Spatiotemporal Variation Characteristics of Precipitation in the Yellow River Basin over the Past Nearly 60 Years and Change Trend in the Next 30 Years: Postprint

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Abstract

Over the past 60 years, the climate of the Yellow River Basin has undergone significant changes, exerting notable impacts on surface hydrological, ecological, and other processes within the basin. Using precipitation data observed at meteorological stations in the Yellow River Basin from 1961 to 2018, this study analyzes the spatiotemporal variation characteristics of precipitation in the Yellow River Basin over the past 60 years. On this basis, utilizing projected results for the next 30 years (2018-2047) under the SSP245 scenario from CMIP6 models, combined with a statistical projection method based on periodic superposition, the possible change trends of precipitation in the Yellow River Basin for the next 30 years are projected. The results indicate that precipitation in the Yellow River Basin exhibits pronounced intra-annual, interannual, and interdecadal variation characteristics, with a significant oscillation period of 2-4 years. Across the entire basin, annual and seasonal precipitation demonstrate in-phase variation characteristics at the interannual scale, whereas the regions with significant interannual variation anomalies differ. The variability of annual precipitation in the Yellow River Basin is modulated by seasonal precipitation: summer precipitation is abundant and exhibits strong regional characteristics, while winter precipitation is scarce with relatively small variation differences across the basin. Precipitation in the source region of the Yellow River demonstrates good stability at both intra-annual and interannual scales. Precipitation in areas affected by summer monsoon activity within the basin decreases, while precipitation in areas influenced by winter monsoon increases. Annual precipitation in the source region of the Yellow River over the past 60 years has shown an increasing trend of 20.96 mm·(10a)-1; it is projected that over the next 30 years, annual precipitation will continue to increase at a rate of 11.53-17.62 mm·(10a)-1; annual precipitation in the Hetao region has continuously increased over the past 60 years at a rate of 2.71 mm · (10a)-1, and future annual precipitation will also increase, but the growth rate will become more gradual at approximately 0.52 mm · (10a)-1; precipitation in the lower reaches of the Yellow River has shown a decreasing trend over the past 60 years, and will continue to decrease at a rate of 5.46 mm · (10a)-1 in the future.

Full Text

Changing precipitation characteristics in the Yellow River Basin in the last 60 years and tendency prediction for next 30 years

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Abstract

The climate of the Yellow River Basin has distinctly changed in the past 60 years, significantly impacting its surface hydrological and ecological processes. Using precipitation observations from meteorological stations in the Yellow River Basin from 1961 to 2018, this study analyzes the spatiotemporal variation characteristics of precipitation in the basin over the past six decades. Building upon this analysis, future precipitation trends for the next 30 years (2018–2047) are projected using CMIP6 model outputs under the SSP245 scenario combined with a statistical extrapolation method based on periodic superposition. The results show that precipitation in the Yellow River Basin exhibits significant intra-annual, inter-annual, and inter-decadal variations, with a prominent oscillation period of 2–4 years. Across the entire basin, annual and seasonal precipitation demonstrates in-phase variation at the inter-annual scale, though the regions with significant inter-annual anomalies differ. The variability of annual precipitation in the Yellow River Basin is modulated by seasonal precipitation, with summer rainfall showing strong regional patterns due to high precipitation amounts, while winter precipitation is low and shows small differences across the basin. Precipitation in the Yellow River source area demonstrates good stability at both intra-annual and inter-annual scales. Precipitation has decreased in regions influenced by summer monsoon activity and increased in regions influenced by winter monsoon activity. Over the past 60 years, annual precipitation in the Yellow River source area has shown an increasing trend of 20.96 mm · $(10a)^{-1}$, with future annual precipitation also expected to increase, though at a slower rate of approximately 11.53–17.62 mm · $(10a)^{-1}$. Annual precipitation in the Hetao area has continued to increase over the past 60 years at a rate

of 2.71 mm · $(10a)^{-1}$, and this increasing trend is expected to continue at 0.52 mm · $(10a)^{-1}$. In the lower reaches of the Yellow River, annual precipitation has shown a decreasing trend over the past 60 years, and this decreasing trend is projected to continue at a rate of 5.46 mm · $(10a)^{-1}$.

Keywords: Yellow River Basin; precipitation variability characteristics; periodic overlay extrapolation; CMIP6

1. Study Area, Data, and Methods

1.1 Study Area Overview

The Yellow River Basin is located between 95°-120°E and 32°-42°N, with a north-south width of approximately 1100 km, an east-west length of about 1900 km, and a drainage area of 7.95$×10^{5}$ km^2 (Yellow River Network, http://www.yrcc.gov.cn/hhyl/hhgk/hd/). The basin contains numerous mountain ranges with significant elevation differences and substantial variations in topography and landforms. The Yellow River source area lies in the semi-arid, alpine region of the northeastern Tibetan Plateau with minimal monsoon influence. The middle Hetao region belongs to arid and semi-arid zones, while the lower reaches are in a semi-humid zone significantly influenced by the summer monsoon. Consequently, climate varies across the basin, with precipitation showing marked spatial differences and decreasing from southeast to northwest (Fig. 1).

To analyze climate change characteristics in different regions of the Yellow River Basin, this study divides the basin into three sub-regions: the Yellow River source area (95°-104°E, 33°-37°N), the Hetao area (104°-112°E, 34.5°-41°N), and the lower Yellow River area (112°-119°E, 34°-38°N) for separate analysis (Fig. 1). Previous studies have mostly adopted the regional division scheme of the Yellow River Water Resources Commission, which considers geological environment, valley landform characteristics, water resources conditions, basin social conditions, and development requirements. Based on this scheme and primarily according to precipitation distribution patterns in the Yellow River Basin, this study narrows the upper region to include only the plateau area (the Yellow River source area), while the middle region includes most of the “几” -shaped bend area, and the lower region includes areas surrounding the Shanxi, Henan, and Shandong sections of the Yellow River.

Annual precipitation shows obvious spatial differences across the Yellow River Basin. The Yellow River source area, located on the eastern Tibetan Plateau with numerous tributaries, has an average annual precipitation of 400-800 mm and is the main water supply area for Yellow River runoff. The Hetao region spans the Hetao Plain, Ordos Plateau, Mu Us Sandy Land, and Loess Plateau, is located in northwestern China with an arid/semi-arid climate, has low annual precipitation with large spatial variability (100-500 mm), and is the region with the least water supply to the basin. The lower reaches belong to a semi-humid climate, with the Shanxi, Henan, and Shandong sections receiving relatively abundant precipitation of 600–1000 mm.

1.2 Station Observations

This study uses daily precipitation data from 1961 to 2017 for 823 meteorological stations in and around the Yellow River Basin (32°–45°N, 95°–120°E). The data were obtained from the China Meteorological Data Network (http://data.cma.cn/) and have undergone quality control and homogeneity testing. For convenience of calculation, the observational data were interpolated onto a 0.25°$×$0.25° grid using radial basis function linear interpolation, which effectively represents the spatial distribution of precipitation in the Yellow River Basin.

1.3 Climate Models

This study employs outputs from the Coupled Model Intercomparison Project Phase 6 (CMIP6) global climate models. Considering actual near-future development conditions, the SSP245 scenario was selected for future climate change projections. Based on previous multi-model evaluation results, this study selected 12 CMIP6 global climate models for analysis of future monthly precipitation projections (https://esgf-node.llnl.gov/projects/cmip6/). Specific model information is provided in Table 1.

1.4 Research Methods

Due to systematic errors in climate model precipitation simulations, this study adopts the correction method proposed by Murphy et al. to bias-correct future precipitation simulated by CMIP6 models. This method uses anomalies and standard deviations of observed and simulated values to correct simulations, effectively reducing systematic biases and providing good correction for climate drift. For precipitation in any given year, the correction is applied using the following formula:

$$P_R = \frac{\sigma(P_{obs})}{\sigma(P_{sim})} \times (P_{sim} - \overline{P_{sim}}) + \overline{P_{obs}}$$

where P is the analysis variable (precipitation in this study), P_{sim} is the simulated precipitation value, P_R is the bias-corrected precipitation, $\overline{P_{obs}}$ is the observed mean, $\overline{P_{sim}}$ is the simulated mean, $\sigma(P_{obs})$ is the observed standard deviation, and $\sigma(P_{sim})$ is the simulated standard deviation.

To facilitate comparison between projections and observations, model data at different resolutions were interpolated onto a 0.25°$×$0.25° horizontal grid using bilinear interpolation. Multi-model ensemble averaging can effectively reduce uncertainty from individual models; therefore, this study uses equal-weight arithmetic averaging for different model simulations. Before ensemble averaging, each model' s projection results were bias-corrected.

To analyze periodic characteristics of precipitation in the Yellow River Basin, wavelet analysis was applied to decompose precipitation series and obtain major oscillation periods, with significance testing performed on the results.

To analyze spatiotemporal variation characteristics of precipitation, Empirical Orthogonal Function (EOF) analysis was conducted on annual and seasonal precipitation in the Yellow River Basin from 1961 to 2017.

The climate system is subject to external periodic or non-periodic forcing at different time scales, making precipitation variation a superposition of processes at various time scales. The basic idea of precipitation projection is to distinguish between external forcing and internal variability components. Precipitation P is approximated as consisting of an external forcing term P_{ext} and an internal variability term P'. The external forcing term is represented by a linear trend, obtained through unary linear regression using precipitation sequence data from 1961 to 2017. Subtracting the linear trend from the original sequence yields the internal variability term P'. The specific approach involves: (1) calculating the external forcing trend and separating the internal variability term P', (2) performing periodic analysis on P' to extract T major periods passing significance tests, (3) superimposing P' according to the first identified period to obtain sequence P_1, fitting and extrapolating it to future period M (where $M = N + 30$) to obtain the first forecast sequence P_{T1}, (4) subtracting P_{T1} from P' and repeating the process with the second period to obtain P_{T2}, and so on until the T-th forecast sequence P_{TT} is obtained, and (5) adding the external forcing forecast P_{ext} and internal variability forecasts P_{T1} to P_{TT} to obtain the final precipitation forecast.

2. Spatiotemporal Variation Characteristics of Precipitation in the Yellow River Basin

2.1 Annual Variation Characteristics of Precipitation

To analyze intra-annual variation of precipitation in different regions of the Yellow River Basin, Fig. 2 shows monthly precipitation variation. Monthly precipitation in the Yellow River source area, Hetao area, and lower Yellow River area shows clear intra-annual variation, with summer (June–August) being the main contribution period to annual precipitation. The maximum precipitation month is July in both the Yellow River source area and lower reaches, while the Hetao area peaks in August. Monthly precipitation in the source and Hetao areas is relatively low, with maximum values below 80 mm (accounting for 22–23% of annual total), while the lower reaches can exceed 175 mm (accounting for 27.6% of annual total). Winter (December–February) is the period with the least precipitation, with monthly precipitation below 10 mm. Comparing inter-annual variation of monthly precipitation across different regions, the standard deviation is largest in July for all regions, indicating that the month with the highest precipitation also has the greatest inter-annual variability. The inter-annual variability of monthly precipitation is smallest in the Yellow River source area (2–21 $\mathrm{mm \cdot a^{-1}}$), moderate in the Hetao area (7–55 $\mathrm{mm \cdot a^{-1}}$), and largest in the lower reaches (2–30 $\mathrm{mm \cdot a^{-1}}$), indicating that precipitation in the source area is relatively stable while precipitation in the lower reaches is more variable.

2.2 Spatiotemporal Variation Characteristics of Precipitation in the Past 60 Years

To analyze spatiotemporal variation characteristics of precipitation in the Yellow River Basin, EOF decomposition was performed on annual and seasonal precipitation from 1961 to 2017. The variance contribution rates of the first EOF mode show that the first mode of annual and seasonal precipitation accounts for more than 24.96% of the total variance. Winter half-year (spring and winter) precipitation shows the best convergence, with winter reaching 69.13%, reflecting that the entire basin is under winter monsoon control with similar precipitation variation patterns. Summer shows the poorest convergence, indicating that although precipitation mainly occurs in summer, spatial differences are large and weather systems affecting precipitation differ across the basin.

To clarify precipitation variation characteristics in the past 60 years, Fig. 4 shows inter-annual variation of precipitation (anomalies) in regions with large absolute load vector values ($|\mathrm{LV}|>0.4$). Annual precipitation across the Yellow River Basin shows an increasing trend in regions with high precipitation variability, with significant increases in winter and decreases in summer and autumn at rates of 1.92–2.51 $\mathrm{mm \cdot (10a)^{-1}}$. In summary, winter half-year precipitation in the Yellow River Basin shows an increasing trend in regions with large inter-annual variability, while summer half-year precipitation shows a decreasing trend. This indicates that precipitation is decreasing in regions influenced by the summer monsoon and increasing in regions influenced by the winter monsoon.

The variability of annual precipitation in the Yellow River Basin is modulated by seasonal precipitation, with summer precipitation showing strong regional patterns due to high amounts, while winter precipitation is low with small differences across the basin. The Yellow River source area shows good stability in precipitation at both intra-annual and inter-annual scales.

2.3 Periodicity of Precipitation in the Yellow River Basin

To analyze periodic characteristics of precipitation variation in the Yellow River source area, Fig. 5 shows wavelet analysis results for precipitation from 1961 to 2016. Annual precipitation in the Yellow River source area shows significant 2–4 year oscillation periods during 1961–1990 and 12–14 year oscillation periods during 1990–2010. Spring precipitation shows significant 3–6 year oscillation periods during 1970–1990. Summer precipitation, the main contributor to annual precipitation, has consistently shown significant 2-5 year oscillation periods since 1961. Autumn precipitation, second only to summer, shows significant 2-5 year oscillation periods over the past 60 years, with particularly significant 4-6 year periods after 2000. Winter precipitation shows 2-5 year oscillation periods during the 1970s and quasi 14-15 year oscillation periods during 1961-1975.

Comparing oscillation periods across different regions of the Yellow River Basin (Table 3), both the Hetao and lower reaches areas show that annual precipitation and summer/autumn precipitation have 2-4 year significant oscillation periods, while winter and spring precipitation oscillation periods, though not significant, persist stably. This indicates that annual precipitation periodicity in the Yellow River Basin is mainly determined by summer and autumn precipitation. The results are generally consistent with previous studies showing that the Yellow River Basin commonly has 2-4 year short periods and relatively stable 14-15 year medium-long periods, which can be used for extrapolation forecasting.

3. Projection of Spatiotemporal Variation Characteristics of Precipitation in the Yellow River Basin for the Next 30 Years

Based on the analysis of basic characteristics and periodicity of precipitation in the Yellow River Basin, which revealed significant short periods and relatively stable medium-long periods in annual and seasonal precipitation, the main periods identified through periodic analysis were used in formula (2) to project future precipitation changes in the Yellow River Basin.

Fig. 6 shows precipitation evolution in the Yellow River source area from 1961 to 2047. Over the past 60 years, annual precipitation in the source area shows a significant increasing trend of 20.96 mm · $(10a)^{-1}$, with all seasons showing increasing trends, particularly spring at 10.16 mm · $(10a)^{-1}$. Based on the periodic superposition extrapolation method, annual precipitation in the Yellow River source area is projected to continue increasing over the next 30 years, but at a slower rate of 11.53-17.62 mm · $(10a)^{-1}$. Seasonal precipitation trends are all positive, but the rates are significantly reduced compared to the past 60 years, with spring showing the largest reduction from 10.16 to 5.94 mm · $(10a)^{-1}$. CMIP6 model projections also indicate increasing trends in annual and seasonal precipitation in the Yellow River source area, with summer precipitation increasing at 4.14 mm · $(10a)^{-1}$—different from statistical method results. Therefore, future annual precipitation change in the source area is dominated by spring precipitation.

Fig. 7 shows precipitation evolution in the middle and lower reaches of the Yellow River Basin from 1961 to 2047. Over the past 60 years, annual precipitation in the Hetao area shows an increasing trend of 2.71 mm · $(10a)^{-1}$, with all seasons except summer showing increasing trends, particularly winter at 2.16 mm · $(10a)^{-1}$. Periodic superposition extrapolation results show that future annual precipitation in the Hetao area will also increase, but at a slower rate of 0.52

mm $\cdot$ (10a)$^{-1}$, mainly due to reduced increasing rates in spring and summer. In contrast, CMIP6 model projections show future annual precipitation in the Hetao area continuing to increase at a much faster rate of 14.44 mm $\cdot$ (10a)$^{-1}$, differing significantly from statistical results by 13.92 mm $\cdot$ (10a)$^{-1}$.

In the lower Yellow River area, annual precipitation has shown a decreasing trend over the past 60 years, with summer and autumn precipitation decreasing while spring and winter precipitation increased. CMIP6 model projections indicate future annual precipitation in the lower reaches will increase at 21.28 mm $\cdot$ (10a)$^{-1}$, while statistical projections show a decreasing trend of 5.46 mm $\cdot$ (10a)$^{-1}$—opposite results. The two methods also show large differences in summer precipitation projections, with statistical results showing a decrease of 7.01 mm $\cdot$ (10a)$^{-1}$ while model results show an increase of 4.14 mm $\cdot$ (10a)$^{-1}$. This indicates large uncertainty in summer precipitation projections for the middle and lower reaches of the Yellow River Basin.

Fig. 8 shows the spatial distribution of projected precipitation changes for the next 30 years (2018-2047) relative to the 1981-2010 climatology. In the Yellow River source area, annual and seasonal precipitation are projected to increase, with main changes in eastern Qinghai. Spring precipitation shows similar spatial distribution to annual precipitation with the most significant increases. In the Hetao area, future annual precipitation will mainly increase, with the largest increases in northern Shaanxi. In the lower Yellow River area, future annual precipitation changes show large spatial differences, with significant increases around Shangqiu and Jinan, while most other areas show decreases. Summer spatial distribution patterns are similar to annual distribution.

Integrated model projections and statistical predictions both indicate that future annual precipitation will increase in the Yellow River source area, but statistical predictions show significantly larger increases than CMIP6 SSP245 scenario projections. Both methods show future annual precipitation increases in the Hetao area, but with large rate differences. For the lower Yellow River area, the two methods show opposite projections, with statistical predictions showing decreases in most areas while model projections show increases, particularly in summer. In summary, future annual precipitation changes in the Yellow River Basin show spatial differences: increases are projected for the Yellow River source area and Hetao area, while changes in the lower reaches show large uncertainty, requiring further investigation.

4. Conclusions

Based on observational data from the past 60 years and CMIP6 model projection results, this study analyzed spatiotemporal variation characteristics of precipitation in the Yellow River Basin and reached the following conclusions:

1) Precipitation in China’ s Yellow River Basin shows multi-timescale variation with significant intra-annual, inter-annual, and inter-decadal changes and significant periods in annual and seasonal precipitation. Precipitation

variation is relatively stable in the Yellow River source area but more variable in the lower reaches. Spatially, annual and seasonal precipitation in the past 60 years shows basically isotropic inter-annual variation across the basin, but with different centers of large inter-annual variability. The variability of annual precipitation is modulated by seasonal precipitation, with summer precipitation showing strong regional patterns while winter precipitation is low with small differences across the basin. Precipitation has decreased in regions influenced by the summer monsoon and increased in regions influenced by the winter monsoon.

2) Over the past 60 years, annual precipitation in the Yellow River source area increased at a rate of 20.96 mm$\cdot$(10a)$^{-1}$, while the Hetao area showed a continuous increase at 2.71 mm$\cdot$(10a)$^{-1}$. The lower reaches showed a decreasing trend at 1.53 mm$\cdot$(10a)$^{-1}$. Integrated dynamic and statistical projections indicate that over the next 30 years, annual precipitation in the Yellow River source area will continue to increase at 11.53–17.62 mm$\cdot$(10a)$^{-1}$, the Hetao area will increase at a slower rate of about 0.52 mm$\cdot$(10a)$^{-1}$, and the lower reaches will continue to decrease at about 5.46 mm$\cdot$(10a)$^{-1}$.

Previous studies have shown that CMIP6 models have relatively large biases in simulating precipitation in the Yellow River Basin. Therefore, combining dynamic and statistical projections can significantly reduce uncertainty. This study reveals precipitation characteristics in the Yellow River Basin over the past 60 years and proposes a combined dynamic-statistical projection method that effectively reduces uncertainty. Although the regional division in this study differs somewhat from previous research, the conclusions are generally consistent. Future projections differ from some existing CMIP5-based studies due to the use of improved CMIP6 models with better parameterization schemes and resolution, combined with statistical methods, making the projections presented here more reasonable for future precipitation changes in the Yellow River Basin.

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Note: Figure translations are in progress. See original paper for figures.