Spatio-Temporal Analysis of Precipitation Patterns in Xinjiang Using TRMM Data and Spatial Interpolation Methods: A Comparative Study

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Abstract : Amidst global climate change, regional climate pattern studies are essential for grasping climate variability and shaping water resource management. This research delves into the spatial and temporal aspects of precipitation in China's Xinjiang region. By analyzing TRMM 3B43 V7 satellite precipitation data from 1998 to 2019, alongside ground-based observations, the study examines the efficacy of four spatial interpolation methods - inverse distance-weighted, kriging, radial basis function, and thin-plate spline. The goal is to evaluate their accuracy in mapping Xinjiang's annual precipitation distribution. Findings indicate that the inverse distance weighting method, when used with TRMM data, yields the most accurate results. Notably, precipitation in Xinjiang has generally increased over the study period, with the northern region experiencing markedly higher precipitation, particularly in summer, compared to the south. Over 63% of Xinjiang exhibited this increasing precipitation trend, predominantly in the north. These insights are vital for comprehending water resource dynamics and climate change in Xinjiang, offering significant guidance for water management and agricultural planning.

Keywords: TRMM Data, Precipitation Variation, Inverse Distance Weighted Interpolation, Xinjiang

1. Introduction

In the context of global climate change, the study of regional climate patterns is particularly important, especially in Northwest China. This region is experiencing significant warming and humidification trends, with the climate of Xinjiang, an integral part of Northwest China, being notably affected [1]. The analysis of Xinjiang's precipitation patterns is essential not only for understanding these regional climatic shifts but also for managing water resources, fostering agricultural development, and safeguarding ecological protection.

Recent years have seen a surge in the use of satellite remote sensing data for climate research. The Tropical Rainfall Measuring Mission (TRMM) data, in particular, have emerged as a vital tool for analyzing precipitation characteristics [2]. However, the limitations of TRMM data in spatial resolution and regional accuracy necessitate

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the use of effective spatial interpolation, coupled with ground-based observations, to enhance data precision [3] [4].

This study utilizes TRMM data spanning from 1998 to 2019 for the Xinjiang region, integrated with ground observation data. Four spatial interpolation methods—inverse distance weighting, kriging, radial basis function, and thin-plate spline—are employed to investigate the spatial and temporal distribution of precipitation in Xinjiang. This research not only delineates the spatial and temporal trends of precipitation in the region but also assesses the effectiveness of various interpolation methods, providing a novel perspective for a more accurate understanding and prediction of precipitation patterns [5].

Positioning the backdrop of global climate change and focusing on the Xinjiang region, this paper aims to explore the spatial and temporal characteristics of precipitation in Xinjiang. By comprehensively analyzing TRMM data and ground observation data, the study offers valuable insights and references for research in related fields [5].

2 Data and analysis

2.1 Overview of the study area and data sources

2.1.1 Overview of the study area

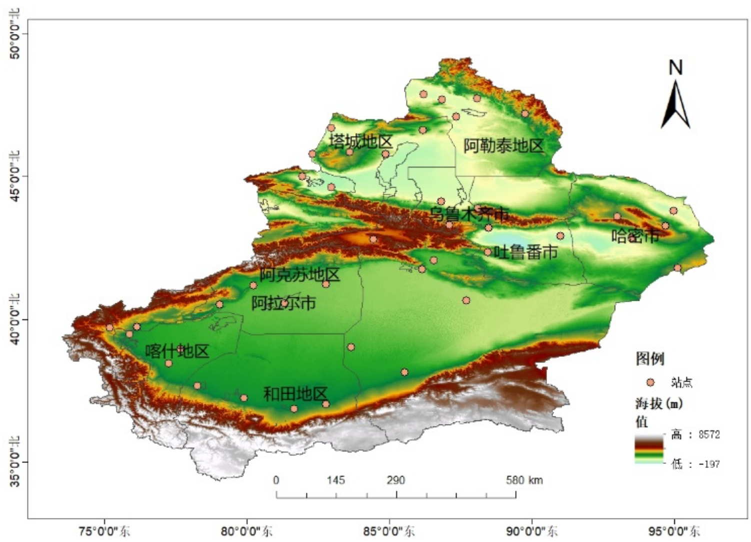

Figure 1. Location of the study area and site distribution.

The region of focus of this study is the Xinjiang Uygur Autonomous Region (XUAR) in the northwest of China, with geographic coordinates ranging from 73°40′ to 96°18′ east longitude and 34°25′ to 48°10′ north latitude. The total area of Xinjiang is 1,660,400 square kilometers, accounting for about one-sixth of China's land area (Figure 1). Located in the hinterland of the Asian-European continent, Xinjiang is far from the ocean and surrounded by high mountains, with Siberia to the north, the Tibetan Plateau to the south, and Central Asia to the west. The Tien Shan mountain range runs through the center of Xinjiang, naturally dividing it into northern and southern Xinjiang. This unique topography of "three mountains and two basins" creates an extremely uneven distribution of precipitation in Xinjiang. Xinjiang has a temperate continental climate, characterized by large temperature differences between day and night, scarce precipitation and high evaporation, making it a typical arid and semi-arid region.

2.1.2 Data sources and pre-processing

The Tropical Rainfall Measuring Mission (TRMM) precipitation data used in this study are derived from NASA's TRMM 3B43_V7 monthly precipitation product. This product has a spatial resolution of 0.25° x 0.25°, with data in millimeters per hour, and covers an area from 50°S to 50°N globally. In addition, the surface precipitation observations are from the China Meteorological Data Sharing Service Center, including the baseline precipitation data from 42 national reference stations in Xinjiang region between January 1998 and December 2019. The TRMM data downloaded from NASA were stored in NetCDF format and were first converted to TIF files in raster format. By calculating the monthly precipitation, combined with the number of days and hours in the month, the corresponding quarterly and annual precipitation totals can be derived.

2.2 Research methodology

In order to obtain the interpolation method with the highest accuracy, this paper combines four interpolation methods with TRMM data and compares the optimal method. In addition, a combination of Theil-Sen Median slope estimation and Mann-Kendall trend analysis is carried out to analyze the spatial trend changes of annual precipitation in Xinjiang.

2.2.1 Spatial interpolation and assessment methods

In this paper, four precipitation interpolation methods were selected and combined with TRMM data for interpolation analysis, and four assessment metrics were used to compare and analyze the data (Table 1):

Table 1. Four methods of spatial interpolation of precipitation.

interpolation method	formula	parameter introduction	advantages of the interpolation method

radial basis function method	$Y = \frac{\left[\sum_{i=1}^{n} Y_i G(d_i)\right]}{\left[\sum_{i=1}^{n} G(d_i)\right]}$	Y is the predicted value of precipitation at the prediction point, Y_i is the actual value of the *ith* site; *d* is the distance from the estimation point to the *ith* site; *n* is the number of measured sites participating in the interpolation; and *G* is the monotonic function of the Euclidean distance.	Different radial basis functions can be selected according to the actual demand, so as to meet different interpolation requirements. By selecting suitable basis functions and adjusting the weight coefficients, high-precision interpolation of data can be realized.
inverse distance weighting	$Y = \frac{\left[\sum_{i=1}^{n} \frac{Y_i}{(D_i)^p}\right]}{\left[\sum_{i=1}^{n} \frac{1}{(D_i)^p}\right]}$	Y is the estimated value of the predicted station; Y_i is the actual value of the *ith* (i=1,2,3,......, *n*) station; *n* is the number of weather station points used for interpolation; *D* is the distance from the predicted point to the known station; *p* is the power of the distance.	The spatial correlation of the surrounding data can be utilized to improve the accuracy of the interpolation, and better interpolation results can be obtained with smaller amounts of data.
kriging (loanword)	$Y = \sum_{i=1}^{n} \lambda Y_i$	Y is the estimated value of the predicted site, Y_i is the actual value of the known site, and λ is the kriging weight coefficient.	The spatial autocorrelation and the temporal stability of the data are taken into account, which can better reflect the real distribution of the data. Compared with other interpolation methods, the results of Kriging interpolation are more stable and reliable with higher accuracy.
thin disk spline method (math)	$Z_i = f(x_i) + b^T$ $e_i(i = 1, ..., N)$	Z_i is the dependent variable; x_i are the independent variables; f is the function to be estimated about the x_i unknown smooth function; y_i is the p-dimensional independent covariate; b is the y_i the number of p-dimensional coefficients; e_i is the random error of the independent variable with expectation 0.	The method allows for the introduction of linear covariate sub-models, such as correlations between e.g. temperature and elevation, evapotranspiration and water vapor pressure difference [6] .

To compare the four interpolation methods and identify the optimal one, this paper evaluates the quality of precipitation interpolation using four metrics (detailed in Table 2).

Table 2. Indicators for assessing precipitation interpolation.

Assessment of indicators	Formula for calculating indicators	Parameter introduction	Meaning of the formula
The coefficient of certainty R^2	$R^2 = 1 - \frac{\sum_{i=1}^{n}\left[Y_i - X_i\right]^2}{\sum_{i=1}^{n}\left[X_i - \overline{X}\right]^2}$	Y_i is the grid point value (mm); X_i is the site value (mm); X is the mean of the measured values of the site (mm); n is the number of grid points.	Measures the degree of agreement between the grid point values and the measured values at the site
Root Mean Square Error RMSE	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left[X_i - Y_i\right]^2}{n}}$		It is the square root of the square of the deviation of the grid point value from the measured value of the site and the average value, reflecting the degree of dispersion of the calculated value relative to the measured value, either positively or negatively.
Mean Bias MBE	$MBE = \frac{\sum_{i=1}^{n}\left[Y_i - X_i\right]}{n}$		It is the average of the difference between the grid point value and the measured value to determine whether there is a systematic positive or negative bias in the calculated value relative to the measured value.
Relative bias BIAS	$BIAS = \frac{\sum_{i=1}^{n}(X_i - Y_i)}{\sum_{i=1}^{n}X_i}$		

Additionally, to enhance the accuracy assessment of TRMM precipitation data, the study employs the correlation coefficient R, calculated as follows:

$$R = \frac{\sum_{i=1}^{n}(X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \overline{X})^2(Y_i - \overline{Y})^2}} \tag{1}$$

2.2.2 Theil-Sen Median slope estimation and Mann-Kendall trend analysis

This research applies the Theil-Sen Median slope estimation method in conjunction with the Mann-Kendall trend analysis to elucidate the spatially varying characteristics of annual precipitation in Xinjiang. The Sen equation is defined as follows:

$$\beta = MEDIAN\frac{(x_i - y_i)}{(j - i)} \quad \forall j > i \tag{2}$$

where MEDIAN represents the median value. If β>0, this signifies an increasing trend in precipitation, and conversely, a negative β indicates a decreasing trend.

The Mann-Kendall (M-K) test, a nonparametric method developed by Mann and others, is utilized for detecting trends in time-series data, particularly suitable for hydrological and meteorological datasets [7]. The specific formula and calculation of the test statistic S are as follows:

$$s = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign(x_j - x_i) \quad (3)$$

where sign() is the sign function, calculated as:

$$sign(x_j - x_i) = \begin{cases} -1 \ (x_j - x_i) < 0 \\ 0 \ \ (x_j - x_i) = 0 \\ 1 \ \ (x_j - x_i) > 0 \end{cases} \quad (4)$$

Trend tests were performed using the test statistic Z, calculated as:

$$Z = \begin{cases} (s-1) / \sqrt{\dfrac{n(n-1)(2n+5)}{18}}, S > 0 \\ 0 \qquad\qquad\qquad\qquad\quad , S = 0 \\ (s+1) / \sqrt{\dfrac{n(n-1)(2n+5)}{18}}, S < 0 \end{cases} \quad (5)$$

A bilateral trend test is conducted. At a designated significance level, the critical value Z1-α/2 is obtained from the normal distribution table. When |Z| ≤ Z1-α/2, the null hypothesis is accepted, indicating no significant trend. Conversely, if |Z| > Z1- α /2, the null hypothesis is rejected, signifying a significant trend. In this study, with α=0.05, the critical value Z1-α/2 equals ±1.96. Trends are considered significant at the 90%, 95%, and 99% confidence levels when the absolute value of Z exceeds 1.65, 1.96, and 2.58, respectively.

3 Results and Analysis

To assess the applicability of TRMM precipitation data in Xinjiang and examine the spatial and temporal distribution characteristics of precipitation, this study is divided into four parts: 1) Validation of TRMM data accuracy; 2) Assessment of interpolation method accuracy; 3) Analysis of spatial and temporal precipitation distribution in Xinjiang; and 4) Examination of spatial variation in annual precipitation.

3.1 TRMM Data Accuracy Validation Analysis

The accuracy of TRMM precipitation data was verified against measurements from 42 meteorological stations in Xinjiang. Measured data from each station were used as the independent variable, and TRMM data as the dependent variable for one-dimensional linear fitting (illustrated in Figure 2).

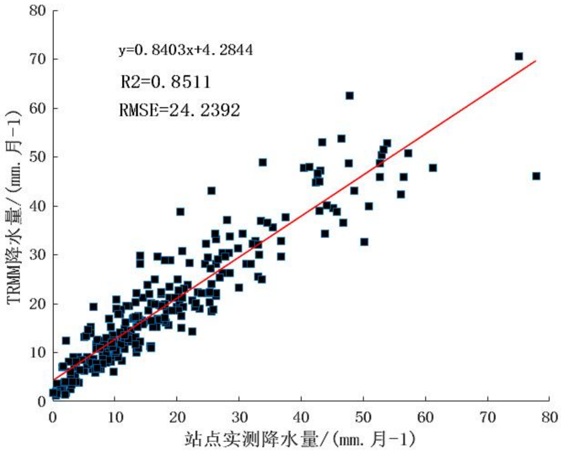

Figure 2. Comparison of site-measured precipitation data with TRMM precipitation data.

From Fig. 2, it is evident that at the monthly scale, the R^2 of the goodness of fit between TRMM data and site data is 0.8511. A value of R^2 closer to 1 signifies a better fit, with values above 0.8 indicating relatively high model accuracy. The correlation coefficients R for each municipal area are predominantly above 0.8, with an average R value of 0.85. This suggests a strong correlation between TRMM and site data, adequate for statistical analysis and interpretation.

3.2 Comparison of Four Interpolation Methods Based on Precipitation Data

Initially, four interpolation analyses were conducted on precipitation data for accuracy assessment. This study summarizes TRMM precipitation data in Xinjiang from 1998 to 2019 into average annual and monthly precipitation values. Spatial interpolation analyses were then performed separately, yielding accuracy assessment tables for each year and month, as shown in Tables 3 and 4:

Table 3. Assessment of spatial interpolation accuracy for mean annual precipitation.

Evaluation coefficient	RBF	IDW	OK	ANUSPLIN
R^2	0.5957	0.6146	0.6064	0.4923
RMSE	74.89	76.75	75.73	86.31
MBE	15.58	9.77	15.60	15.57
BIAS	7.92%	7.47%	7.52%	8.03%

Table 4. Assessment of spatial interpolation accuracy for monthly mean precipitation.

Evaluation coefficient	RBF	IDW	OK	ANUSPLIN
R^2	0.6141	0.6146	0.6115	0.4907
RMSE	6.248	6.250	6.270	7.178
MBE	1.303	1.299	1.300	1.436
BIAS	7.48%	7.48%	7.48%	8.26%

Considering R^2, RMSE, MBE, and BIAS, the accuracy ranking for the four interpolation methods, when combined with TRMM data, is IDW > OK > RBF > ANUSPLIN. Furthermore, spatial interpolation maps (Fig. 3) illustrate the interpolation effects of these methods in Xinjiang, using the average monthly precipitation value as an example.

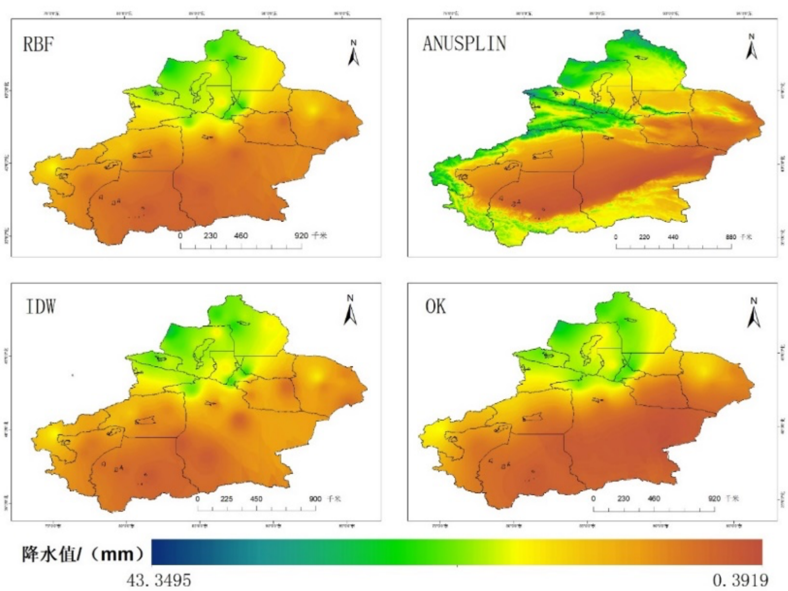

Figure 3. Spatial interpolation of monthly average precipitation.

Tables 3 and 4 indicate that the inverse distance-weighted interpolation (IDW) has the highest R^2 and the lowest mean bias, making it the most suitable of the four methods for interpolation with TRMM data. The annual mean precipitation interpolation shows higher RMSE and MBE than the monthly mean, suggesting higher accuracy in monthly interpolation. Additionally, the spatial interpolation maps reveal that RBF, IDW, and OK interpolations all indicate higher precipitation in the northern border and lower in the southern border, while ANUSPLIN interpolation shows a similar high value in the northern border and a slightly higher value in some southern parts.

3.3 Characteristics of Spatial and Temporal Distribution

This section aims to analyze the spatial and temporal distribution characteristics of precipitation in Xinjiang, understanding the general precipitation trends and their implications for future predictions. This analysis provides a scientific basis for water resource distribution and rational utilization in Xinjiang.

3.3.1 Spatial Distribution haracteristics

Precipitation in Xinjiang decreases gradually from north to south (Figure 3). The annual precipitation typically ranges from 10-350 mm, characterizing the region as arid. Northern Xinjiang, especially in Tacheng, Altay, and Urumqi, receives the most precipitation. This is attributed to the region's relatively flat terrain and the climatic influences, including water vapor transport from the Arctic Ocean and westerly winds from the Atlantic Ocean, which are blocked by the Tianshan Mountains, resulting in precipitation. Eastern Xinjiang receives the next highest amount of precipitation, while the southern part is severely arid, with average annual precipitation below 100 mm.

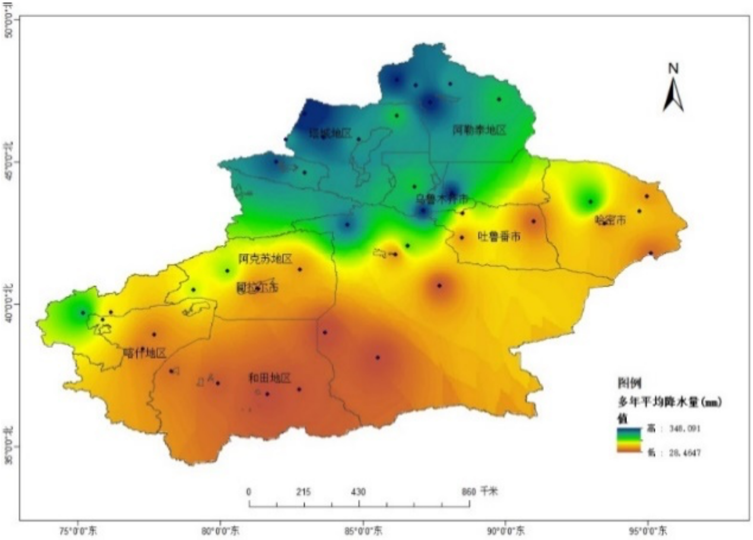

Figure 3. 1998-2019 average precipitation map for xinjiang region.

3.3.2 Interannual Precipitation Distribution Characteristics

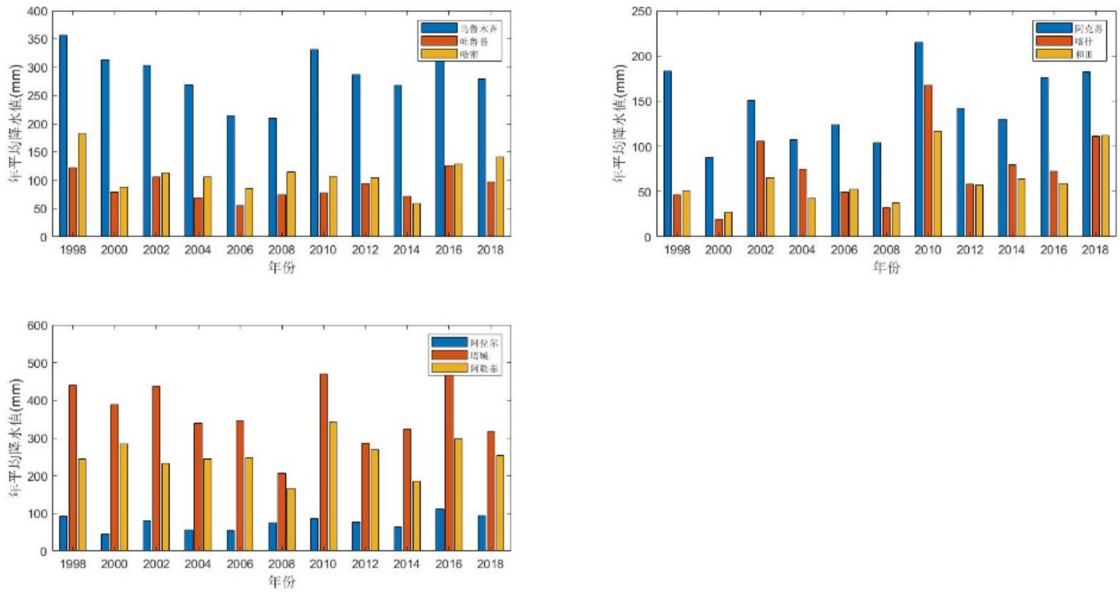

Figure 4. 1998-2019 precipitation changes in Xinjiang region.

This section analyzes interannual precipitation distribution in Xinjiang from 1998-2019, with histograms for each year in nine municipal regions shown in Fig. 4. The annual precipitation exhibits a fluctuating pattern, generally increasing, with notable increases in regions like Aksu, Kashgar, Hotan, and Aral. The year-over-year trends, particularly evident in 2015 and 2016, are beneficial for local water resource development. The reasons for these increases may be linked to global warming and alpine meltwater [7] .

3.3.3 Characteristics of Monthly Seasonal Precipitation Distribution

This section discusses the distribution of seasonal precipitation in Xinjiang, indicating that most precipitation occurs in summer, followed by spring, with the least in fall and winter (Figure 5). Summer precipitation constitutes 39% of the annual total, with peak values in cities like Urumqi. The abundant summer precipitation is a critical resource for water conservation in the region.

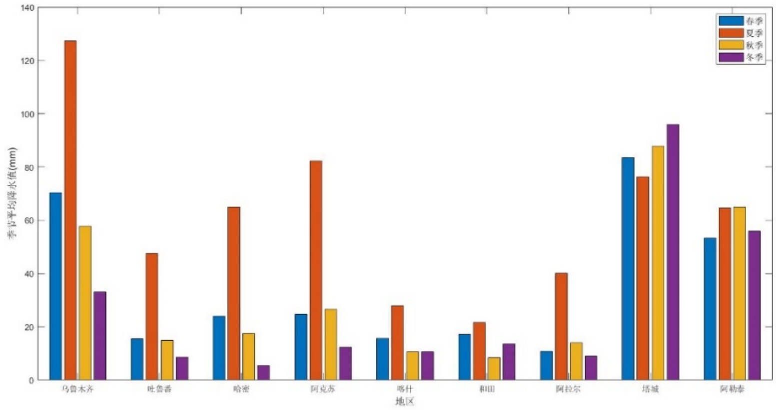

Figure 5. Seasonal precipitation variation in Xinjiang region, 1998-2019.

The monthly precipitation pattern aligns with the seasonal trends, with the highest precipitation in June, July, and August, and the lowest in March, October, and December (Figure 6). Peak precipitation in regions like Urumqi, Turpan, and Hami occurs primarily in summer and winter.

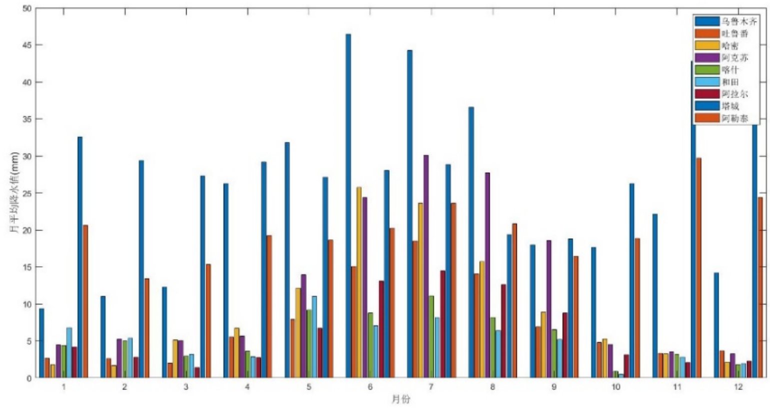

Figure 6. Monthly precipitation variations in prefecture-level cities of Xinjiang region, 1998-2019.

3.4 Results of the characterization of the spatial variability of annual precipitation

This study analyzed TRMM annual precipitation data using Theil-Sen median trend analysis combined with the Mann-Kendall test (Figure 7) [8][9]. The analysis reveals a predominantly increasing annual precipitation trend in Xinjiang from 1998 to 2019. Over 63.64% of Xinjiang's area exhibited an increasing trend, with significant increases in regions such as Aral, Aksu, Tacheng, and Kashgar. The areas with decreasing precipitation made up 36.36% of Xinjiang, with most decreases being non-significant.

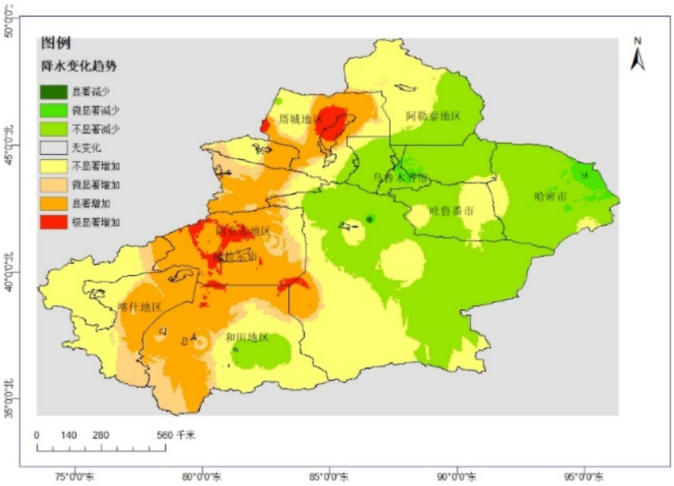

Figure 7. Maps of sudden change analysis of annual precipitation.

The annual precipitation in Xinjiang from 1998 to 2019 mainly shows an increasing trend. More than 63.64% of the total area of Xinjiang showed an increasing trend, of which 2.22% of the area was a highly significant increase and 20.87% of the area was a significant increase, mainly in Aral, Aksu, Tacheng and Kashgar. The areas with decreasing precipitation accounted for 36.36% of the total area of Xinjiang, of which the areas with minimally significant decreases and significant decreases accounted for only 1.30%, and most of the areas with decreasing precipitation were in a non-significant decreasing trend.

4 Conclusion

Xinjiang's vast area and sparse, uneven station distribution make it challenging to rely solely on ground observation for studying temperature and precipitation variability. To overcome this, the study combined TRMM 3B43 V7 satellite precipitation data with ground observations to analyze spatial and temporal precipitation changes in nine municipal regions of Xinjiang from 1998 to 2019. By comparing four spatial interpolation methods, the study concludes:

(1) Annual precipitation in Xinjiang exhibited a general increasing trend, particularly in the northern region. This trend, observed in over 63.64% of Xinjiang, is crucial for understanding climate change and water resource management.

(2) The inverse distance weighting method, when combined with TRMM data, showed the highest interpolation accuracy, making it suitable for analyzing Xinjiang's precipitation distribution. This offers an effective methodological reference for future studies.

(3) Significant regional differences in precipitation distribution exist in Xinjiang, with notably higher amounts in the northern border than in the south. This disparity is

important for developing water resource allocation and utilization strategies.

(4) The study's results lay the groundwork for more in-depth climate change impact analyses. Future research could leverage higher resolution satellite data to refine understanding of precipitation patterns and climate change in Xinjiang.

In summary, this study not only highlights the trends and regional characteristics of precipitation in Xinjiang but also compares the effectiveness of different interpolation methods. These findings have practical significance and theoretical value for water resource management, agricultural development, and climate change research in the region.

Reference

[1] Shi, Yafeng, Shen, Y.P. & Hu, R.G., A preliminary discussion of signals, impacts, and prospects for a warm-dry to warm-humid climate transition in the Northwest. Glacial Permafrost, 2002(03): pp. 219-226.

[2] Yao, J., et al., Recent climate and hydrological changes in a mountain-basin system in Xinjiang, China. Earth-Science Reviews, 2022. 226. Earth-Science Reviews, 2022. 226: p. 103957.

[3] Yosefi Kebriya A, N.M.J.M., Combining interpolation methods and precipitation products of TRMM satellite to increase the accuracy of rainfall maps in Mazandaran province. Journal of Water and Soil Conservation, 2021: p. 28(3): 49-70.

[4] Hu, W., et al., Changes in precipitation amounts and extremes across Xinjiang (northwest China) and their connection to climate indices. peerJ, 2021. 9(6903): p. e10792.

[5] Zhang, L., et al., Influence of solar activity and EI Niño-Southern Oscillation on precipitation extremes, streamflow variability and flooding events in an arid-semiarid region of China. Journal of Hydrology, 2021. 601: p. 126630.

[6] Weyn., J., Spatial and temporal variability of precipitation over the last 50 years in the Qinling region based on Anusplin. Soil and Water Conservation Research, 2020.

[7] Mostowik, K.J.M.K., Runoff trends in a changing climate in the Eastern Carpathians (Bieszczady Mountains, Poland). Catena: An Interdisciplinary Journal of Soil Science Hydrology-Geomorphology Focusing on Geoecology and Landscape Evolution, 2019. 182.

[8] Chon Liu, Study on the effect of vegetation restoration on soil moisture in the Loess Plateau, 2021.

[9] Wu, H., et al., A spatiotemporal deep fusion model for merging satellite and gauge precipitation in China. Journal of Hydrology, 2020. 584: p. 124664.