Analysis of Characteristic of Meteorological Variables in Golmud, China during 1955-2015 and Prediction of its Future Change

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Abstract. Global warming and its impact on socio-economic and eco-environment in the more drought-prone regions have attracted great attention. Arid regions account for about 30% of the total China's land area, which are quite sensitive and vulnerable to climate change. The annual trends of three meteorological variables were analyzed in Golmud City during 1955-2015. The linear regression, cumulative anomaly and R/S methods were used to determine the characteristics of the meteorological variables. The Morlet wavelet transforms method was employed to detect the dynamic periodic features of the meteorological variables. The results were obtained as follows: 1) the significant increasing trends were indicated in both temperatures (0.5°C/10a, p<0.01) and precipitation (3.3mm/10a, p<0.05), the decreasing trend in evaporation (118.4mm/10a, p>0.05). This states that the climate of Golmud City was turned from cold-dry to warm-wet. 2) The Hurst indexes of each annual variable were all greater than 0.5, it suggested that there would be obvious Hurst phenomenon in the future. 3) The wavelet analysis revealed that the temperature, precipitation, evaporation, had the periods of 12-14a, 7-9a, 11-12a oscillations, respectively. 4) According to the analysis results by synthesis we can predict that there will still keep the warming and increasing trend of temperature and precipitation in the future. In general, the results of using the Mann-Kendall and R/S proved the good consistency in detection of the trend for temperature and precipitation. This study can be used as a reference for further analysis of climate as well as the impacts of climate change. More importantly it can provide theoretical support for context-specific plan for water resources development and agricultural and animal husbandry production in Golmud City.

Keywords: Meteorological Variables, Trend Analysis, Mann-Kendall Test, R/S Analysis, Wavelet Analysis, Golmud City
1 Introduction
In 2015, due to the increase in greenhouse gas (GHG) emissions and the continuing effects of the El Nino phenomenon, the long-term warming of our planet caused global temperatures to rise by 0.76±0.09°C compared to the middle of the 20th century. The surface air temperature in China also presented a warming trend of 0.244±0.021°C/10a from 1951-2015[1]. Precipitation exhibited spatial and temporal variability depending on the distance to coastal line, topography and elevation, and this arouses heterogeneity at local scales [2]. Check the temporal dynamics of meteorological variables in the context of climate change, especially in arid and rainy areas where rainfed agriculture[3-7]. Gocic and Trajkovic found that the increasing trend in air temperature, significant decreasing trend in relative humidity and no significant trends in precipitation in Serbia[8,9]. Viste et al. and Kiros et al. analyzed the precipitation tendency since 1971 in Ethiopia, found a decline trend in southern Ethiopia and no significant trend in central and northern Ethiopia, respectively[10,11].

The Tibetan Plateau (TP) referred to as "the third pole" is considered a booster for drastic global climate change[12-16]. Zhou et al. have proved that the 1.5°C additional global warming will lead to higher extreme temperature increase in the TP[17]. Many studies on temperature, precipitation and evaporation variability and trends in TP covering different spatial and temporal scales have analyzed. Achievements of temperature are generally consistent with each other in reporting warming trends. Precipitation is characterized by an upward trend in central TP, and a decrease in evaporation near the center of TP is observed. Overall, in TP, the rising temperature and precipitation and the declining evaporation trends have reached a general consensus, but inevitably there would be inconsistent results. For instance, Huang et al. found a decreasing trend of periodical annual precipitation in the northeastern TP. Also, Liao et al. have found decreasing trend of the annual mean temperature in city of TP: Nielamu, Pulan, Lhasa, Gongga, Langkazi, Jiangzi[18].

Golmud City is located in the south-central Qaidam Basin and the hinterland of the TP, is more vulnerable to climate change than other regions in the TP. The increasing temperature in Colmud City has given rise to glacier recession, grassland degradation, permafrost thaws, wetland reduction and other disastrous environmental problems. Therefore, long-term observation, recording and analysis of meteorological data are extremely important. Many studies have been done for inspecting possible climate trends and changes in Golmud City. Nevertheless, most of these studies have only concentrated on short-term changes.

Climate change occurs on a global scale, its impacts often vary from region to region. Moreover, local-scale trend surveys are important because research on large-scale meteorological variables is not useful for local agriculture, especially where precipitation varies widely and geophysical characteristics change within a closed area. Consequently, the analysis of changes in meteorological variables in local scale represents a significant task in climate change projections.

This paper is to detect the variability of three meteorological variables for Golmud station from 1955 to 2015. Specifically, the targets of this study are: 1) to analyze and investigate the tendency of meteorological variables in detail; 2) to quantify the significance of changes by adopting the non-parametric Mann-Kendall test (MK) and R/S analysis; 3) to analyze the periodic variations by wavelet analysis.

2 Material and Methods

2.1 Study area description
Golmud is located in the hinterland of TP with an area of 11.89 km²(Fig.1). The terrain of the territory is complex, which can be divided into two parts: the basin plateau and the northern foot of Tanggula Mountain. Golmud in China ranges from 35˚10’ to 37˚45’ N and from 91˚25’ to 95˚12’ E, where the typical continental climate dominates with the annual mean temperature 5.3°C, the annual mean precipitation less than 100 mm and the annual mean evaporation 2709.7 mm. The prevailing westerly wind in Golmud with mean wind speed about 3 m/s. Climate aridification has caused sparse vegetation and further led to the desertification.
2.2 Data and methods
Monthly meteorological variables data were obtained from Golmud Meteorological Bureau, Qinghai Province. Monthly data were averaged to obtain yearly variables.

Linear regression was used to detect yearly data changes and trends of each meteorological variable. It is given as:

\[ y = kx + b \]  

where \( y \) is dependent variable, \( k \) is the slope, \( x \) is independent variable and \( b \) is the intercept.

Using the least squares method to calculate the slopes of regression lines trend.

Cumulative anomaly method can more intuitively and accurately judge the inter-annual change stage, which is widely used in climate change. The equation is:

\[ CA_i = \sum_i (R_i - \bar{R}) \]  

where \( CA_i \) is the value of cumulative anomaly in the \( i \) year, \( R_i \) is the observed meteorological variable value of the \( i \) year, \( \bar{R} \) is mean.

The MK test statistic of \( Z \) was the statistical significance used to determine the trend. Testing related null hypotheses, a statistic \( S \) is obtained as:

\[ S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \]  

where \( n \) is the number of yearly data, \( x_j \) and \( x_i \) are the data values in time series \( j \) and \( i \), \( j > i \); \( sgn \) is known as the Sign function, the \( sgn (x_j - x_i) \) is calculated as:

\[ sgn (x_j - x_i) = \begin{cases} 1, & x_j - x_i > 0 \\ 0, & x_j - x_i = 0 \\ -1, & x_j - x_i < 0 \end{cases} \]  

The mean of the statistic, \( \bar{S} = 0 \), is conformed to normal distribution. The variance is computed as

\[ Var(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} (t_i-1)(2t_i+5)t_i}{18} \]  

where \( n \) is the number of yearly data, \( m \) is the number of tied groups and \( t_i \) represents the number of ties of extent \( i \). In case where the sample size \( n > 10 \), the standard normal test statistic of \( Z \) is computed using Eq. (6)\textsuperscript{[9]}.
\[ Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & S < 0 \end{cases} \] \quad (6)

Positive values \( S \) suggest increasing trend while negative \( S \) values suggest decreasing trend. Testing trend is done at specific \( \alpha \) confidence level. When \(|Z| > Z_{1-\alpha/2}\), it indicates that the null hypothesis is rejected and a significant trend exists. According the confidence level, at the 0.05 confidence level, the null hypothesis of no trend is rejected when \(|Z| > 1.64\), and rejected when \(|Z| > 2.32\) at the 0.01 confidence level. The MK statistical test has been widely used to quantify the significance of trends in precipitation, runoff, temperature and water quality time series \(^{2,8}\).

At the beginning of the 20th century, hydrologist Hurst (H. E. Hurst 1900-1978) studied the flooding records of the Nile River in Egypt from 622 to 1469 A.D. and proposed the Rescaled Range analysis (R/S) method \((\text{Hurst et al., 1965})^{20}\). This method quantitatively analyses the characteristics of time series, and get the Hurst exponent named by Benoit B. Mandelbrot. The R/S is defined by the empirical relationship as follows:

\[ R(t)/S(T) = (c t)^H \]

where \( R \) is the distance covered Range, \( S \) is the D-value between the maximum and minimum of the cumulative of time series, \( c \) is a constant, \( t \) is the time interval, and \( H \) is the Hurst exponent.

The results of \( H \) represent three kinds of trends. When \( H = 0.5 \), it means that the time series is an independent random process. Also, This means that events are irrelevant and current trends will not predict future trends. When \( 0 < H < 0.5 \), it indicates that the time series is anti-persistent, in other words, the future trend will be opposite to the past. The smaller the \( H \) value, the stronger the resistance to persistence. When \( H > 0.5 \), it signifies that each observation series carries a persistence of all the case that preceded it; The larger the \( H \) value, the stronger the persistence.

Wavelet transform is a joint time-frequency analysis method developed in the 1980s. The difficulty of Fourier transform is solved by progressive multi-scale refinement of signal functions through scaling and translation operations. Among many kinds of wavelet functions, Morlet is widely used in hydrologic system because it has a good locality of the time and frequency domains. For a given Morlet wavelet and meteorological times series, the continuous wavelet transform is:

\[ W_f(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(t) \phi \left( \frac{t-b}{a} \right) \, dt \]

where \( W_f(a, b) \) is wavelet coefficient, \( \phi(t) \) is mother wavelet, \( a \) is scaling factor, reflecting the periodic length of wavelet; \( b \) is translation factor, reflecting the translation of time. In fact, the time series is discrete, for \( f(k \Delta t) \) \((k=1, 2, 3 \ldots N, \Delta t \) is the time interval of sampling\), so the discrete form of formula (8) can be expressed as:

\[ W_f(a, b) = \frac{1}{\sqrt{a}} \Delta t \sum_{k=1}^{N} f(k \Delta t) \phi \left( \frac{k \Delta t - b}{a} \right) \]

In addition, in order to detect the distribution of wave energy with scale, the squares of all wavelet transform coefficients of scale "\( a \)" in time domains are integrated to obtain the wavelet variance:

\[ var(a) = \int_{-\infty}^{+\infty} |W_f(a, b)|^2 \, db \]

where \( var(a) \) is wavelet variance on scale "\( a \)". According to the process map of wavelet variance varying with scale "\( a \)", the main time scale in meteorological series, namely the main period is determined. All the calculation process is realized by programming in Matlab software.
3 Result and Discussion

3.1 Meteorological variables trend

The linear regression model, cumulative anomaly method and MK were used to detect the trends of the three meteorological variables.

The mean precipitation during 1955-2015 is 33.85 mm. The annual mean precipitation shows an increasing tendency since 1979. The rate of change is defined by the slope of regression line which is 3.3 mm/10a (Fig.2a). Also, especially since 2010, the precipitation anomaly lines and trends due to interannual changes have become more apparent than long-term averages. The positive slope of the cumulative anomaly represents the increasing trend.

The MK test and R/S were used to quantify meaning the time series data from 1955 to 2015. The Z value of MK test for trend analysis is 1.8, which means a statistically significant growth trend each year. The Hurst exponents (H) for precipitation calculated using R/S analysis method, the H values for precipitation is 0.71, greater than 0.5. This implies that relatively higher dependence of precipitation in future time domain on the previous values. The results of using the MK and R/S proved the good consistency in detection of the trend for precipitation.

The average annual temperature of the study area is between 2.9 ℃ (1967) and 7.1 ℃ (2006) with mean temperature 5.2 ℃. The rate of temperature is found to be 0.5 ℃/10a during 1955-2015 (Fig.2b). The long-term anomaly of the annual average temperature shows interannual changes, and the trend has increased significantly since 1983, indicating a warming trend. Furthermore, the increasing rate in Golmud is high than Qinghai (0.41 ℃/10a) and China (0.25 ℃/10a) [21-22]. This is closely related to the geographical, local ecological environment and social and economic development of Golmud. Golmud is a sub-basin in the Qaidam Basin, the hinterland of the TP, surrounded by high mountains, and heat is not easy to dissipate, so the temperature rise is more significant than other regions. More important, the vegetation coverage in Golmud area is very low, and there are many deserts, which will make the temperature change greatly; the external hot airflow is strong, when it sinks over the mountain, the warming effect is strong. The increasing urbanized area owing to population growth since the late 20th century [2] and the increase of industrial and civil buildings and vehicles, coal-fired heating, etc., all will increase greenhouse gas emissions and result in rise in temperature.

The MK test result indicates that annual mean temperature has been increasing pronounced (at 1% level of significance). Also, the H value is 1.05>0.5, which can be predicted in future time domain using the previous values.

The evaporation in Golmud is far greater than precipitation with the annual mean evaporation 2587.1mm, while the rate shows decreasing trend with 118.4 mm/10a during 1955-2015(Fig.2c). According to Dalton's linear formula, wind speed is direct proportion to evaporation. The long-term anomalies of annual mean evaporation has been decreased since 1983. Although the temperature in Golmud area has been rising in recent years; while, the significant decrease of wind speed compensates for the increase of evaporation caused by the increase of temperature, so the evaporation reduces; This may be the main reason for the continuous decline in annual average evaporation.

The result of MK test for evaporation trends analysis is at 10% level of significantly, which suggests it has a non-significant decreasing trend. The H value of evaporation is 0.95, it illustrates relatively higher dependence of evaporation in future time domain using the previous value.
Fig. 2 Variation of annual mean precipitation (a), temperature (b) and evaporation (c)

3.2 The main period analysis of the meteorological variables

The contour map of the real part of the wavelet coefficients can reflect the periodic changes of the annual meteorological variable sequences at different time scales and their distribution in the time domain, and further judge the future trends at different time scales.

From the Fig.3a, the real part isoline map of annual mean precipitation shows four wetter centers and five drier centers overall, and the positive and negative phase appear alternately. The timescales of 7 to 9 years are the most obvious.

Fig.3b shows the variation of different timescales of the annual mean temperature anomaly series, and the 4 warmer centers and 3 colder centers appear alternately. The timescales of 12 to 14 years are the most obvious.

Fig. 3c shows the variation of different timescales of annual mean evaporation anomaly. The timescales of 11 to 12 years are most obvious, and the 4 positive and 3 negative phases appear alternately.

4 Conclusions

The climate variability and periodic time series have not been greatly analyzed in Golmud. The main purpose of this study was to carry out an analysis of the three meteorological variables in Golmud from 1955 to 2015. The analysis results was obtained by the linear regression, the MK, the R/S and wavelet analysis. The meteorological data had good quality datasets with detailed and accurate record length.

The obtained results indicate that there is a significant increasing trend in annual mean temperature and precipitation with the rate 0.5℃/10a and 3.3mm/10a. However, there exhibited a decreasing trend in evaporation with the rate 118.4mm/10a at the 0.1 significance level. From the above results, it is obvious that
the climate in Golmud is changing cold and dry to warm and wet.

In general, the results of significance and trend detection by using Mann-Kendall and R/S are in good agreement in temperature and precipitation.

The investigation of multi-period structures of time series is a crucial part of meteorological data mining. Although the meteorological data seem to be irregular and random, the obvious periodicity can be gained by the wavelet analysis. Wavelet analysis is one such practical and highly efficient tool well-suited to study multi-period, nonstationary process occurring over finite temporal domains. From the results, the first dominant period of annual mean temperature, precipitation, evaporation, are 28 years, 21 years, 28 years, respectively.

Since temperature and precipitation are the two most important meteorological variables in the hydrological cycle and climate science, we comprehensively utilize the above results and forecast the future annual mean temperature and precipitation. It is predicted that the next 28 years and 21 years oscillation, the annual mean temperature and precipitation will increase to 7.59 ℃ and 52.24 mm, respectively. The prediction reminds local managers to draw up corresponding measures in water resources development and actively respond to climate change.

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