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A spatial analysis of hydro-climatic and vegetation condition trends in the Yellow River Basin

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Abstract

Stream-gauge data indicate that the flow of the Yellow River has declined during the past several decades. The zero-flow in sections of the river channel, i.e. the Yellow River drying up phenomenon, has occurred since the 1970s. In this paper we present an analysis of changes in the spatial patterns of climatic and vegetation condition data in the Yellow River basin based on data from meteorological stations and satellites. The climatic data is from 1960 to 2000 and the vegetation condition data is from 1982 to 2000. Angular distance weighted (ADW) interpolation method is used to get climatic data coverage from station observations. The spatial distribution of tendency is detected with the Student's t-test. The spatial patterns of climatic and vegetation condition change was analyzed together with the statistical data on human activities. The analysis indicates that the precipitation decreases, temperature increases in most part of the Yellow River basin, evaporative demand of the atmosphere decreases in upper reaches and increases in lower reaches, and human activities have improved the vegetation condition in the irrigation districts.

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The Loess Plateau, the Tibetan Plateau, and the irrigation districts are suggested as precipitation, temperature, and human activity hot spots of the Yellow River drying up phenomenon, respectively.

Key words: climate change, human activity, vegetation condition, drying up, Yellow River

1 Introduction

The Yellow River is the second longest river in China. The headwaters of the Yellow River begin on the Tibetan Plateau and the river flows eastward, passing though the Loess Plateau and the North China Plain before emptying into the Bohai Gulf (Figure 1). The river flows 5464 km in distance in the main course and has a drainage area of 752,443 km^2. The watershed area is as large as 794,712 km^2 if the endoric inner flow area is included. The Yellow River has been facing serious water problems, such as water shortage and eco-environmental degradation (Xu et al., 2002; Feng et al., 2005). In particular, the lower Yellow River Basin has suffered from the river drying up phenomenon, i.e., zero-flow in sections of the river channel, since the 1970s. The water crisis in the Yellow River Basin has raised a critical question: what contributes to the river drying up? The Yellow River research has been a hot topic in hydrology study in China. Many researches had been done to investigate the hydrological cycle change in the Yellow River Basin and targeted on the river drying up phenomenon (Liu and Zheng, 2004; Fu et al., 2004; Xia et al., 2004; Yang et al., 2004; Xu, 2005).

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Liu and Zheng (2004) analyzed the monthly precipitation and runoff data and detected the trends in the hydrological cycle components at several hydrological stations. Human activities are thought to have a great impact on the hydrological cycle in the Yellow River Basin. The similarities in trends of natural runoff and precipitation imply that the change in natural runoff is related to the change in precipitation. Fu et al. (2004) used Kendall's test to analyze the hydro-climatic trends of the Yellow River over the last half century. The analysis was based on the meteorological data from forty-four standard meteorological station with monthly precipitation, monthly means of daily mean temperature, and monthly means of daily maximum and minimum temperatures. Three hydrological gauges at the main steam were used to represent an overview of the hydrological regime of the entire river. The natural runoff has been found decreased. The river basin has become warmer with a more significant increase in minimum temperature than in mean and maximum temperatures. The observed precipitation trend at the rain gauges are not significant. Xia et al. (2004) investigated the water balance items of the river channel system. The river discharge and precipitation data were used in the analysis. The renewability of water resources has had a significant declining trend since the 1950s in the Yellow River Basin. Especially, the renewability indicator was greatly reduced during the 1990s at the downstream. Yang et al. (2004) gives the annual precipitation, mean temperature, pan evaporation, and river discharged trends in the Yellow River basin from the 1950s to the 1990s. It was found that the annual precipitation showed a nonsignificant decreasing trend of 45.3 mm while the air temperature increase 1.28 ℃ from 1951 to 2000. The main reason for the drying up of the Yellow River was addressed to the increase in irrigation water uses. However, climate fluctuations could have greatly alleviated or aggravated the drying up situation according to the observed precipitation and pan evaporation. Xu (2005) used a multiple regression equation to estimate the change in water fluxes to the sea caused by the changes in precipitation, air temperature, water diversion and consumption, erosion, and sediment control measures based on annual data. The contribution of water diversion and consumption to the change in annual water flux to the sea from the Yellow River is estimated to be 41.3%, that of precipitation is 40.8%, that of temperature is 11.4%, and that of erosion and sediment control measures is 6.5%. All these studies try to detect hydro-climatic change trend by analyzing observed data at the station point scale or over the entire basin. General discussions on the upper, middle, or downstream of the Yellow River were given according to the controlled drainage area of the hydrological stations. Station points rather than spatial distributions of the hydro-climatic trends are represented. The human activities were only analyzed on the statistical data on the irrigated area and water consumption. There are few distributed representations of the land cover change according to human activities.

The previous researches contributed on the change of the hydro-climatic conditions in station point scale or lumped river basin scale. On the basis of previous studies, the present study will focus on the spatial distribution of the hydro-climatic and vegetation condition secular trend in the Yellow River Basin. Four decades years of hydro-climatic data and two decades of vegetation condition data have been collected. The spatial distributions of climatic change and vegetation condition change together with gauged river discharge secular trend in the main stem of the river are examined to describe the trends in different parts of the basin.

2 Data and Methods

2.1 Data

The climate data from 120 meteorological stations inside and closed to the study basin (Figure 1) were obtained from the China Meteorological Administration (CMA). The data set is available from 1950 to 2000 with the daily precipitation, daily mean temperature, daily maximum and minimum temperatures, daily mean surface relative humidity, daily sunshine duration, and daily cloud amount. Several stations on the Qinghai-Tibet Plateau were established from the end of 1950s, limiting the study period from 1960 to 2000 (Liu and Chen, 2000).

Six major hydrologic gauges at the main stream of the Yellow River, Tangnaihai, Lanzhou, Toudaoguai, Sanmenxia, Huayuankou and Lijin stations (Figure 1) were collected from Hydrological Year Book by the Hydrological Bureau of the Ministry of Water Resources of China (Information Center of Water Resources, 1950-1990). The watershed above the Tangnaihai station is the source region of the Yellow River. The water withdrawals from the river are small in this region. The Toudaoguai station is after two large irrigation districts (Qingtongxia and Hetao IDs). The Lanzhou-Toudaoguai section is a "net" water consumption zone of the Yellow River, i.e. the annual discharge at the Toudaoguai station is less than the discharge at the Lanzhou station. The drainage area between Toudaoguai and Sanmenxia station is located on the Loess Plateau and is in a transitional zone from semi-arid to semi-humid climate. The Huayuankou station is another important station at the main stream, dividing the middle and lower reaches. The annual discharge at this station reaches its maximum value. The Lijin station is the last hydrological station before the river emptying into the Baohai Gulf. Between Huayuankou and Lijin station, the runoff into the river channel is small because the elevation of the riverbed is higher than the land surface behind artificial levees. In addition, there are large irrigation districts in the lower reaches, which are located outside the watershed and channeled river water (Fu et al., 2004; Jiang et al., 2004). It is another net water consumption zone of the Yellow River.

The data related to irrigation was collected from the Yellow River Conservancy Commission (Yellow River Conservancy Commission, 1986, 1991-2000) and publications from previous researches (Liu and Zhang, 2002; Yang et al., 2004; Xia et al., 2004). The data included annual or decadal irrigation area and river water consumption in upper, middle, and lower reaches of the Yellow River. Figure 2 shows the irrigated area in the Yellow River basin.

The vegetation condition index leaf area index (LAI) was obtained from Myneni et al. (1997). The LAI data was estimated from atmospherically corrected Normalized Difference Vegetation Index (NDVI) observations with a simple three dimensional radiative transfer model. The LAI data set is available with monthly temporal frequency and 16×16 km spatial resolution from 1982 to 2000. It was used as surrogate of the vegetation conditions in this study.

2.2 Methods

The meteorological data at the stations was interpolated to 10×10 km gridded data set to observe spatial distribution of the climatic change. Several methods were investigated to interpolate the daily station observations. These included surface-fitting procedure thin-plate splines (Hutchinson, 1995), Thiessen polygon area averaging (Thiessen, 1911), and angular distance weighted (ADW) averaging (New et al., 2000). The thin-plate splines interpolation was found to be unsuitable because there were considerable undershoot and overshoot in the edge of the study area. Thiessen polygon interpolation employs a limited number of data points in the estimation of grid point values. Interpolation using distance weighting has a number of variants in both the selection of stations that contribute to a grid point estimate and the form of the distance weighting function. The ADW method was selected for this study.

In estimating each grid point using ADW method, eight nearest stations regardless direction and distance are used to contribute to grid point estimation and form the distance weighting function (Piper and Stewart, 1996). Weights for the eight stations were determined in a two-stage process following New et al. (2000). All stations were first weighted by distance from the gird point of interest. The second component of the distance weight was determined by the directional (angular) isolation of each the eight selected stations.

Based on the interpolated data, the linear regression model was used to estimate the trend magnitude in each grid point. The regression weight was calculated as:

$$\beta = \frac{n\sum_{i=1}^{n} t_i y_i - \sum_{i=1}^{n} t_i \sum_{i=1}^{n} y_i}{n\sum_{i=1}^{n} (t_i)^2 - (\sum_{i=1}^{n} t_i)^2} \quad (1)$$

where n is the time series number, t_i is the time number, and y_i is the data value at the time t_i. The statistical significance of the annual trends is evaluated using the Students t-test (Haan, 1977). The significance of a correlation coefficient is tested with

$$t = \frac{r}{\sqrt{(1-r^2)/(n-2)}} \tag{2}$$

where t is distributed approximately for t-test with degrees of freedom $df = n-2$. The non-directional test is then performed with the t-ratio and the degrees of freedom. If the trend is detected, the trend magnitude during the study period was then estimated from the regression weight:

$$\Delta Y = \beta \cdot T \tag{3}$$

where T is the span of time during the study period. The relative trend magnitude was represented as:

$$\Delta Y^{'} = 100 \cdot n \cdot \Delta Y \bigg/ \sum_{i=1}^{n} y_i \tag{4}$$

The distributed trend of precipitation (P), mean relative humidity (U_m), sunshine duration (D_s), mean cloud amount (C_a) and LAI data was presented using relative trend magnitude. The distributed trend of mean temperature (T_m), minimum temperature (T_{min}), maximum temperature (T_{max}) and diurnal temperature range (DTR) data was presented using trend magnitude. The relative trend magnitude of reference evapotranspiration (ET) was used to watch the change in evaporative demand of the atmosphere (Allen et al., 1998).

Table 1

Observed annual discharge change at hydrologic gauges from 1960 to 2000

Stations	Discharge ($10^9 m^3$)	Avg. [a] (mm)	Trend [b] (mm)	Relative trend (%)
Tangnaihai	20.8	171	-	-
Lanzhou	31.5	141	-48	-34
Toudaoguai	22.1	60	-35	-58
Sanmenxia	34.2	50	-35	-71
Huayuankou	38.4	53	-40	-77
Lijin	29.8	40	-59	-149

[a] Annual discharge is presented as the water depth over the controlled drainage area of each gauge.
[b] A significance level of 5% is used to detect the trend.

3 Results and Discussions

Observed annual discharge changes at the six gauges during the study period are shown in Table 1. There are significant decreasing trends for all the gauges except for Tangnaihai gauge. The annual discharge at the Toudaoguai gauge is less than that at Lanzhou gauge and the discharge at Lijin gauge is less than that at Huayuankou gauge, suggesting the runoff absorbing processes are more significant than runoff generating processes in the Lanzhou-Toudaoguai and Huayuankou-Lijin sections.

Figure 3 illustrates the time series of hydro-climatic data over the Yellow River Basin from 1960 to 200 and LAI value variation from 1982 to 2000. In the figure 3, the linear regression lines from 1960 to 2000 are shown with solid straight line, and the regression lines from 1982 to 2000 are shown with dot straight line. For most hydro-climatic items, the regression line from 1982 to 2000 gives the same increase or decrease tendency and larger slope comparing with that in a long period, from 1960 to 2000. The exceptions occur for reference evapotranspiration, sunshine duration time and diurnal temperature range. Large increase tendency on reference evapotranspiration is found from to 1982 to 2000 although there is not significant tendency in the long period. Sunshine duration time decreases for the long period but slightly increased from 1982 to 2000. The DTR increased in the 1980s and 1990s because the rapid increase in daily maximum temperature during this period while the DTR decreases during the long period. The LAI values increased from 1982 to 2000. The LAI values in the irrigation districts increased much rapidly than that over the entire river basin.

Table 2 lists the detail numbers of hydro-climatic and vegetation condition change in the Yellow River Basin. The precipitation shows a decreasing trend with a significance level of 6%. Taking a significance level of 0.1, there is no significant trend in reference evapotranspiration. Our results shows that the evaporative demand of the atmosphere has no significant trend even there are reports about the pan evaporation decrease in the Yellow River basin. Yang et al. (2004) used the pan evaporation observations as an agency of the evaporation trend and implied the pan evaporation increase in the 1970s would contribute to the river drying up. However, the pan evaporation trend is not consistent with the terrestrial evaporation trend. Liu and Zeng (2004) reported that the rate of pan evaporation has steadily decreased from 1960 to 2000 in the Yellow River basin. Brutsaert and Parlange (1998) explained the difference between pan evaporation and terrestrial evaporation and argued that pan evaporation had not been used correctly as an indicator of climate change. Roderick and Farquhar (2002) showed that the decrease in pan evaporation was consistent with decreases in sunlight resulting from increasing cloud coverage and aerosol concentration. The decreasing in the river discharge possibly responds to the decrease in precipitation. There are no significant trends in relative humidity. Decreasing sunshine duration and cloud amount trends are found. The cloud amount decrease trend over China was also reported by Kaiser (1998). Unlike in other areas of the world, the decrease of cloud amount was not accompanied by an increase in solar irradiance and then an increase of pan evaporation. The decrease sunshine duration is one of the reasons for decrease of pan evaporation. Liu et al. (2004) investigated the pan evaporation trends and speculated that aerosols may play a critical role in the decrease of solar irradiance and pan evaporation in China. The Yellow River did become warmer according to the increasing trends in temperatures. The mean temperature increased 1.44 ℃ during the study period. The increase magnitude of daily minimum temperature is larger than the increase magnitude of daily maximum temperature, causing a narrower diurnal temperature range. The DTR became 0.43 ℃ smaller. During the 1980s-1990s, the averaged LAI value over the Yellow River basin shows no significant trend, but the LAI value in irrigation districts (IDs) increases 48% with a significance level of 13%. This indicates vegetation condition in the IDs might become better from 1982 to 2000. The water consumptions and irrigation area increases are accompanied by the vegetation condition change, implying human activities have altered the land cover in the Yellow River basin (Liu and Zhang, 2002).

Figure 4(a-e) shows the spatial distribution of relative trend magnitudes in precipitation, reference evapotranspiration, relative humidity, sunshine dura-

Table 2

Change in climate and vegetation condition in the Yellow River basin

Items	Averaged	Trend	Relative trend (%)	Significance (%)
P (mm/year)	443	-46	-10	6
ET (mm/year)	1040	-6	-1	47
U_m	0.58	0.00	0	18
D_s (hour/day)	7.16	-0.43	-6	1
C_a	0.52	-0.07	-13	0
T_m (℃)	7.00	1.44	-	0
T_{min} (℃)	1.23	1.68	-	0
T_{max} (℃)	14.01	1.25	-	0
DTR	12.78	-0.43	-3	0
LAI	1.50	0.24	16	32
LAI in IDs	1.09	0.53	48	13

tion, and cloud amount over the Yellow River basin with a significant level of 5%. The grid cells where the trend detection cannot pass the Student's t-test display blank in the figure 4. The spatial pattern of precipitation trend shows increase in part region before the Tangnaihai gauge and decrease over the Loess Plateau. It can explain why there is no discharge decreasing trend at Tangnaihai gauge but decreasing trends at the other gauges. Reference evapotranspiration increases in the eastern Tibetan Plateau and Qingtongxia district, suggesting the evaporative demand of the atmosphere becomes larger in these regions. The relative humidity decreasing trend is obvious in the Qingtongxia-Hetao district, showing this region become drier. The drier climate might require more irrigation water for crops and imply more water withdrawals for irrigated area. Reduction in sunshine duration is observed in the lower reaches. There is decreasing cloud amount trend over the basin as mentioned before. The mean LAI value over the entire basin shows non-significant increase. But the LAI values show decreasing trends on the Tibetan Plateau and headwaters of tributaries at middle reaches. Wang et al. (2001) investigated the causes responsible for the environmental changes in the source region of the Yellow River. Human activities, rodent and insect damage are the main factors causing the eco-environmental degradation. They found the annual precipitation in the headwater area showed no noticeable decreasing tendency between the 1950s and the 1990s. But summer precipitation (from June to September) showed a tendency to decline. Such climatic changes might have affected the vegetation in the source region of the river basin. The temperature rise caused the thawed soil area to expand, thickening the seasonal thawing layer or even leading to the entire disappearance of the permafrost. The degradation of the permafrost resulted in soil moisture reduction in root zone, surface soil desiccation, the swamps drying up. Further more, it resulted in the degradation of the high-cold meadow and swamp meadow vegetation. The vegetation degradation in the source region was also reported by Feng et al. (2005). They concluded the degradation was mainly caused by human activities such as overgrazing and over-cultivating.

Figure 4(f) shows relative trend magnitude in LAI value over the basin and the lower reaches IDs, with the marked zone of 20% significant level. The LAI values in Qingtongxia-Hetao and lower reaches IDs show obvious increasing trends, accompanied by the irrigation area increase. This indicates human activities improve vegetation condition in IDs and degrade vegetation condition outside of IDs. The large discharge decreasing trends at the Toudaoguai and Lijin gauges should respond to the vegetation improvement and consequential water consumption in the Qingtongxia-Hetao and lower reaches IDs.

The trend magnitudes of temperatures and DTR are shown in Figure 5 with a significant level of 5%. There are grand increasing trends in temperatures over the whole basin, except for the Sanmenxia-Huayuankou section. The mean temperature increase magnitude is large in the Tibetan Plateau and Qingtongxia-Hetao district. Compared with the same latitudinal zone in the same period, the warming of the Tibetan Plateau is large. This suggests that the Tibetan Plateau is one of the most sensitive areas to respond to global climate change. The larger temperature increase magnitude in the Tibetan Plateau was also reported by Liu and Chen (2000). Minimum temperature shows increasing trends in the Tibetan Plateau and Qingtongxia-Hetao district, where cloud amount shows decreasing trends. Increases in cloud amount have been offered as a possible explanation for increasing minimum temperatures in other parts of the world (Kaiser, 1998). However, it seems other mechanisms should be considered in the Yellow River. Maximum temperature shows increasing trend over most of the basin except for one part of the lower reaches irrigation district. In the Tibetan Plateau and Qingtongxia-Hetao district, the maximum temperature increasing magnitudes are obviously less than that of minimum temperature. A narrowing of the DTR is found in the Tibetan Plateau, Qingtongxia-Hetao district and lower reaches irrigation district. The narrowing DTR in the Tibetan Plateau and Qingtongxia-Hetao district is due to differential changes in daily maximum and minimum temperatures. This is consistent with the global DTR trend (Easterling et al., 1997). The widening DTR is observed in the northern Loess Plateau, where has increasing trend in maximum temperature but no significant trend in minimum temperature.

4 Conclusion Remarks

Four decades data of ground hydro-climate observations and two decades data of remote sensing vegetation condition observations were used to analyze climate and land cover change spatial distributions and speculate the reasons for the drying up of the Yellow River.

There is high spatial variability in climate from the upstream to the downstream. It is found that the precipitation decreased much in the region between the Lanzhou and Huayuankou gauge, which implies that the reductions of discharge are due, at least in part, to less precipitation. The precipitation decreasing region concentrates in the Loess Plateau. It suggests that the Loess Plateau is a precipitation hot spot, where the precipitation has special activity within a larger area of normal activity, of the Yellow River drying up phenomenon.

The mean air temperature shows increasing trend over the whole basin, and the largest increase regions are the Tibetan Plateau and Qingtongxia-Hetao district. The large increase in minimum temperature in the Tibetan Plateau and Qingtongxia-Hetao district contributes to the mean temperature increase and the reduction of DTR in these regions. The evaporative demand of the atmosphere in eastern Tibetan Plateau and Hetao district shows a significant increasing trend. The Tibetan Plateau and Qingtongxia-Hetao district could be temperature hot spots of the basin drying up phenomenon.

The Qingtongxia-Hetao IDs show an obvious increasing trend in LAI values, indicating intensive human activities have changed the vegetation condition in that region. The vegetation improvement and water consumption in the Qingtongxia-Hetao IDs might affect the regional hydro-climatic regimen and contribute to the discharge reduction at downstream gauges. The vegetation improvement is also observed in the lower reaches IDs. The Qingtongxia-Hetao and the lower reaches IDs would be human activities hot spots of the Yellow River drying up phenomenon.

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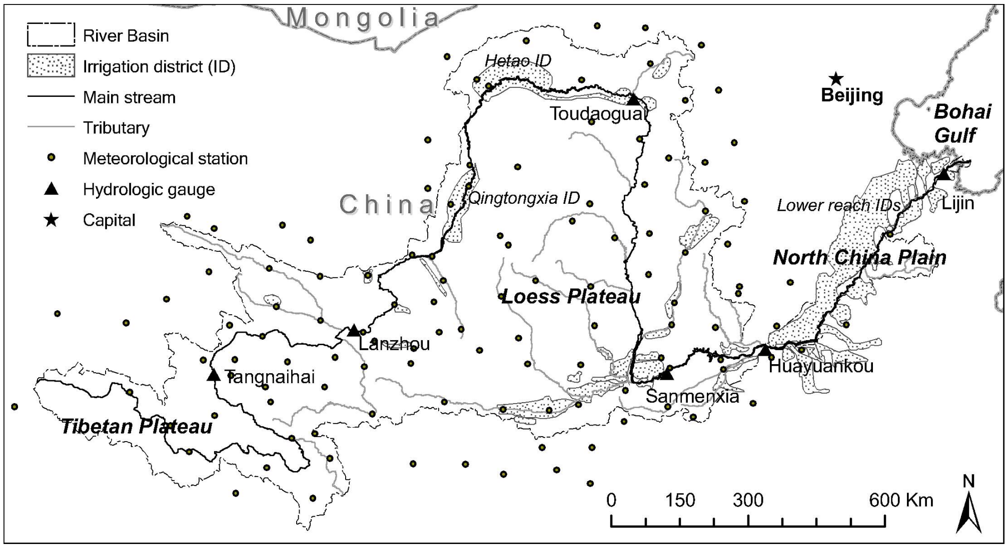
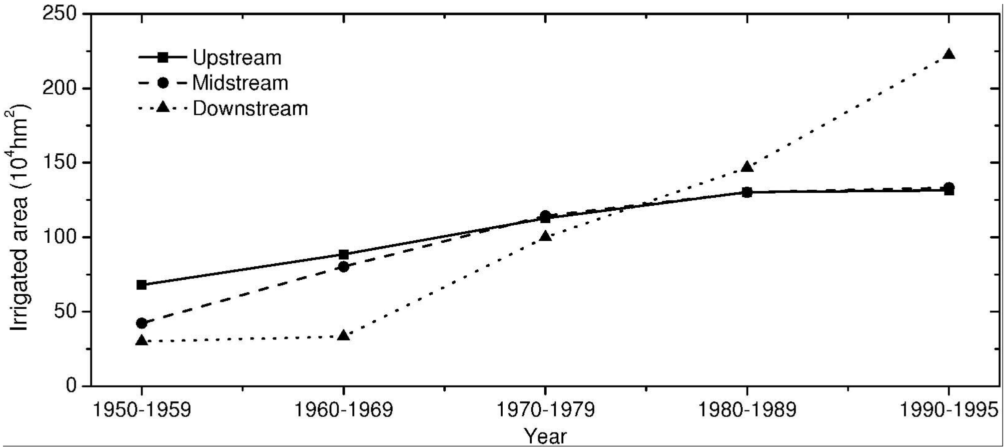
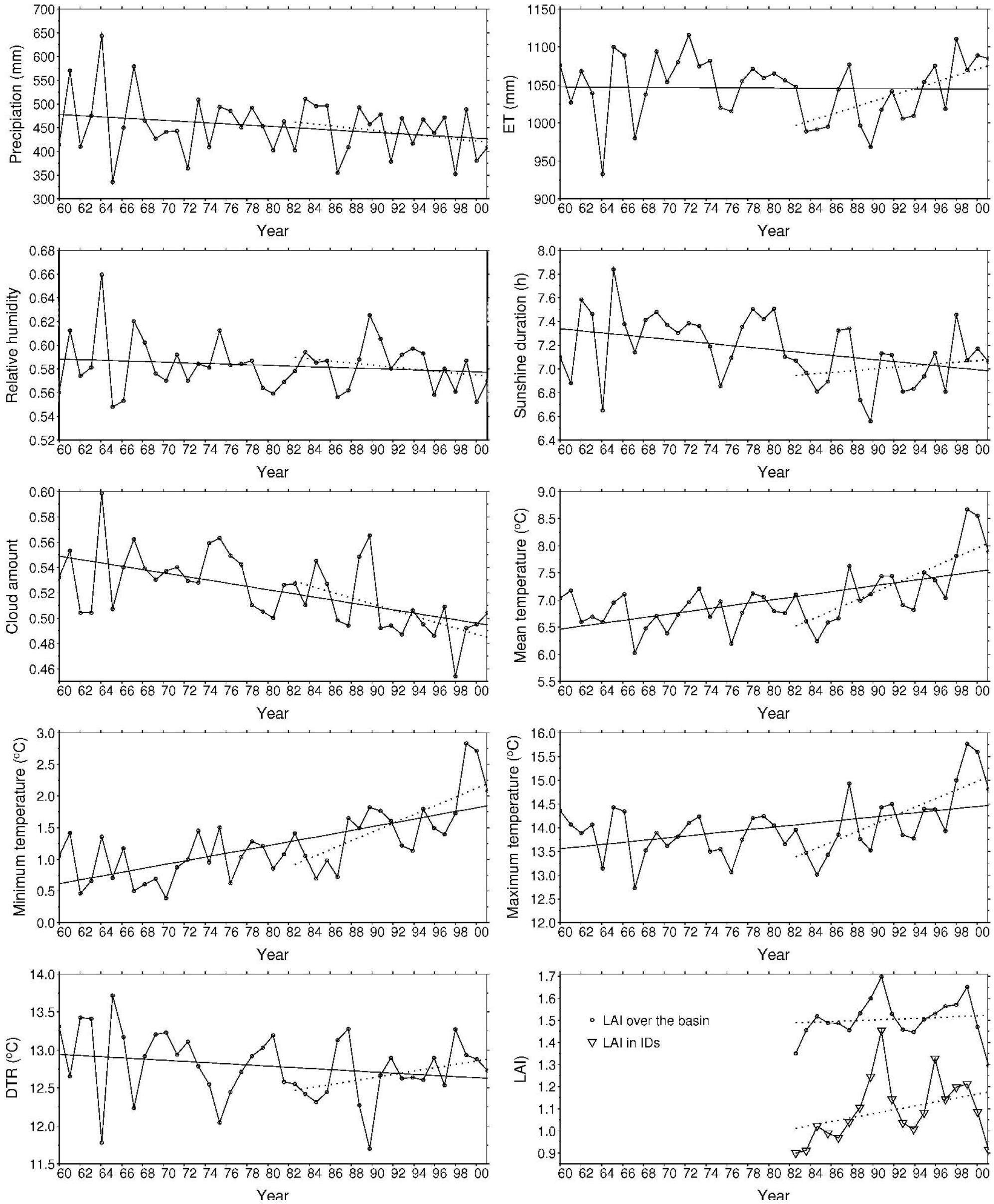


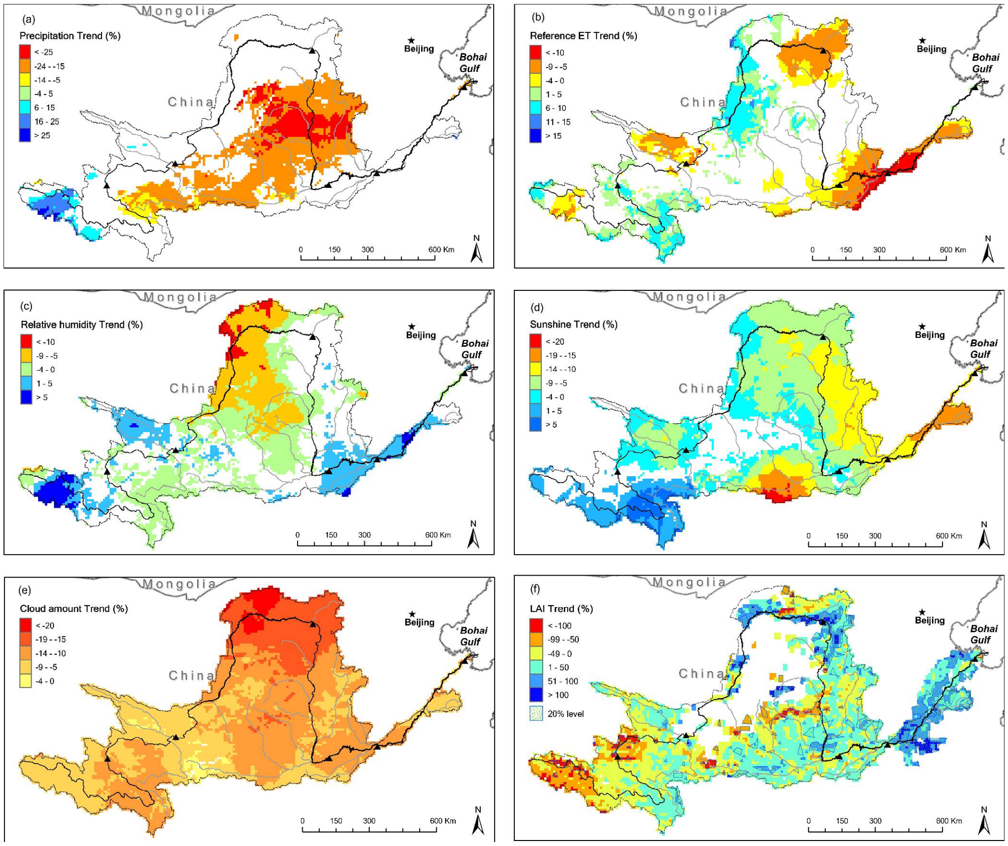
The Yellow River basin



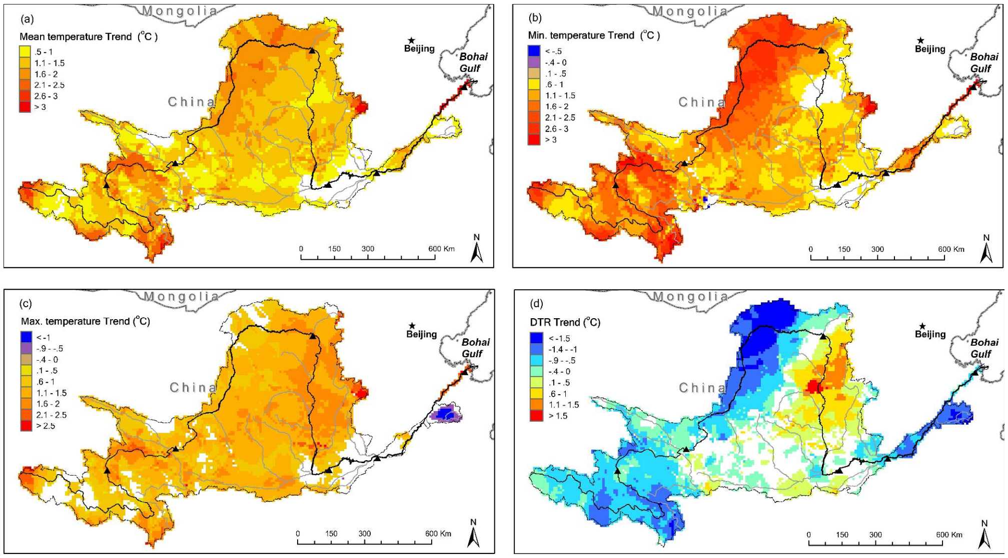
Irrigated area in the Yellow River basin.



Hydro-climatic variations over the Yellow River Basin from 1960 to 2000 and LAI value change from 1982 to 2000



Relative trend magnitude of precipitation (a), reference evapotranspiration (b), relative humidity (c), sunshine duration (d), cloud amount (e) from 1960 to 2000 and LAI value (f) from 1982 to 2000



Trend magnitude of mean temperature (a), minimum temperature (b), maximum temperature (c) and diurnal temperature range (d) from 1960 to 2000.