrological drought increases by ~~122~~~~1~~%-~~839~~~~9~~% under human interventions. There is no significant change in drought severity down to Xiaheyan gauge (the 5th gauge in Fig. 8c), but the severity increases by up to ~~6~~-~~8~~ times over the lower reaches (Fig. 8c). Therefore, human interventions not only increase the drought frequency over most areas of the Yellow River basin, but also increase the drought severity dramatically over the lower reaches. As compared with the results based on a constant climatology (cyan and pink bars in Fig. 8), the non-stationarity generally reduces the human influence on drought frequency, but increases the human impact on drought duration and severity.

To investigate the preference of the occurrence of seasonal hydrological drought, the onset seasons are identified based on individual hydrological drought events. And the ratios of the number of drought onsets during different seasons to the total number of drought events are plotted in Figure 9. Without human interventions, most seasonal hydrological droughts start in summer, especially for the upper and lower gauges (Fig. 9a-b). While for the gauges over middle reaches, autumn is also a preferred season for drought onset (Fig. 9a-b). However, Fig. 9 shows that human intervention changes the seasonality of the hydrological drought onset significantly, where the spring is the preferred season for the drought onset for the lower reaches, and the ratio for summer season is also increased for the upper reaches. With human interventions, the hydrological drought onset becomes earlier, no matter using transient or constant climatology (Fig. 9c-d).

3.3 Seasonal forecasting of hydrological drought with human interventions

To demonstrate the capability of predicting hydrological drought in the anthropocene, a drought case of 2001 is selected to verify the ensemble forecasting of SSI. In terms of meteorological condition, 2001 is a moderate dry year, with the precipitation less than the climatology by 9.4%. However, 2001 is a severe hydrological drought year, with observed streamflow less than the climatology by 26%-37% over the upper reaches and by 51%-86% over the lower reaches (<http://www.yellowriver.gov.cn/>). Figure 10 shows the ensemble forecasts started from February and June of 2001 for the selected five gauges from upper to lower reaches. As verified by the offline simulated SSI, the climatological forecast method (ESP/VIC) has some skill in the February forecast, but totally misses the drought in the June forecast with the ensemble mean SSIs (blue lines in the left panels of Fig. 10) close to zeros that are larger than the drought threshold lines (black horizontal lines) of -0.8. By using the climate-model-based approach (NMME/VIC, see Yuan (2016) for details),

there are not significant improvements for the forecasts started from February, but a number of ensembles can capture the hydrological drought conditions, with the ensemble mean SSIs (blue lines in the right panels of Fig. 10) close to the drought threshold lines. This suggests the added values from climate forecast models in the hydrological drought forecasting.

The results shown in Figure 10 neglect the errors or uncertainties in hydrological model because the offline simulated hydrological drought index is used as the reference to verify the forecasts. To compare with observed SSI, the forecast streamflow series are post-processed (see Section 2.3 for details), and the results for 2001 are shown in Figure 11. Both ESP/VIC and NMME/VIC can predict a drought condition with ensemble mean SSIs much lower than the -0.8 for the middle and lower gauges (Hekouzhen, Huayuankou and Lijin), but both underestimate the drought severity. NMME/VIC shows non-trivial improvement against ESP/VIC in terms of the drought forecasting. An interesting difference is that five gauges have similar ensemble spreads in the natural conditions (Fig. 10), but the spreads vary among upstream and downstream gauges in the anthropogenic conditions (Fig. 11). This is because the hydrological post-processing is applied for each target months and for each gauge independently, the ensemble spreads do not necessarily increase over forecast leads after the post-processing, while they indeed depend on the magnitude or intensity of human interventions.

To assess the probabilistic forecast skill for hydrological droughts during the hindcast period of 1982-2010, the Brier Score (BS; Wilks, 2011) is used. It is defined as:

$$BS = \frac{1}{n} \sum_{k=1}^n (y_k - o_k)^2,$$

where k denotes a number of n forecast-reference pairs of hydrological drought conditions; o_k is probability from the reference (offline simulated SSI for the natural condition, and observed SSI for the anthropogenic case) for the k^{th} pair, with $o_k=1$ if the drought occurs ($SSI < -0.8$) and $o_k=0$ if it does not ($SSI > -0.8$); y_k is the corresponding probability of drought occurrence from the forecast, for example, if 6 of 10 ensemble forecast members have $SSI < -0.8$, then $y_k=0.6$. BS is similar to the root mean squared error, so a smaller BS represents a better performance.

Figure 12 shows the BS for the ensemble hydrological drought forecasts at different hydrological gauges and at different lead times. The statistics are based a set of comprehensive hindcasts, where for each month during the 29-year (1982-2010) period there is a 6-month hindcast. This consists of 348 hindcast cases, each one is 6-month long, and has 28 or 99 realizations for ESP/VIC and NMME/VIC respectively. For the natural condition (upper panels of Fig. 12), the BS values increase as the forecast leads increase, indicating that the performance generally decreases over leads. The performance of probabilistic hydrological drought forecasting is better over lower reaches than that over upper reaches both for ESP/VIC and NMME/VIC, suggesting the influence of catchment memory. As compared with ESP/VIC, NMME/VIC has a better performance, with BS decreased by 11%-26% in the first month, by 3%-14% in the second and third months.

As verified against observed SSI (lower panels of Fig. 12), the performances for ESP/VIC and NMME/VIC are surprisingly better than the natural cases, and the performances do not necessarily degrade over forecast lead times. This is because human interventions increase the occurrence and severity of hydrological drought, and outweigh the climate variations in many cases. The hydrological post-processing imparts the first-order control in the forecasting, and many post-processed

forecasts can represent drought conditions (SSI<-0.8), although they may underestimate the severity as shown in Fig. 11 (right panels). The differences in BS between ESP/VIC and NMME/VIC for the anthropogenic case are smaller than that for the natural case. In other words, seasonal predictability of hydrological drought in the anthropocene greatly depends on the information of human water use, or the predictability of human interventions.

5 4. Concluding Remarks

This paper investigates the effects of human interventions on hydrological drought processes and the drought forecasting. Naturalized and observed monthly streamflow are standardized to calculate the hydrological drought index, the Standardized Streamflow Index (SSI). Comparison between naturalized and observed SSI at 12 hydrological gauges along the mainstream of the Yellow River basin (the second largest river basin in China with a drainage area of $7.52 \times 10^5 \text{ km}^2$) shows that human
10 interventions decrease the correlation between hydrological and meteorological droughts, and make the hydrological drought respond to longer time scale of meteorological drought. The relation between meteorological drought and hydrological drought over lower reach of Yellow River is not stationary, anthropogenic climate change and human interventions add more nonlinearity to the propagation from meteorological to hydrological droughts. Seasonal hydrological drought events are identified with monthly SSI<-0.8 for at least three continuous months. Due to heavy human water consumptions over the
15 middle and lower reaches of the Yellow River, there are ~~118%-262%~~~~two to four fold~~ increases in the drought frequency and up to ~~six~~~~eight~~-fold increases in the drought severity, the drought duration increases by ~~1221-9983%~~, and the hydrological drought onset becomes earlier.

The naturalized streamflow datasets are used to calibrate the VIC land surface hydrological model and the routing model, and both the climatological forcings (ESP) and the climate model predicted forcings (NMME) are used to drive the
20 hydrological models to provide seasonal streamflow forecasts. For a severe hydrological drought event occurred over the Yellow River in 2001, ESP/VIC does not capture it while NMME/VIC has some skill when they are verified against naturalized SSI. The added values from climate-model-based seasonal hydrological drought forecasting are decreased in the anthropocene, where both methods can predict a drought condition after the hydrological post-processing but underestimate the severity. Unlike the naturalized hydrological drought forecasting, the ensemble spreads do not necessarily increase over
25 forecast leads in the anthropocene because of the seasonality of human interventions that have been implicitly incorporated in the hydrological post-processing. Based on the assessment of all hindcasts during 1982-2010, it is found that NMME/VIC decreases (improves) the Brier Score (BS) against ESP/VIC by 11%-26% in the first month and by 3%-14% in the second and third months for the probabilistic hydrological drought forecasting in the naturalized conditions. In the anthropocene, the performances for both forecast methods become better in terms of BS, and the forecast skill does not necessarily decreases
30 over forecast leads due to dominant influence of human water consumption on the hydrological drought processes.

While the effects of human interventions on hydrological drought processes have been studied in the past, to our knowledge, this study is among the first to investigate seasonal hydrological drought forecasting in the anthropocene. Intensive and direct influence of human water use challenges our understanding of hydrological drought predictability. Traditionally, hydro-climate predictability usually refers to the struggle between deterministic and chaotic physical processes. In the

anthropocene, the human influence sometimes outweighs those natural hydro-climate variations and variability, and can be a major source of predictability (or uncertainty if it is not fully understood) for hydrological drought. Current hydrological post-processing procedure accounts for the seasonality of human water use by adding/deducting water to/from the predicted streamflow, and adjusting the forecast results based on the Bayesian theory. Another popular method is to parameterize the human interventions directly in hydrological models (e.g., Wada et al., 2014; Zhou et al., 2016 among many others), where the irrigated area can be estimated for crop water demand, and the diversion and return flows can also be simulated in those models. This modeling framework could be further pushed forward by the availability of Surface Water and Ocean Topography (SWOT) satellite data in the near future, where surface water storage in reservoirs and rivers can be at 250m resolution (Biancamaria et al., 2016). However, it is difficult to account for the inter-annual variability of human water use in a “real” forecasting mode. During severe hydrological drought events, the human water use tends to be more intensive to adapt to the drought conditions. How to quantify and model the variability of human water use is an interdisciplinary question for both physical and social sciences. In addition, the interdisciplinary collaboration is also indispensable to objectively quantify and to accurately predict drought impact, as the drought impact and drought are quite different.

15 | **Acknowledgement.** We would like to thank Prof. Dennis Lettenmaier and ~~two~~^{three} anonymous reviewers for their helpful comments. This work was supported by the National Natural Science Foundation of China (No. 91547103), China Special Fund for Meteorological Research in the Public Interest (Major projects) (GYHY201506001), National Key Research and Development Program (2016YFA0600403), CAS Key Research Program of Frontier Sciences (QYZDY-SSW-DQC012), and the Thousand Talents Program for Distinguished Young Scholars. This paper is submitted to the special issue
20 "Observations and modeling of land surface water and energy exchanges across scales" in honor of Professor Eric F. Wood. The first author would like to thank Eric for his inspiring guidance.

References

- AghaKouchak, A., Feldman, D., Hoerling, M., Huxman, T., and Lund, J.: Water and climate: Recognize anthropogenic drought, *Nature*, 524, 409–411, doi:10.1038/524409a, 2015.
- Barker, L. J., Hannaford, J., Chiverton, A., and Svensson, C.: From meteorological to hydrological drought using standardised indicators, *Hydrol. Earth Syst. Sci.*, 20, 2483–2505, 2016.
- 5 Biancamaria, S., Lettenmaier, D. P., and Pavelsky, T. M.: The SWOT mission and its capabilities for land hydrology, *Surv. Geophys.*, 37, 307–337, 2016.
- Bloomfield, J. P., Marchant, B. P., Bricker, S. H., and Morgan, R. B.: Regional analysis of groundwater droughts using hydrograph classification, *Hydrol. Earth Syst. Sci.*, 19, 4327–4344, 2015.
- 10 Dutra, E., Magnusson, L., Wetterhall, F., Cloke, H. L., Balsamo, G., Boussetta, S., and Pappenberger, F.: The 2010–2011 drought in the Horn of African ECMWF reanalysis and seasonal forecast products, *Int. J. Climatol.*, 33, 1720–1729, doi:10.1002/joc.3545, 2012.
- Folland, C. K., et al.: Multi-annual droughts in the English Lowlands: a review of their characteristics and climate drivers in the winter half-year, *Hydrol. Earth Syst. Sci.*, 19, 2353–2375, 2015.
- 15 Haslinger, K., Koffler, D., Schoner, W., and Laaha, G.: Exploring the link between meteorological drought and streamflow: Effects of climate catchment interaction, *Water Resour. Res.*, 50, 2468–2487, doi:10.1002/2013WR015051, 2014.
- Hoerling, M., and Kumar, A.: The perfect ocean for drought, *Science*, 299, 691–694, doi:10.1126/science.1079053, 2003.
- Hong, S. Y., and Kalnay, E.: Role of sea surface temperature and soil-moisture feedback in the 1998 Oklahoma–Texas drought, *Nature*, 408, 842–844, doi:10.1038/35048548, 2000.
- 20 Kirtman, B. P., Min, D., Infanti, J. M., et al.: The North American Multimodel Ensemble: Phase-1 Seasonal-to-Interannual Prediction; Phase-2 toward Developing Intraseasonal Prediction, *B. Am. Meteorol. Soc.*, 95, 585–601, doi:10.1175/BAMS-D-12-00050.1, 2014.
- Koster, R. D., Mahanama, S. P. P., Livneh, B., Lettenmaier, D. P., and Reichle, R. H.: Skill in streamflow forecasts derived from large-scale estimates of soil moisture and snow, *Nat. Geosci.*, 3, 613–616, doi:10.1038/ngeo944, 2010.
- 25 Kumar, R., et al.: Multiscale evaluation of the Standardized Precipitation Index as a groundwater drought indicator, *Hydrol. Earth Syst. Sci.*, 20, 1117–1131, 2016.
- Liang, X., Wood, E. F., and Lettenmaier, D. P.: Surface soil moisture parameterization of the VIC-2L model: Evaluation and modifications, *Global Planet. Change*, 13, 195–206, doi: 10.1016/0921-8181(95)00046-1, 1996.
- López-Moreno, J. I., Vicente-Serrano, S. M., Beguería, S., García-Ruiz, J. M., Portela, M. M., and Almeida, A. B.: Dam effects on droughts magnitude and duration in a transboundary basin: The Lower River Tagus, Spain and Portugal, *Water Resour. Res.*, 45, W02405, doi:10.1029/2008WR007198, 2009.
- 30 Luo, L. and Wood, E. F.: Monitoring and predicting the 2007 U.S. drought, *Geophys. Res. Lett.*, 34, L22702, doi:10.1029/2007GL031673, 2007.

- Ma, F., Yuan, X., and Ye, A.: Seasonal drought predictability and forecast skill over China, *J. Geophys. Res.-Atmos.*, 120, 8264–8275, doi:10.1002/2015JD023185, 2015.
- McKee, T. B., Doesken, N. J., and Kleist, J.: The relationship of drought frequency and duration to time scales. Preprints, Eighth Conf. on Applied Climatology, Anaheim, CA, Amer. Meteor. Soc., 179–184, 1993.
- 5 [Milly, P. C. D., et al.; Stationarity is dead: Whither water management? *Science*, 319, 573–574, 2008](#)
- [Milly, P. C. D., et al.; On Critiques of et al.Whigv, Anaheim, CA, Amer. Meteor.anagement?’’ *Water Resour. Res.*, 51, 7785–7789, doi:10.1002/2015WR017408, 2015.](#)
- Mo, K., Shukla, S., Lettenmaier, D. P., and Chen, L.: Do Climate Forecast System (CFSv2) forecasts improve seasonal soil moisture prediction?, *Geophys. Res. Lett.*, 39, L23703,doi:10.1029/2012GL053598, 2012.
- 10 Niu, J., Chen, J., and Sun, L.: Exploration of drought evolution using numerical simulations over the Xijiang (West River) basin in South China, *J. Hydrol.*, 526, 68-77, 2015.
- [Piao, S., et al.: The impacts of climate change on water resources and agriculture in China. *Nature*, 467, 43-51, 2010.](#)
- Pozzi, W., et al.: Towards global drought early warning capability: Expanding international cooperation for the development of a framework for global drought monitoring and forecasting, *Bull. Amer. Meteor. Soc.*, 94, 776–785,doi:10.1175/BAMS-D-11-00176.1, 2013.
- 15 Rimkus, E., et al.: Dynamics of meteorological and hydrological droughts in the Neman river basin, *Environ. Res. Lett.*, 8, 045014, 2013.
- Sheffield, J., Wood, E. F., and Chaney, N., Guan, K., Sadri, S., Yuan, X., Olang, L., Amani, A., Ali, A., Demuth, S., and Ogallo, L.: A Drought Monitoring and Forecasting System for Sub-Sahara African Water Resources and Food Security, *B. Am. Meteorol. Soc.*, 95, 861–882, doi:10.1175/BAMS-D-12-00124.1, 2014.
- 20 Shukla, S., and Wood, A. W.: Use of a standardized runoff index for characterizing hydrologic drought, *Geophys. Res. Lett.*, 35, L02405, doi:10.1029/2007GL032487, 2008.
- Sikder, S., Chen, X., Hossain, F., Roberts, J. B., Robertson, F., Shum, C. K., and Turk, F. J.: Are general circulation models ready for operational streamflow forecasting for water management in the Ganges and Brahmaputra river basins?, *J. Hydrometeorol.*, 17, 195–210, doi:10.1175/JHM-D-14-0099.1, 2016.
- 25 Staudinger, M., Weiler, M., and Seibert, J.: Quantifying sensitivity to droughts-an experimental modeling approach, *Hydrol. Earth Syst. Sci.*, 19, 1371-1384, 2015.
- Stoelzle, M., Stahl, K., Morhard, A., and Weiler, M.: Streamflow sensitivity to drought scenarios in catchments with different geology, *Geophys. Res. Lett.*, 41, 6174–6183, doi:10.1002/2014GL061344, 2014.
- 30 Teuling, A. J., et al.: Evapotranspiration amplifies European summer drought, *Geophys. Res. Lett.* 40, 2071–2075, doi: 10.1002/grl.50495, 2013.
- Thober, S., Kumar, R., Sheffield, J., Mai, J., Schafer, D., and Samaniego, L.: Seasonal soil moisture drought prediction over Europe using the North American Multi-Model Ensemble (NMME), *J. Hydrometeorol.*, 16, 2329–2344,doi:10.1175/JHM-D-15-0053.1, 2015.

带格式的: 字体: (默认) Times New Roman, (中文) Times New Roman, 10磅, 字体颜色: 文字 1, 英语(英国)

带格式的: 字体: (默认) Times New Roman, (中文) Times New Roman, 10磅, 字体颜色: 文字 1, 英语(英国)

带格式的: 缩进: 左侧: 0 厘米, 悬挂缩进: 2.25 字符

带格式的: 字体: (默认) Times New Roman, (中文) Times New Roman, 10磅, 字体颜色: 文字 1, 英语(英国)

带格式的: 字体: (默认) Times New Roman, (中文) Times New Roman, 10磅, 字体颜色: 文字 1, 英语(英国)

带格式的: 字体: (默认) Times New Roman, (中文) Times New Roman, 10磅, 字体颜色: 文字 1, 英语(英国)

带格式的: 字体: (默认) Times New Roman, (中文) Times New Roman, 10磅, 字体颜色: 文字 1, 英语(英国)

带格式的: 字体: (默认) Times New Roman, (中文) Times New Roman, 10磅, 字体颜色: 文字 1, 英语(英国)

带格式的: 字体: (中文) Times New Roman, 字体颜色: 黑色

带格式的: 字体: (中文) Times New Roman, 字体颜色: 黑色

- Trambauer, P., Werner, M., Winsemius, H. C., Maskey, S., Dutra, E., and Uhlenbrook, S.: Hydrological drought forecasting and skill assessment for the Limpopo River basin, southern Africa, *Hydrol. Earth Syst. Sci.*, 19, 1695–1711, doi:10.5194/hess-19-1695-2015, 2015.
- Van Loon, A. F., Van Huijgevoort, M. H. J., and Van Lanen, H. A. J.: Evaluation of drought propagation in an ensemble mean of large-scale hydrological models, *Hydrol. Earth Syst. Sci.*, 16, 4057–4078, doi:10.5194/hess-16-4057-2012, 2012.
- Van Loon, A. F., Gleeson, T., Clark, J., Van Dijk, A. I. J. M., Stahl, K., Hannaford, J., Di Baldassarre, G., Teuling, A. J., Tallaksen, L. M., Uijlenhoet, R., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T., Rangelcroft, S., Wanders, N., and Van Lanen, H. A. J.: Drought in the Anthropocene, *Nature Geosci.*, 9, 89–91, doi:10.1038/ngeo2646, 2016a.
- Van Loon, A. F., et al.: Drought in a human-modified world: reframing drought definitions, understanding, and analysis approaches, *Hydrol. Earth Syst. Sci.*, 20, 3631–3650, 2016b.
- Vicente-Serrano, S. M. and López-Moreno, J. I.: Hydrological response to different time scales of climatological drought: an evaluation of the Standardized Precipitation Index in a mountainous Mediterranean basin, *Hydrol. Earth Syst. Sci.*, 9, 523–533, doi:10.5194/hess-9-523-2005, 2005.
- Villarini, G. F., Serinaldi, F., Smith, J. A., and Krajewski W. F.: On the stationarity of annual flood peaks in the continental United States during the 20th century. *Water Resour. Res.*, 45, W08417, doi: 10.1029/2008WR007645, 2009.
- Wada, Y., van Beek, L. P. H., Wanders, N., and Bierkens, M. F. P.: Human water consumption intensifies hydrological drought worldwide, *Environ. Res. Lett.*, 8, 034036, 2013.
- Wada, Y., Wisser, D., and Bierkens, M. F. P.: Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources, *Earth Syst. Dynam.*, 5, 15–40, doi:10.5194/esd-5-15-2014, 2014.
- Wen, L., Rogers, K., Ling, J., and Saintilan, N.: The impacts of river regulation and water diversion on the hydrological drought characteristics in the Lower Murrumbidgee River, Australia, *J. Hydrol.*, 405, 3–4, 382–391, 2011.
- Wilks, D. S.: *Statistical Methods in the Atmospheric Sciences*, Int. Geophys. Ser., vol. 100, 3rd ed., 676 pp., Academic, San Diego, Calif., 2011.
- Wood, A. W., Mauer, E. P., Kumar, A., and Lettenmaier, D. P.: Long-range experimental hydrologic forecasting for the eastern United States, *J. Geophys. Res.*, 107, 4429, doi:10.1029/2001JD000659, 2002.
- Wood, A. W. and Lettenmaier, D. P.: An ensemble approach for attribution of hydrologic prediction uncertainty, *Geophys. Res. Lett.*, 35, L14401, doi:10.1029/2008GL034648, 2008.
- Wood, A. W., Hopson, T., and Newman, A., Brekke, L., Arnold, J., and Clark, M.: Quantifying streamflow forecast skill elasticity to initial condition and climate prediction skill, *J. Hydrometeorol.*, 17, 651–668, doi:10.1175/JHM-D-14-0213.1, 2016.
- Wood, E. F., Schubert, S. D., and Wood, A. W., et al.: Prospects for advancing drought understanding, monitoring, and prediction, *J. Hydrometeorol.*, 16, 1636–1657, doi: 10.1175/JHM-D-14-0164.1, 2015.

带格式的: 字体: (默认) Times New Roman, (中文) Times New Roman, 10 磅, 字体颜色: 文字 1, 英语(英国)

带格式的: 字体: (默认) Times New Roman, (中文) Times New Roman, 10 磅, 字体颜色: 文字 1, 英语(英国)

带格式的: 缩进: 左侧: 0 厘米, 悬挂缩进: 2.25 字符

带格式的: 字体: (默认) Times New Roman, (中文) Times New Roman, 10 磅, 字体颜色: 文字 1, 英语(英国)

带格式的: 字体: (默认) Times New Roman, (中文) Times New Roman, 10 磅, 字体颜色: 文字 1, 英语(英国)

带格式的: 字体: (默认) Times New Roman, (中文) Times New Roman, 10 磅, 字体颜色: 文字 1, 英语(英国)

带格式的: 字体: (默认) Times New Roman, (中文) Times New Roman, 10 磅, 字体颜色: 文字 1, 英语(英国)

- Yuan, X., and Wood, E. F.: Multimodel seasonal forecasting of global drought onset, *Geophys. Res. Lett.*, 40, 4900–4905, doi:10.1002/grl.50949, 2013.
- Yuan, X., Wood, E. F., Chaney, N. W., Sheffield, J., Kam, J., Liang, M., and Guan, K.: Probabilistic seasonal forecasting of African drought by dynamical models, *J. Hydrometeor.*, 14, 1706–1720, doi:10.1175/JHM-D-13-054.1, 2013.
- 5 Yuan, X., Wood, E. F., and Ma, Z.: A review on climate-model-based seasonal hydrologic forecasting: physical understanding and system development, *WIREs Water*, 2, 523–536, doi:10.1002/wat2.1088, 2015a.
- Yuan, X., Roundy, J. K., Wood, E. F., and Sheffield, J.: Seasonal forecasting of global hydrologic extremes: system development and evaluation over GEWEX basins, *B. Am. Meteorol. Soc.*, 96, 1895–1912, doi:10.1175/BAMS-D-14-00003.1, 2015b.
- 10 Yuan, X., Ma, F., Wang, L., Zheng, Z., Ma, Z., Ye, A., and Peng, S.: An experimental seasonal hydrological forecasting system over the Yellow River basin – Part 1: Understanding the role of initial hydrological conditions, *Hydrol. Earth Syst. Sci.*, 20, 2437–2451, doi:10.5194/hess-20-2437-2016, 2016.
- Yuan, X.: An experimental seasonal hydrological forecasting system over the Yellow River basin – Part 2: The added value from climate forecast models, *Hydrol. Earth Syst. Sci.*, 20, 2453–2466, doi:10.5194/hess-20-2453-2016, 2016.
- 15 Zhang, R., Chen, X., Zhang, Z., and Shi, P.: Evolution of hydrological drought under the regulation of two reservoirs in the headwater basin of the Huaihe River, China, *Stoch. Env. Res. Risk A.*, 29(2), 487–499, 2015.
- [Zhang, Z., Chen, X., Xu, C.-Y., Yuan, L., Yong, B., and Yan, S.: Evaluating the non-stationary relationship between precipitation and streamflow in nine major basins of China during the past 50 years. *J. Hydrol.*, 409, 81-93, 2011.](#)
- Zhou, T., Nijssen, B., Gao, H., and Lettenmaier, D. P.: The contribution of reservoirs to global land surface water storage variations. *J. Hydrometeor.*, 17, 309-325, 2016.
- 20

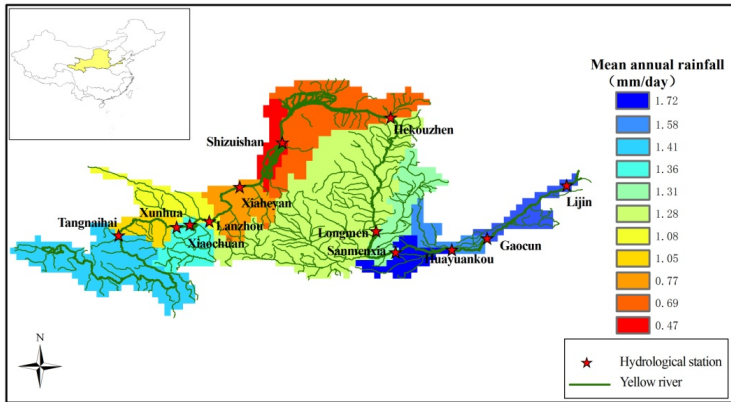
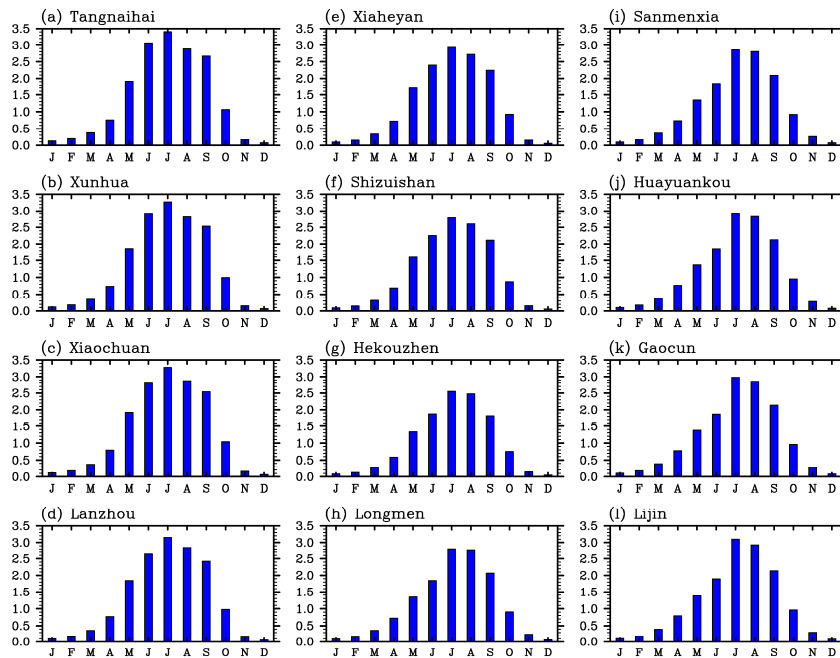


Figure 1. Locations of hydrological stations over the Yellow River basin. Shaded areas are regional mean annual rainfall (mm/day) averaged during 1961-2010.



5 **Figure 2.** Monthly mean rainfall (mm/day) averaged over 1961-2010 for each sub-basin.

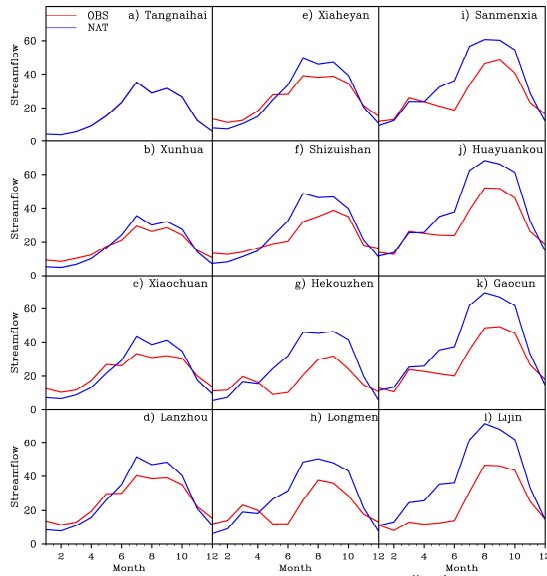
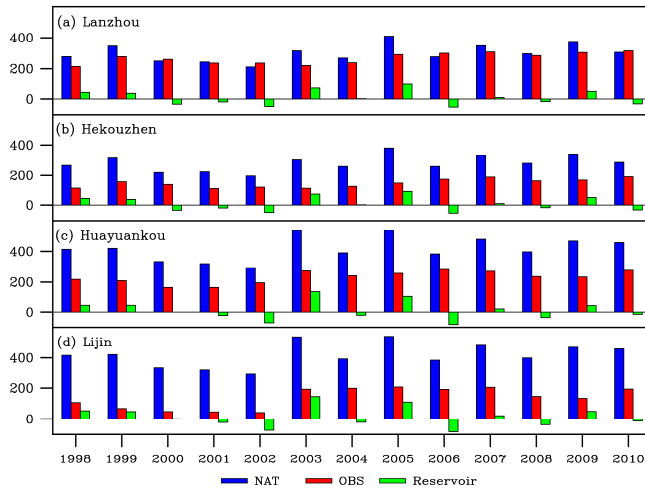
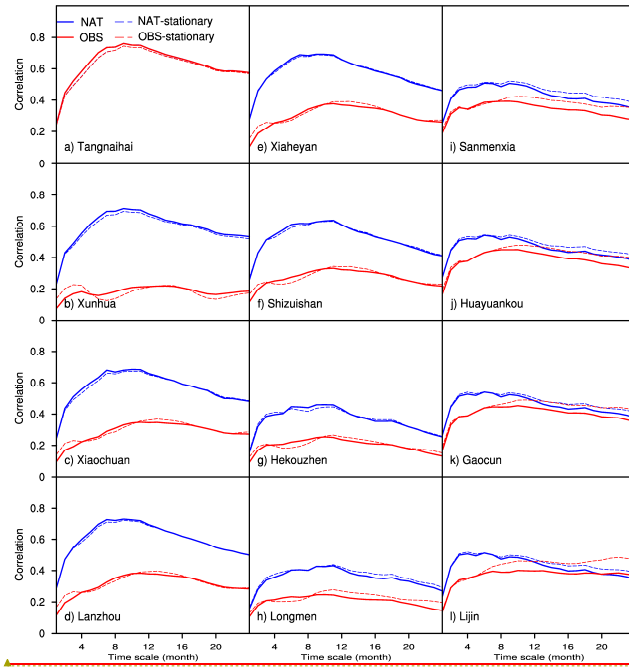


Figure 3. Monthly mean naturalized (blue) and observed (red) streamflow (10^8 m^3) averaged over 1961-2010 for 12 hydrological gauges located from upper to lower mainstream of the Yellow River.



5 **Figure 4.** Annual mean naturalized (blue) and observed (red) streamflow (10^8 m^3), and reservoir storage change (10^8 m^3 , negative green values represent reservoir water distribution) accumulated within four selected sub-basins (from headwater down to the gauge) during 1998-2010.



带格式的: 字体: (中文) +中文正文

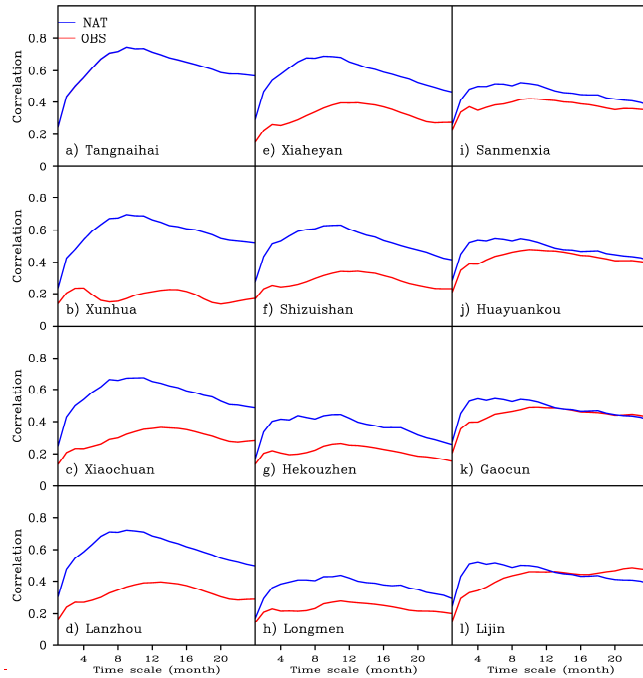


Figure 5. Correlations between Standardized Precipitation Index (SPI) at different time scales and monthly naturalized (blue) or observed (red) Standardized Streamflow Index (SSI) for 12 hydrological gauges located from upper to lower mainstream of the Yellow River. The solid lines are for SPI and SSI calculated based on transient 30-year climatologies with consideration of non-stationarity, while the dashed lines are for those based on the 50-year (1961-2010) climatology.

带格式的: 字体: (中文)+中文正文

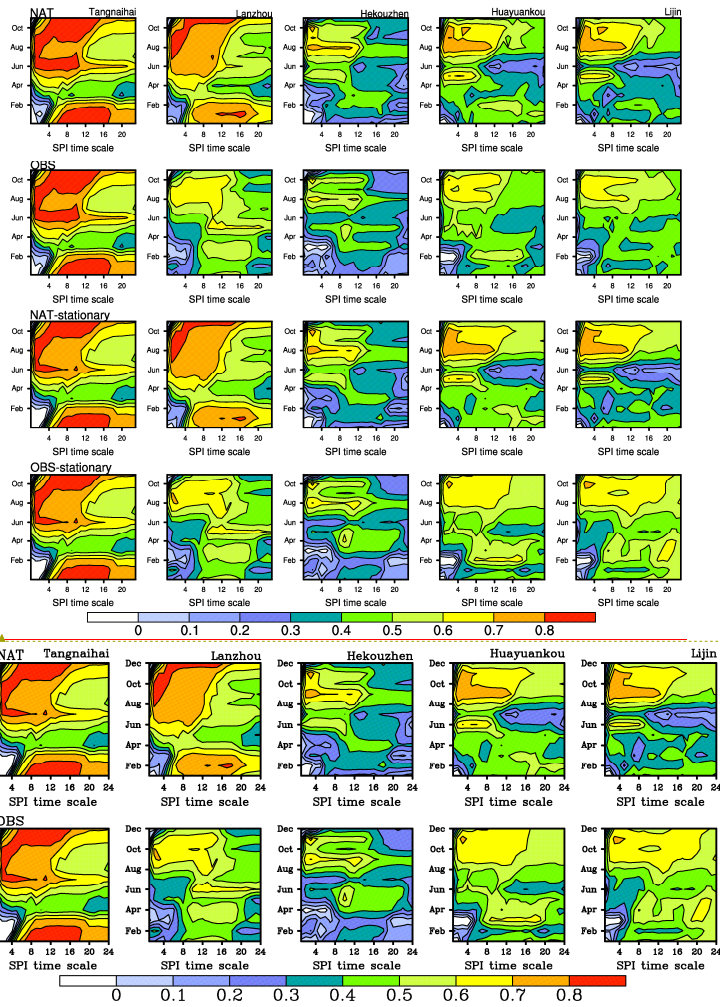
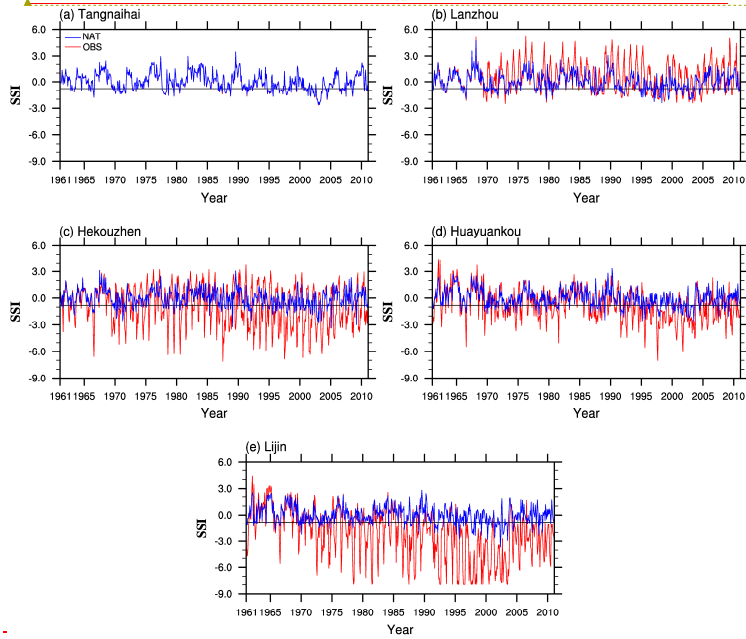
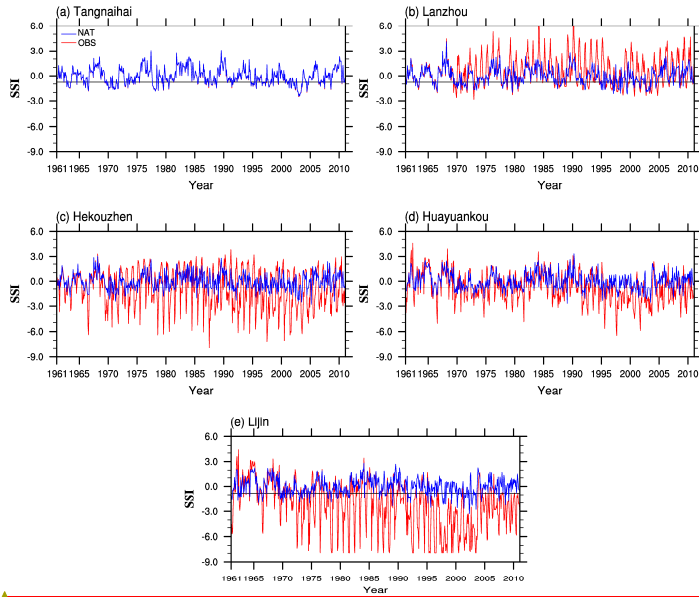
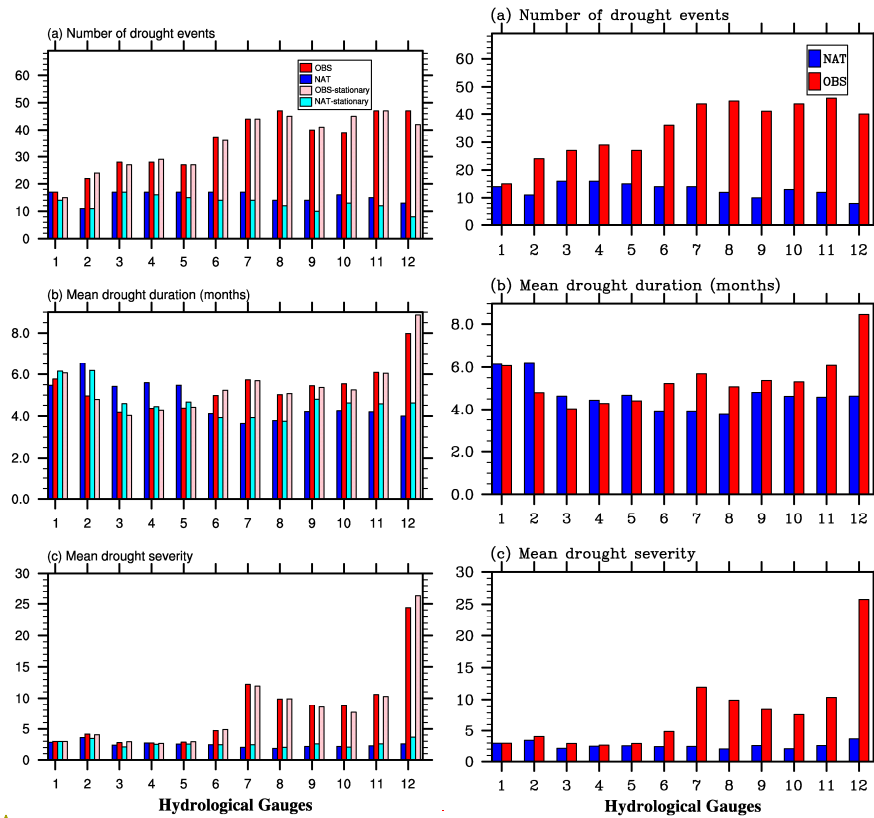


Figure 6. The same as Fig. 5, but for each target month for five selected hydrological gauges.



带格式的：字体：(中文)+中文正文

Figure 7. Time series of naturalized (blue) and observed (red) 1-month Standardized Streamflow Index (SSI) for five selected hydrological gauges. SSI is calculated based on transient 30-year climatologies. The horizontal black lines represent the threshold of -0.8 for drought conditions.

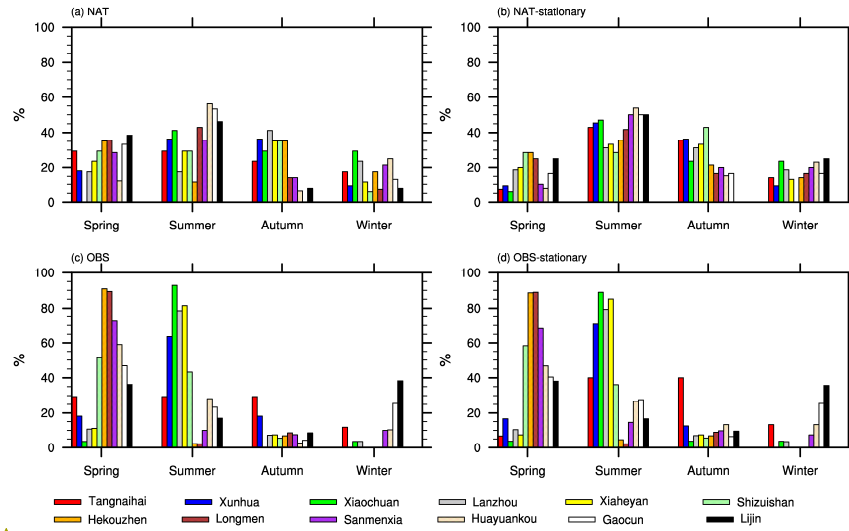


带格式的: 字体: (中文) +中文正文

5 **Figure 8.** Characteristics of hydrological drought events based on the streamflow time series with ~~(red)~~ or without ~~(blue)~~ human influences during 1961-2010 for 12 hydrological gauges. A hydrological drought event is selected when the Standardized Streamflow Index (SSI) is continuously below -0.8 for at least 3 months. Blue and red bars are for the results based on transient 30-year climatologies, and cyan and pink bars are for results based on the 50-year (1961-2010) climatology.

10

Seasonal onset ratio of hydrological drought



带格式的: 字体: (中文) +中文正文, 加粗

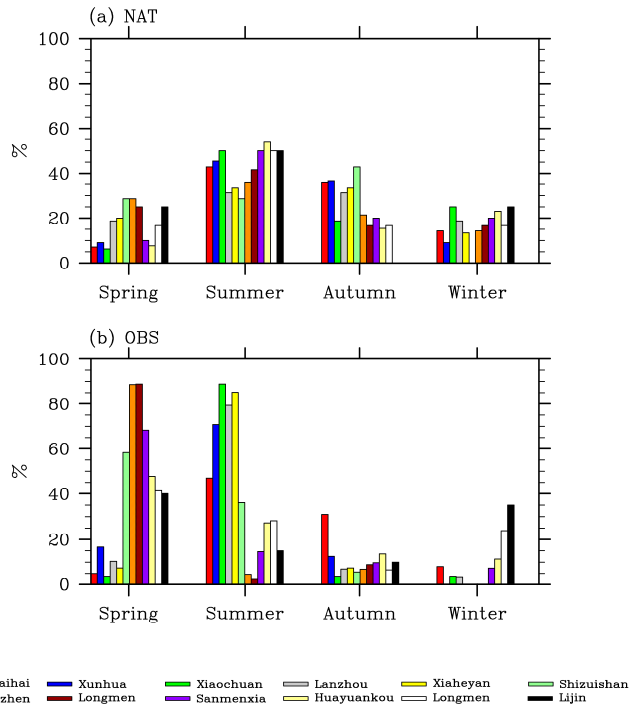


Figure 9. Ratios of the number of hydrological drought onsets occurring in different seasons to the total number of hydrological drought events for the 12 hydrological gauges during 1961-2010. Drought events are classified the same as those in Fig. 8. The left for the results based on transient 30-year climatologies, and the right are for results based on the 50-year (1961-2010) climatology.

5

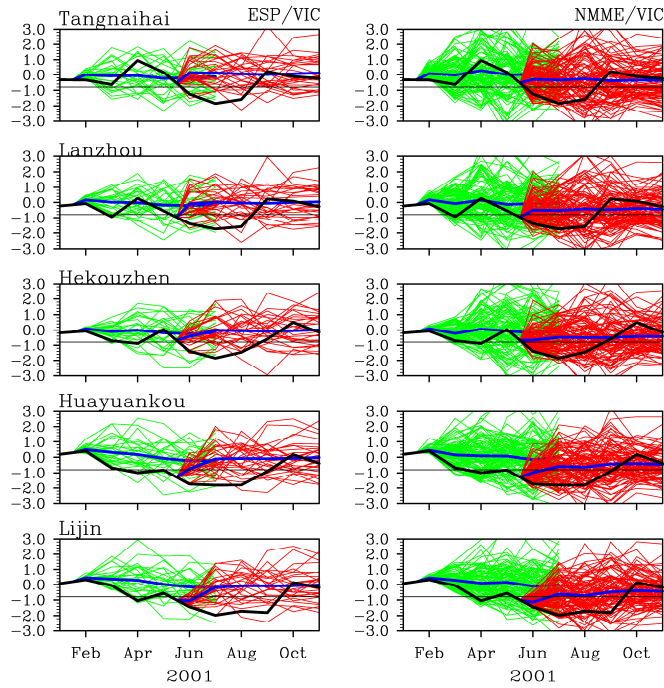


Figure 10. Seasonal ensemble hindcast of the 2001 Yellow River hydrological drought from upstream to downstream gauges by using a climatology method (ESP/VIC) and the climate-model-based approach (NMME/VIC). Vertical axes are Standardized Streamflow Index (SSI), where $SSI < -0.8$ represents a hydrological drought condition. Solid black lines represent the offline simulated SSI by the hydrological model VIC, green and red lines are for individual ensemble members from the hindcasts started from the beginnings of February and June respectively, and blue lines are the ensemble means of the hindcasts.

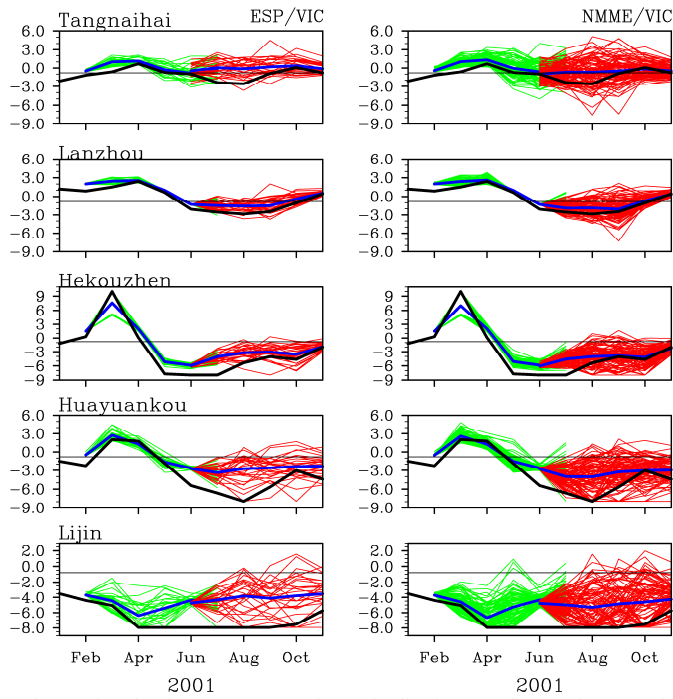


Figure 11. The same as Fig. 10, but for the post-processed Standardized Streamflow Index (SSI) hindcasts from ESP/VIC and NMME/VIC (see Section 2.3 for details) as verified by observed SSI.

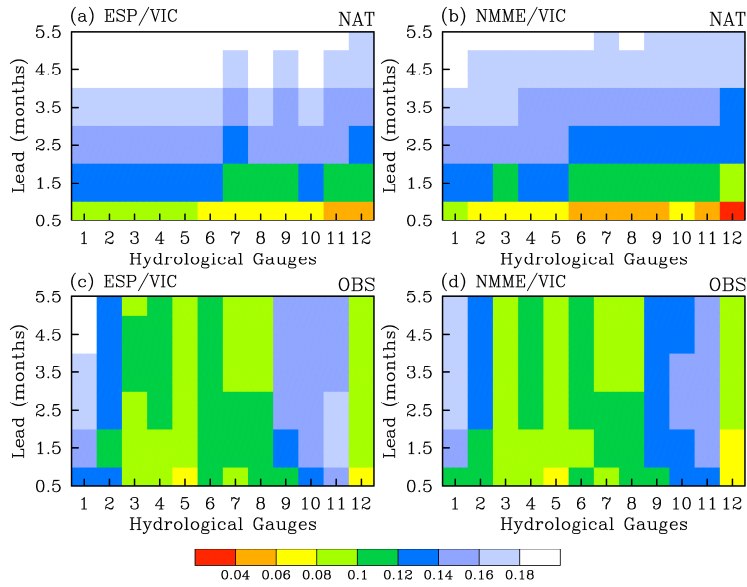


Figure 12. Brier score (BS) for ensemble hydrological drought forecasts at different lead times from a climatology method (ESP/VIC) and the climate-model-based approach (NMME/VIC) for different hydrological gauges as verified against VIC offline simulated (a, b) and observed (c, d) streamflow over the Yellow River basin during the period of 1982-2010. For the verification against observed streamflow, the forecasts have been post-processed.

Xing Yuan
Professor/Dr
Institute of Atmospheric Physics
Chinese Academy of Sciences
Beijing 100029, China
Email: yuanxing@tea.ac.cn
Tel: +86-10-82995385
<http://www.escience.cn/people/yuanxing>
May 7, 2017

5

10 Prof. Dennis Lettenmaier
Special Issue Editor
Hydrology and Earth System Sciences
RE: manuscript #hess-2016-592

15 Dear Prof. Lettenmaier,

Thank you for your kind decision letter on our manuscript entitled “Understanding and seasonal forecasting of hydrological drought in the anthropocene” (hess-2016-592). We have carefully considered the third reviewer’s comments and incorporated them into the revised manuscript to the extent possible. Major changes include clarifying the naturalized streamflow data and the groundwater overdraft, considering the non-stationarity by using transient 30-year climatology for the calculation of SPI/SSI and the analysis, and updating Figs. 5-9 and corresponding results. The non-stationarity generally amplifies the human influence on hydrological drought duration and severity over the middle and lower reaches of Yellow River, while reduces the influence on hydrological drought frequency. We hope that you find the revised manuscript and the response to the reviews acceptable to *HESS*. The detailed responses to the comments are attached.

20

25

We appreciate the effort you spent to process the manuscript and look forward to hearing from you soon.

30 Sincerely yours,



Xing Yuan

Responses to the comments from Reviewer #3

We are very grateful to the reviewer for the positive and careful review. The thoughtful comments have helped improve the manuscript. The reviewer's comments are italicized and our responses immediately follow.

5

This paper aims to understand the effect of human activities on the occurrence of hydrological droughts. By making use of this understanding and the seasonal climate forecasts from multiple GCMs, the paper also aim to demonstrated potential of performing seasonal forecasting of hydrological droughts. I think the authors did a reasonable job on highlighting the importance of accounting for human activities in understanding and forecasting hydrological droughts, especially in Yellow River basin in North China, where human activities have significant effects on hydrological processes.

10

Response: Thanks for the positive comments.

After reading through the paper, the authors seem to have ignored a couple of huge factors, that is, the groundwater overdraft can cause significant leakage of surface water to groundwater, and Yellow river is famous for its changing geomorphology due to heavy sediments from the Loess Plateau carried downstream, which would elevate the riverbed over the years, making streamflow time series non-stationary, i.e., even without human activities, hydrological response to the same meteorological forcing could change over time. I don't think the authors have considered those factors adequately.

15

Response: We greatly thank the reviewer for the positive and helpful comments. After consulting the local authorities of Yellow River, we have also improved our understanding of the naturalized streamflow data and the hydrological condition over Yellow River. Yes, the riverbed leakage due to groundwater overdraft is significant over the middle and lower reaches of Yellow River. However, the calculation of naturalized streamflow has already considers such surface-subsurface water exchanges (please see our response to the comment on naturalized streamflow data below). Therefore, we believe our analysis based on the naturalized and observed streamflow data has considered the groundwater overdraft effect, and we have clarified it in the revised manuscript.

20

25

For the seasonal hydrological forecasting part, we acknowledge that we use a VIC model that does not consider the groundwater overdraft effect. Actually the VIC model used here does not have a groundwater component, but it does calculate the subsurface runoff (baseflow) by using a conceptual ARNO formulation (Todini, 1996) which is based on a three-parameter nonlinear recession curve. In the natural condition, the VIC model and the corresponding routing model (which routes both surface runoff and baseflow) are calibrated to reproduce the naturalized streamflow, where the effect of

30

riverbed leakage processes is implicitly considered in order to capture the dynamics of naturalized streamflow. For the observed conditions with human interventions, the effect of groundwater overdraft is also implicitly considered in the hydrological post-processing procedure that transfer the VIC simulated streamflow to those comparable to the observed streamflow (which includes the groundwater overdraft effect) based on the Bayesian merging technique. Therefore, we believe the seasonal hydrological forecasting has also considered the groundwater overdraft effect to some extent, although we totally agree a more physically-based hydrological model is needed for future study (please see discussion at the end of the manuscript).

The effect of sediment accumulation on streamflow is limited as compared with other factors such as irrigations, industrial and civil water uses. In fact, the sediment accumulation is decreasing in recent years due to the Grain for Green ecological conservation project.

However, there are many other reasons that may lead to the non-stationarity of streamflow, e.g., climate change, land use/land cover changes, and human water consumption. To address this issue, we have augmented the calculation of SSI that based on the 50-year (1961-2010) climatology with that based on a transient climatology (i.e., 30-year moving window), re-calculated the results from Figure 5 to Figure 9, and revised the manuscript as follows:

“Due to large water consumptions over the middle and lower reaches, there are 118%-262% increases in the hydrological drought frequency and up to eight-fold increases in the drought severity, the drought duration increases by 21-99%, and the drought onset becomes earlier. The non-stationarity due to anthropogenic climate change and human water use basically decreases the correlation between meteorological and hydrological droughts, reduces the effect of human interventions on hydrological drought frequency while increase the effect on drought duration and severity.” (P1, L15-20)

“Both the 50-year (1961-2010) data and a series of 30-year transient climatology (e.g., 1961-1990 climatology was used for year 1975, 1962-1991 climatology was used for 1976, and so on) were used to calculate the stationary and non-stationary SPI/SSI values respectively.” (P5, L25-27)

“By considering the non-stationarity, the correlations decrease generally from Longmen gauge (Fig. 5h) to the downstream areas, and the decrease are more obvious for the observed streamflow and for the longer timescale of SPI. This suggests that the relation between meteorological drought and hydrological drought over lower reach of Yellow River is not stationary, anthropogenic climate change and human interventions add more nonlinearity to the propagation from meteorological to hydrological droughts.” (P7, L8-12)

“Again, non-stationarity basically weakens the relation between meteorological and hydrological drought over the lower reaches, regardless of seasons.” (Figure 6; P7, L19-20)

“The results based on the 50-year climatology generally have lower SSI in 1990s-2000s and higher SSI in 1960s-1970s (now shown), suggesting there are decreasing trends in streamflow over Yellow River basin that is consistent with previous studies (e.g., Piao et al., 2010).” (Figure 7; P7, L28-31)

“As compared with the results based on a constant climatology (cyan and pink bars in Fig. 8), the non-stationarity generally reduces the human influence on drought frequency, but increases the human impact on drought duration and severity.” (P8, L14-16)

“With human interventions, the hydrological drought onset becomes earlier, no matter using transient or constant climatology (Fig. 9c-d).” (P8, L23-24)

10 *Also, I echo with editor's concern on how naturalized streamflow is computed. Based on the paper, it is hard to figure how naturalized streamflow is truly computed. I wonder if the authors have access to the paper version of Water Resources Bulletins for all years between 1961-2010, because the website <http://www.yellowriver.gov.cn/zwzc/gzgb/> has only annual observed streamflow, annual water withdrawals and consumptions for 1998 to 2015. Further the bulletins have only annual numbers, not*
15 *the monthly numbers used in the study, so I wonder how they are obtained. Besides, I don't see direct naturalized data from the website. So the authors basically estimated the natural streamflow themselves by adding water consumptions by different sectors. I don't know if such a simple addition/substraction is proper because of the complex interactions between surface water and subsurface water and changing geomorphology, as mentioned above.*

20 **Response:** We thank the author for the scrutinization! We actually obtained the monthly data from local authority of Yellow River, and was told to use the “Water Resources Bulletins” as an official reference to the data. But we have now realized that the publically available data in the bulletin are annual mean data, although they do have monthly data in the internal bulletin. After consulting the local authority about the procedure of calculating naturalized streamflow in details, we have now clarified the data as
25 follows:

“Both the natural and observed streamflow datasets at monthly time scale during 1961-2010 were provided by local authority of the Yellow River. The naturalized streamflow (W_{nat}) was calculated as follows:

$$W_{nat}=W_{obs}+W_{irr}+W_{idu}+W_{civ}+W_{div}+W_{res},$$

30 where W_{obs} is the observed streamflow; W_{irr} is surface water consumed in irrigation, i.e., irrigated surface water that is transpired from crop, evaporated from bare ground and river/channel water surface, absorbed into soil (through infiltration, percolation and recharge to shallow groundwater), leaked from river/channel bed to groundwater during transportation, so the W_{irr} is not simply those withdrew from

river, while it is actually the surface water consumption in the processes of irrigation that already considers the flow return to the river; similarly, W_{idu} and W_{civ} are surface water consumed by industrial and civil sectors, by considering the waste water returned to the river; W_{div} is the interbasin water diversion, and W_{res} is the water regulated by reservoirs. To account for the non-stationarity both from anthropogenic climate change (Milly et al., 2008, 2015) and land use/land cover changes (Villarini et al., 2009; Zhang et al., 2011), the variable runoff coefficient (annual runoff divided by annual precipitation) and more physically based methods that consider the soil conservation (e.g., Grain for Green project over Loess Plateau), effect of groundwater overdraft on surface water, and evaporation loss from reservoirs or channels, are used to correct the naturalized streamflow. Such correction is critical over Yellow River due to significant climate change and human interventions (Zhang et al., 2011). For example, small, medium and heavy rainy days decreased by 20-26% over the areas between Hekouzhen and Longmen gauges in 1980s as compared with those in 1950s and 1960s, with duration of extremely heavy rainfall decreased from 0.82 day to 0.38 day. The annual streamflow over the middle reaches of Yellow River could decrease by 19% with the same annual precipitation due to ecological conservation, and could decrease by 47% due to the riverbed leakage induced by groundwater overdraft. The corrections for the annual mean streamflow over the areas from Tangnaihai to Lanzhou, and down to Hekouzhen, Longmen, Sanmenxia, Huayuankou and Lijin are 3.16×10^8 , 0.80×10^8 , 6.17×10^8 , 10.99×10^8 , 9.23×10^8 and 2.61×10^8 m³, respectively. To our knowledge, this is the most comprehensive estimation of naturalized streamflow over Yellow River basin so far, based on abundant data from different sectors. Yuan et al. (2016) used the naturalized streamflow to calibrate the Variable Infiltration Capacity (VIC) land surface hydrological model (Liang et al. 1996) during 1961-1981, when the human interventions were supposed to be limited. The naturalized streamflow was then compared with VIC simulations during the validation period 1982-2010, and it is found that the naturalized streamflow agreed with VIC simulations quite well with Nash–Sutcliffe efficiency (NSE) varied between 0.71-0.91 (Figure 4 in Yuan et al., 2016).” (P4, L1-30)

Except for my concerns on how to account for full effect of human activities and non-stationarity, I have no big problem on the design on figuring out the relational between meteorological drought and hydrological drought, nor do I question hydrological forecasting experiments. I tend to agree that human activities worsen the hydrological droughts. The questions the authors need to address if those quantitative numbers measuring the effects of human activities are truly reliable. In summary, I think that the authors still to clarify those points to make sure all effects of human activities are

comprehensively considered and naturalized streamflow are truly reflective of natural conditions. My recommendation is to return for further revision.

Response: Thanks for the comments. For the groundwater and non-stationary issues, please see our responses above. The clarification of natural conditions is also presented above. By adding analysis of non-stationarity in the first part of the paper according to the reviewer's helpful suggestion, we have now obtained more objective numbers with a certain range.

Some specific comments:

P1, Abstract, line 14-15: Something is missing in this phrase: "... make the hydrological drought respond to longer time scale of meteorological drought especially during rainy seasons". Especially what?

Response: Human interventions increase the response time of hydrological drought to meteorological drought, especially during rainy seasons. We have removed "especially during rainy seasons" (P1, L15)
P1, line 27: I am not sure if "recursive" is the right word for describing an event occurred repeatedly. According to www.thefreedictionary.com, "Recursive" is term "relating to a repeating process whose output at each stage is applied as input in the succeeding stage." Estimation of future soil moisture can be recursive as future soil moisture can use current soil moisture as input. This doesn't apply to droughts as future drought cannot use current drought condition as input.

Response: We have removed the word "recursively". (P1, L37)

P3, line 34-35: see my comments above. I feel how naturalized streamflow is obtained needs further clarification.

Response: Thanks for the suggestion. We have augmented the clarification of the naturalized streamflow. Please see our response above.

P4, line 10-15: Again, I would like to point out that the lower natural streamflow can also be due to riverbed leakages because of the overdraft of groundwater and of changing geomorphology due to sediment accumulation downstream.

Response: Thanks for the comment. We have revised it as follows:

"Over the lower reaches, the observed streamflow is significantly lower than the naturalized streamflow during wet season due to heavy water consumption, and riverbed leakages because of groundwater overdraft and possible geomorphology change caused by sediment accumulation" (P5, L5-7)

P5, line 1-24: here, the streamflow non-stationarity question needs to be addressed.

Response: The reviewer raised an interesting yet very challenging issue: how to address non-stationarity in the seasonal hydrological forecasting? However, to my knowledge, there is currently

almost NO publication that addresses this issue. The reasons are multifold. First, seasonal hydrological forecasting is to try to forecast hydrological variables (e.g., streamflow, soil moisture) in the next few months (e.g., 3-6 months), where the hydrological model is initiated with current hydrological conditions, and is forced by climate model predictions that are always assumed that the climate within the next 3-6 months is stationary. Second, although there might be unexpected non-stationarity such as UNEXPECTED land cover change in the next 3-6 months, researchers tend to focus more on how to improve the climate and hydrological predictive skill by investigating the sources of hydro-climate predictability, which have been shown a steady improvement during the past 30 years (e.g., ENSO teleconnection, climate-model-driven hydrological forecasting, high-resolution forecasting). In my opinion, the non-stationarity in the seasonal hydrological forecasting could be addressed in the adaptation stage, by focusing on the science questions such as how does human respond to a changing environment (both climate and hydrology, and etc.), how to add human dimension in the seasonal hydrological forecasting scenarios.

Back to our manuscript, the non-stationarity was actually already considered to some extent. We have now clarified it as follows:

“To account for the non-stationarity, the hydrological post-processing was carried out by using observed streamflow during 1982-2010 in a cross-validation mode (Yuan, 2016), and the corresponding SSI was also calculated by using the concurrent hindcast period (i.e., 1982-2010). It should be pointed out that the non-stationarity could be reduced further in a real-time forecasting mode because of the gradual use of concurrent climate and hydrology information for the calibration and initialization of hydrological model for the (seasonal) hydrological forecasting in the next 3-6 months.” (P6, L21-26)

References:

- Milly, P. C. D., et al.: Stationarity is dead: Whither water management? *Science*, 319, 573–574, 2008.
- Milly, P. C. D., et al.: On Critiques of “Stationarity is Dead: Whither Water Management?” *Water Resour. Res.*, 51, 7785–7789, doi:10.1002/2015WR017408, 2015.
- Piao, S., et al.: The impacts of climate change on water resources and agriculture in China. *Nature*, 467, 43-51, 2010.
- Todini, E.: The ARNO rainfall-runoff model. *J. Hydrol.*, 175, 339–382, 1996.
- Villarini, G. F., Serinaldi, F., Smith, J. A., and Krajewski W. F.: On the stationarity of annual flood peaks in the continental United States during the 20th century. *Water Resour. Res.*, 45, W08417, doi: 10.1029/2008WR007645, 2009.

Zhang, Z., Chen, X., Xu, C.-Y., Yuan, L., Yong, B., and Yan, S.: Evaluating the non-stationary relationship between precipitation and streamflow in nine major basins of China during the past 50 years. *J. Hydrol.*, 409, 81-93, 2011.