Spatio-temporal evolutions of precipitation in the Yellow River basin of China from 1981 to 2013
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ABSTRACT
The partial thin plate smoothing splines method was applied to evaluate spatiotemporal trends of precipitation in the Yellow River basin from 1981 to 2013 by considering the basin’s digital elevation model. Results indicate the following. (1) The spline method can greatly improve the spatial interpolation accuracy of meteorological data and can be applied to spatial modeling of meteorological elements for large regions with complex terrain. (2) Overall, annual precipitation in the Yellow River basin shows a decreasing trend from east to west, with the isohyet equipluvi distribution of 400 mm being basically consistent with the dividing line between semi-humid and semi-arid regions in China. Sichuan has the highest annual average precipitation while Neimeng has the lowest; Shandong and Henan both have relatively significant changes of annual precipitation while Gansu and Qinghai have small changes. (3) The average monthly precipitation of the basin from 1981 to 2013 presents an overall increasing trend from north to south; the annual precipitation in each province was mainly concentrated in 7–9 months of the whole year. The highest monthly average precipitation in most provinces occurred in July, while the highest at Ningxia occurred in August. Results may provide a scientific basis for understanding future precipitation changes and improving our ability to cope with climate change.

Key words | partial thin plate smoothing splines, precipitation, spatial interpolation, spatio-temporal trend, Yellow River basin

INTRODUCTION
Global climate change leads to changes of precipitation patterns, and precipitation is an important aspect of the study of climate change (Chen et al. 2011). The change of precipitation is closely related to ecological environment security (Ding et al. 2006), and it has a profound impact on water resources, agriculture and ecological systems (Ju et al. 2015; Yao et al. 2013). The Yellow River, located in the northern part of China, is an important source of water in North and Northwest China (Zhao et al. 2011). The Yellow River basin is an important grain production area, but water is scarce in this region. It contains 15% of China’s cultivated land and 12% of China’s population, reliant on 2% of runoff in China (Wang et al. 2013; Yan et al. 2015). So the basin’s serious water shortage affects the development of industrial and agricultural production and urbanization.

Precipitation in the Yellow River basin is the fundamental source of water resources. Due to effects of atmospheric and monsoon circulations, precipitation varies significantly between various regions of the basin (Li et al. 2013). The seasonal distribution of precipitation is extremely uneven in the Yellow River basin due to changes of monsoon circulation intensity. The specific pattern of dry winter, drought-affected spring, rainy summer and rainy autumn has important effects on the agricultural production of the basin (Xu & Zhang 2006; Zhao et al. 2015). Based on observations of rainfalls over the last 50 years, the annual precipitation in the
Yellow River basin shows a downward trend (Xu & Zhang 2006). The change of the extreme precipitation index is not obvious, but there are temporal and spatial differences (Zhao et al. 2015). Li et al. (2002) investigated spatiotemporal variations of summer precipitation over eastern China during 1880–1999. Zhang et al. (2015) evaluated temporal and spatial distributions of precipitation and air temperature in Shaanxi using average monthly climate data released by CRU (Climate Research Unit of the University of East Anglia). Cui et al. (2015) analyzed the distribution characteristics of temperature and precipitation in different seasons of China using the SVD (Singular Value Decomposition) method. Based on the summer monthly precipitation data of 310 stations from 1960 to 2012 in eight regions of China, Yin & Yin (2015) analyzed spatial and temporal distribution characteristics of summer precipitation by trend features index, Mann-Kendall mutation testing and spatial interpolation. In general, the spatial interpolation of meteorological information is an effective method to allow for the uneven distribution of the meteorological stations (Hutchinson 1998; Peng 2010; Bai et al. 2011; Wang 2014). Local fitting methods are commonly used in spatial data interpolation, such as the Thiessen polygon method, the polynomial interpolation method, the inverse distance weighted method, the spline function method, the Kriging method and so on (Hutchinson & Gessler 1994; Peter & Chris 1998; Lin et al. 2002; Liu et al. 2008; Cai et al. 2009; Kong & Xiang 2012; Hu & Shu 2014). Of all these methods, the Thiessen polygon method is suitable for intensive site areas; it demands basically identical terrain, and does not account for impacts of elevation (Wang & Chen 2005). The inverse distance weighted method adjusts spatial interpolation contour structure by changing weights, but this method does not consider the influence of topographical factors on rainfall (He et al. 2005). The spline function method, the global polynomial interpolation method and the local polynomial interpolation method all overcome shortcomings of the previous statistical models, which can improve the accuracy of spatial simulation (Zhao & Yang 2012). The Kriging method, based on statistical interpolation techniques using the semi variance function to reflect spatial correlation of interpolation objects, is considered to be the best spatial data interpolation method (Li et al. 2006). The thin plate smoothing spine method is a kind of spline function method (Wan et al. 2011), which gives attention to both the smoothness and precision of the interpolation surface (Liu et al. 2006). Hijmans et al. (2005) consider it to be the most suitable interpolation method for climate data.

Therefore, the partial thin plate smoothing splines method was applied to study spatial and temporal distribution characteristics of precipitation in the Yellow River basin from 1981 to 2013. By considering the digital elevation model, the results may help us to better understand the evolution of water resources, and assist in the scientific management of water resources, and the early warning of flood disasters.

MATERIAL AND METHODS

Study area

The Yellow River is the second longest river in China, and is also one of the great rivers of the world. The source of the Yellow River is Bayankala mountain in Qinghai Province; it flows through nine provinces, including Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan and Shandong, and finally flows into the Bohai Sea in Kenli County of Shandong province. It has a total length of 5,464 kilometers (Figure 1(a)).

The Yellow River basin is located between 96°–119° E and 32°–42° N. Its length from east to west is 1,900 km, the width from north to south is 1,100 km, and the basin area is 7,52,443 km² (Figure 1(b)). The multi-year average runoff is 58 billion m³, and the average annual runoff depth is 77 mm. The underlying surface types of the basin are complex, and the differences of the terrain and landforms are relatively large. The climate of the basin is broadly divided into three climate zones: arid, semi-arid and semi humid; on the whole, the west is arid and the east is humid. In this study, the precipitation data of 121 meteorological stations were used to study the spatiotemporal evolution of precipitation in the Yellow River basin (Figure 2(a)). The annual mean temperature in the basin is about –4–14 °C, and the mean annual precipitation is about 466 mm (Figure 2(b)). The precipitation over 6–10 months accounts for 65–85%
of the annual precipitation, and the maximum rainstorm mainly occurs in 7–8 months.

**Methodology**

The partial thin plate smoothing splines method is an extension of thin plate smoothing splines; it introduces a linear covariant model in addition to ordinary spline independent variables, such as the correlation between precipitation and elevation (Liu et al. 2006, 2008). In this study, the ANUSPLIN meteorological interpolation model based on the partial thin plate smoothing splines method (Hutchinson 2006) was used to spatially interpolate long time series of precipitation in the Yellow River basin with complex terrain. In this application, latitude and longitude were used as the independent variables, and elevation was taken as the covariate. The optimal solution of the spline number was determined as three. The theoretical statistical model of partial thin plate smoothing splines (Liu et al. 2012) is expressed as

\[ z_i = f(x_i) + b^T y_i + e_i \quad (i = 1, \ldots, n) \]  

where each \( x_i \) is a \( d \)-dimensional vector of spline independent variables, \( f \) is an unknown smooth function of \( x_i \), each \( y_i \) is a \( p \)-dimensional vector of independent covariates, \( b \) is an unknown \( p \)-dimensional vector of coefficients of the \( y_i \), and each \( e_i \) is an independent, zero mean error term with variance \( \omega_i \sigma^2 \), where \( \omega_i \) is termed the relative error variance (known), \( \sigma^2 \) is the error variance. The model reduces, on the one hand, to an ordinary thin plate spline model when there are no covariates (\( p = 0 \)) and to a simple multivariate linear regression model when \( f(x_i) \) is absent.
The function $f$ and the coefficient vector $b$ are determined by minimizing

$$
\sum_{i=1}^{n} \left( \frac{y_i - f(x_i)}{\alpha_i} \right)^2 + \rho J_m(f)
$$

where $J_m(f)$ is a measure of the complexity of $f$, the ‘roughness penalty’ defined in terms of an integral of $m$th order partial derivatives of $f$, and $\rho$ is a positive number called the smoothing parameter. As $\rho$ approaches zero, the fitted function approaches an exact interpolant. As $\rho$ approaches infinity, the function $f$ approaches a least squares polynomial, with order depending on the order $m$ of the roughness penalty. The value of the smoothing parameter is normally determined by minimizing a measure of predictive error of the fitted surface given by generalized cross validation.

**RESULTS AND DISCUSSION**

Spatiotemporal characteristics and statistical analysis of annual precipitation

Figure 3 shows the spatial distribution of annual precipitation in the Yellow River basin from 1981 to 2013. It can be seen that the annual precipitation in the Yellow River basin has obvious regional differences. The distribution overall shows a significant decreasing trend from the southeast to the northwest. The climate also changes from the semi-humid climate in the southeast to the semi-arid and arid climate of the northwest. The precipitation in the northwest of the basin (in Inner Mongolia and Ningxia) is less than that of the other regions, and the precipitation in the southern regions of Shaanxi, Sichuan, Henan, and Shandong is more than that of the remaining two provinces. The isohyet equipluwe distribution of 400 mm is basically consistent with the dividing line between semi-humid and semi-arid regions in China. Annual precipitation changes from 1981 to 2013 show that the annual precipitation in the northern part of Gansu province is decreasing. The annual variations of precipitation in local areas within the basin are obvious, where most areas of Shanxi province and the middle area of Shaanxi province showed the most significant variations.

Figure 4 displays changing trends of annual precipitation and multi-year average precipitation in each province of the Yellow River basin. Figure 4(a) shows annual precipitation and multi-year average precipitation in each province. It can be seen that the difference of precipitation in each province is obvious. The average annual precipitation in Sichuan province is the highest, with an average annual precipitation of 696 mm, and then Shandong province, with a precipitation amount of 661 mm. This is followed by Henan, Shaanxi, Shandong, Shaanxi, and Qinghai. The precipitation in Ningxia is 300 mm, and Inner Mongolia has the lowest precipitation of 271 mm. Figure 4(b) shows annual minimum precipitation and multi-year average minimum precipitation in each province. The multi-year average minimum precipitation over 500 mm occurs in Sichuan, Shandong and Henan. The multi-year average precipitation and the multi-year average minimum precipitation in Gansu have the biggest difference, between 457 mm and 220 mm. Figure 4(c) shows annual maximum precipitation and multi-year average maximum precipitation in each province. Eight provinces have annual average maximum precipitation over 500 mm, with Shaanxi having the highest precipitation amount of 848 mm, followed by Sichuan, Henan and Shandong. Inner Mongolia has the lowest precipitation amount of 431 mm. As far as each province is concerned, there is a significant change in annual precipitation, particularly in Shandong and Henan provinces. The annual precipitation amounts of Shandong province in 1990 and 2005 were 797 mm and 485 mm, respectively, decreasing by 39.2%. The annual precipitation amounts of Henan province in 1981 and 2005 were 797 mm and 485 mm, respectively, decreasing by 39.2%. The annual precipitation changes of Gansu province and Qinghai province are relatively small.

In summary, the water resources system is very sensitive to climate change in the arid and semi-arid area of the Yellow River basin, and the precipitation in the Yellow River basin has changed significantly in recent decades. In the 1990s, the precipitation in the Yellow River basin decreased significantly, and then increased slightly in the 21st century.

Spatiotemporal characteristics and statistical analysis of monthly precipitation

Figure 5 shows spatial distributions of multi-year average monthly precipitation from 1981 to 2013. It can be
seen that precipitation values from January to December have large spatial variations. Most of the remaining regions have less rainfall, and some local areas have precious little precipitation. The specific distribution area of precipitation concentration is shown in Table 1.

Figure 6 displays changing trends of multi-year average monthly precipitation, multi-year average monthly minimum precipitation, and multi-year average monthly maximum precipitation in each province of the Yellow River basin. As far as each province is concerned, the multi-year average monthly precipitations in each province
are mainly distributed over 7–9 months, which most obviously occurred in Shanxi, Inner Mongolia, Shandong, Henan, Shaanxi, Gansu and Ningxia. The precipitation values in Qinghai and Sichuan are more concentrated over 5–10 months. As far as the monthly precipitation is concerned, the precipitation from July to September in Shandong province accounted for 65.8% of the annual precipitation, the precipitation from July to September in Henan province accounted for 62.2% of the annual precipitation, while the highest monthly average precipitation of all occurred in July, and the highest in Ningxia occurred in August. The changing trends of multi-year average monthly precipitation in each province are basically the same as for the multi-year average monthly minimum or maximum precipitation. Inner Mongolia has the lowest multi-year average monthly precipitation. The precipitation distribution of Sichuan province is relatively uniform; the difference of precipitation distribution in Shandong province is the most significant from January and December.

CONCLUSIONS

1. Based on the thin plate smoothing spline function, this study introduced the linear sub model to establish the partial thin plate smoothing splines method, which allows multiple independent variables and independent covariant variables to be used in the spatial interpolation of meteorological elements, and the model coefficients can be automatically determined according to the data. It can greatly improve the accuracy of spatial interpolation of meteorological factors. At the same time, the model can handle samples of more than two dimensions, so the method may provide a means of transparent...
Figure 5 | Spatial distributions of monthly average precipitation in the Yellow River basin from 1981 to 2013.
2. The annual precipitation distribution in the Yellow River basin overall presents a decreasing trend from east to west; the isohyet equipluve distribution of 400 mm is obvious for the whole basin and basically consistent with the dividing line between semi-humid and semi-arid regions in China. Sichuan has the highest annual average precipitation of 696 mm, while Inner Mongolia has the lowest precipitation of 271 mm. The multi-year average minimum precipitation in Sichuan, Shandong and Henan is more than 500 mm. An annual average maximum precipitation over 500 mm occurs in eight provinces. Shaanxi has the highest precipitation of 848 mm, while Inner Mongolia has the lowest precipitation of 431 mm. Shandong and Henan provinces both have relatively significant inter-annual changes of precipitation in 1990 and 2005, with decreases of 43.2% and 39.2%, respectively.

3. The spatial distributions of multi-year average monthly precipitation from 1981 to 2013 show great changes.
On the whole, precipitation is generally higher in the south than in the north. The multi-year average monthly precipitation in each province is mainly distributed over 7–9 months. The precipitation from July to September in Shandong and Henan provinces accounted for 65.8% and 62.2% of annual precipitation, respectively. The highest monthly average precipitation occurred in July in all provinces, except for Ningxia, which had its highest rainfall in August. The changing trends of multi-year average monthly precipitation in each province are basically the same as the trends for multi-year average monthly minimum and maximum precipitation.

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