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Assessment of Air Temperature Trends in the Source Region of Yellow River and Its Sub-Basins, China

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Abstract: Changes in climatic variables at the sub-basins scale (having different features of land cover) are crucial for planning, development and designing of water resources infrastructure in the context of climate change. Accordingly, to explore the features of climate changes in sub-basins of the Source Region of Yellow River (SRYR), absolute changes and trends of temperature variables, maximum temperature (Tmax), minimum temperature (Tmin), mean temperature (Tavg) and diurnal temperature range (DTR), were analyzed annually and seasonally by using daily observed air temperature dataset from 1965 to 2014. Results showed that annual Tmax, Tmin and Tavg for the SRYR were experiencing warming trends respectively at the rate of 0.28, 0.36 and 0.31°C $(10\,\text{yr})^{-1}$. In comparison with the 1st period (1965-1989), more absolute changes and trends towards increasing were observed during the 2nd period (1990-2014). Apart from Tangnaihai (a low altitude sub-basin), these increasing trends and changes seemed more significant in other basins with highest magnitude during winter. Among sub-basins the increasing trends were more dominant in Huangheyan compared to other sub-basins. The largest increase magnitude of Tmin, 1.24 and 1.18°C $(10\,\text{yr})^{-1}$, occurred in high altitude sub-basins Jimai and Huangheyan, respectively, while the smallest increase magnitude of 0.23°C $(10\,\text{yr})^{-1}$ occurred in a low altitude sub-basin Tangnaihai. The high elevation difference in Tangnaihai probably was the main reason for the less increase in the magnitude of Tmin. In the last decade, smaller magnitude of trend for all temperature variables signified the signal of cooling in the region. Overall, changes of temperature variables had significant spatial and seasonal variations. It implies that seasonal variations of runoff might be greater or different for each sub-basin.

Key words: Temperature, changes and trends, source region of the Yellow River, sub-basins, runoff and water management

1. Introduction

Understanding the climate change in a river basin is important for an effective management and water resources infrastructures since its development requires additional considerations in the perspective of climate change. The climate change is likely to have a significant impact and probably will be a major threat on the water resources of a basin in future. According to IPCC (2013) AR5, the air temperatures has increased globally by 0.85°C during 1880-2012, and climate change is expected to alter stream flows that impose stress on water resources due to increase in population and irrigated agriculture over the Asian region. Temperature being one of the most important climatological parameters affects the hydrological processes within a basin and commonly used to detect the fluctuations of climate (Singh et al., 2008).

There are some researches on the changes of temperature within basins in the world. The annual temperature of Colorado River basin increased 0.5°C between 1950-1999, and was projected to increase 1.0, 1.7, and 2.4°C in the periods of 2010-2039, 2040-2069, and 2070-2098, respectively (Christensen et al., 2004). The annual average temperature of Columbia River Basin was projected to increase 0.5, 1.3, and 2.1°C in the periods of 2010-2039, 2040-2069, and 2070-2098, respectively by using statistically downscaled PCM scenario, and to increase 1.2°C by RCM in the period of 2040-2060 (Payne et al., 2004). Similar results were also obtained by Christensen and Lettenmaier (2007) using a multimodel ensemble approach. The annual and seasonal mean maximum and minimum temperature of the Yangtze River Basin were characterized by positive trends and the strongest trend was found in the winter mean minimum on the basis of the daily data from 108 meteorological stations from 1960 to 2002 (Su et al., 2006). In Upper Indus Basin, temperature data for seven instrumental records have been analyzed for seasonal and annual trends over the period 1961-2000. Winter mean and maximum temperature showed significant increase while mean and minimum summer temperatures showed consistent decline. Meanwhile, the increase in diurnal temperature range (DTR) was consistently observed in all seasons and the annual dataset, a pattern shared by much of the Indian subcontinent

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but in direct contrast to both GCM projections and the narrowing of DTR seen worldwide (Fowler and Archer, 2005). From these studies, it is found that general increasing trends of mean, maximum and minimum temperature and decreasing trend of DTR were found in most of the worldwide basins, however decreasing trends still existed in some basins. Thus, it is necessary to study the changes of temperature variables at seasonal and sub-basin scales.

The Source Region of the Yellow River (SRYR) characterized by complex orography and fragile ecosystem, is expected to be sensitive to global climate change (Beniston et al., 1997; Beniston, 2003; Hu et al., 2011), and climate change is occurring in this basin (Hu et al., 2011; Zhang et al., 2008). In the SRYR, degradation in alpine eco-system and acceleration in melting of glacier, snow and permafrost causing land desertification, soil-water loss and degradation of vegetation and wetlands under global warming and long term grazing, (Li et al., 2016; Ran et al., 2016). Most likely, due to permafrost environment and complex underlying surfaces, spatio-temporal temperature variation is not homogenous. Specifically freeze-thaw process in high altitude areas and albedo and soil-water content changes in low altitude areas due to vegetation degradation results in more diverse temperature variations in the SRYR (Wang et al., 2015). In addition, some meteorological factors, such as clouds, water vapor, and aerosols in the troposphere also influence temperature variation in high altitude regions (Rangwala and Miller, 2012). This region characterized with different land cover (snow glaciers frozen soils etc.), so air temperature is an important climate variable which can effect on runoff in this region, especially in spring and summer. Since, it is important source of water resource for North of China, it is urgent to study the features of temperature changes in this basin to provide knowledge for water resource management, especially at seasonal scale. Moreover, the altitude change greatly in this region and temperature varies significantly, so it is necessary to study the temperature on the sub-basins scale. In addition, four hydrological stations (Huangheyan, Jimai, Maqu and Tangnaihai) along the mainstream of the SRYR make easier to divide the basin into four sub basins.

The temperature changes of the SRYR had been explored by many researchers (Lan et al., 2010; Hu et al., 2012; Wang et al., 2015; Yuan et al., 2015). Most of them (Hu et al., 2012; Wang et al., 2015; Yuan et al., 2015) were based on stations not on sub-basins, consequently ignored the fact that what can effect on runoff in a basin is the regional average within the basin, not any single station, this gap should be bridged to better understand the runoff contribution of a basin. Lan et al. (2010) studied the changes of average temperature from 1959 to 2008 in the SRYR and its three sub-region such as the head river area, the runoff producing area and the downstream area, dividing simply according to their different underlying surfaces. They found the annual mean temperature increasing at the rate of 0.32°C $(10\,\mathrm{yr})^{-1}$, 0.30°C $(10\,\mathrm{yr})^{-1}$, 0.32°C $(10\,\mathrm{yr})^{-1}$ and 0.41°C $(10\,\mathrm{yr})^{-1}$ respectively for the SRYR, the riverhead, the runoff producing and the downstream areas, indicating that the low elevation sub-region has the larger rising extent of temperature. However, the way they divided sub-regions is not strict because catchments are determined directly by the water flow route, not the underlying surface and only annual Tavg changes were analyzed. Moreover, Lan et al. (2010) and Yuan et al. (2015) used the datasets only until 2008 and 2010 respectively, and the temperature may have changed significantly in recent years. Therefore, it is necessary to study longer dataset in which recent years are covered.

Thence, to comprehensively understand the features of temperature changes and to provide scientific knowledge for water resource management in the SRYR and its sub-basins, this study aimed to reveal the absolute changes and trends of Tmax, Tmin, Tavg, and DTR by using the observed daily temperature dataset from 1965 to 2014. This study complements previous work by including recent time series of data and analyzing the variation characteristics on both annual and four standard seasons in the SRYR and its four sub-basins. As to the best of our knowledge, this is the first most comprehensive sub-basins analysis of temperature changes for the SRYR and its sub-basins.

2. Materials and methods

a. Study area

The SRYR or its Sub-basins Tangnaihai, Maqu, Jimai and Huangheyan is situated in the northeast of Qinghai-Tibet Plateau. The SRYR, is surrounded by mountains in the north and south and highlands in the west. The drainage area of the SRYR (upstream of the Tangnaihai hydrological station) is 121,972 km^2. Since the SRYR supplies 35% of the total annual flow with 15% area of the total Yellow River Basin, it is also reputed as “Water Tower”. The elevation in the SRYR decreases from west to east direction with the maximum altitude of 6253 m and minimum of 2666 m. Among sub-basins, Tangnaihai lower altitude sub-basin, has a great elevation change from 2666 m to 6253 m because the low elevation drainage outlet of the SRYR and the highest elevation of Anyemaqen Mountains exist in this sub-basin. Most of the higher altitude areas of the basin is situated in the Jimai and Huangheyan sub-basins. Permanent snow covers and 58 glaciers, accounting for 95.8% of total glacier areas (134 km^2) in the SRYR are in Tangnaihai sub-basin, (Meng et al., 2016). About 5300 lakes with total area of 2000 km^2 exist in the SRYR and 4000 lakes including two big lakes Gyaring (550 km^2) and Ngoring (610 km^2) are located at Huangheyan sub-basin (Hu et al., 2011; Li et al., 2013). Moreover, the land surface in this region is characterized by glaciers, snow, lakes and frozen soils. The vegetation type is mostly grassland, covering 80% of this region. Climatically, the SRYR is cold and semi-humid that is described by wet summer and dry winter. The climate conditions vary within the study area. The southern and eastern plateau is dominated by the southwest monsoon from the Indian Ocean and the southeast monsoon from the Pacific Ocean, respectively (Li et al., 2010). The southwest monsoon from the Indian Ocean is strong in summer and weak in winter, so the south of this region is warm and wet in summer, dry and cold in winter. The annual average rainfall in the SRYR is about 530 mm yr^{-1}. The potential evaporation ranges from 800.0 to 1200.0 mm yr^{-1}. From the southeast to the northwest annual average temperature changes between 2°C and −4°C (Hu et al., 2011).

b. Database and temperature time series

Figure 1 indicates geographical location of the meteorology stations and characteristics of study area. Most recent record of daily maximum, minimum and average temperature of 11 stations have been collected from China Meteorological Administration. As each station has different length of record due to station installation time, the data in the period of 1965 to 2014 were used to perform the proposed objective. DTR was computed by subtracting the Tmin from Tmax. The quality of the recorded climatic data such as identifying outliers, looking for missing values and also administering the internal consistency test was primarily important. To ensure the quality of the deployed datasets, outliers from data were fixed with the nearest stations records and missing observations were completed by their nearby stations that have high correlations with the simple linear regressions. The homogeneities of all stations maximum and minimum temperature series were inspected by double mass curve method (Tabari et al., 2011). It is a graphical method to find or adjust the inconsistent records of the station by plotting its accumulated records with the other station or an average accumulated record of several stations. Bends or non-linearity can be the signs of reposition of the station or change of the instrument (Buishand, 1982). Results of the double mass curves for all stations are straight lines, and no apparent breakpoints were found in the time series of maximum and minimum temperatures (Fig. 2). This confirms that all the deployed datasets are reliable.

In order to obtain the characteristics of the air temperature at sub-basin scale, the whole study area was divided into four sub-basins on the basis of four hydrological stations, the named as Tangnaihai, Maqu, Jimai and Huangheyan (Fig. 1). In this study, we used daily temperature data for the period of 1965-2014, which are divided into two periods between 1965 to 1989 and 1990 to 2014 to make the comparison before and after 1990. As it was found in a previous study of China (Qi and Wang, 2012), the year 1990 can be considered as a turning point for trend analysis of temperature. Additionally, Lan et al. (2010) found in the SRYR, runoff has been decreasing continuously since 1990 because the precipitation in the runoff producing area (Maqu sub-basin) obviously decreases and the annual average temperature continuously rises. Areal annual and seasonal temperature time series of Tmax, Tmin, Tavg and DTR for the SRYR and sub-basins in all the periods including 1965-2014, 1965-1989 and 1990-2014 were derived by using the Thiessen polygon method. This method has been widely used to estimate the areal average from observation data for hydrology and meteorology variables (Shi et al., 2016; Yuan et al., 2015). The detail of this method is well documented in Thiessen (1911) and Brassel and Reif (1979). This method assumes that at any point in the basin, temperature is equal to

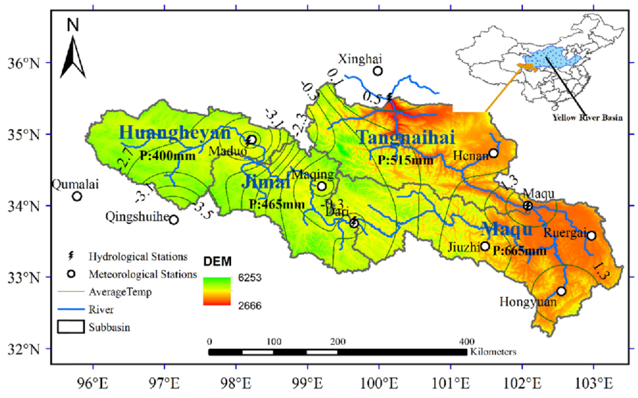

Fig. 1. Source Region of the Yellow river (SRYR) location, river, elevation, hydro and meterological stations and climatic characteristics. Black boundaries represent the four sub-basins (Tangnaihai, Maqu, Jimai and Huangheyan) and P represent their average annual precipitation. Average temperature contour are also indicated.

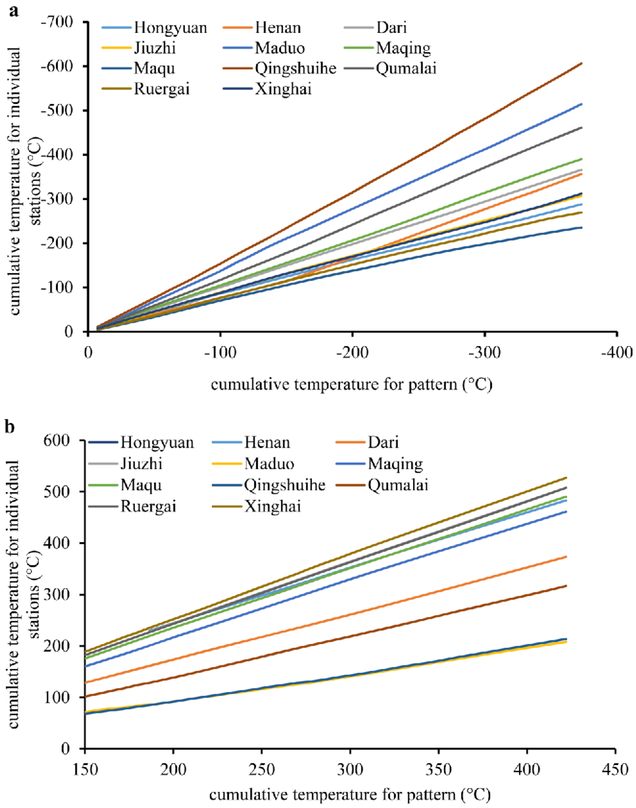

Fig. 2. The double-mass curve for all stations showing homogeneity in temperature data series a) Minimum temperature b) Maximum temperature.

Fig. 3. Intersection of the SRYR sub-basins with stations and associated Thiessen polygons. The weighing factors of each station polygon in their respective sub-basin are showing in the table.

Table 1. Meteorological station weighing factors corresponding to their sub-basins where, A_i is the area defined by intersection of Thiessen polygon and sub-basins boundary; S_i is Thiessen-based station weight, A_i/A_t; T_i is the values of temperature variable (Tmax, Tmin, Tavg and DTR) for considered Periods.

Basin Area, At (km^2)	Station	Bisectional Area, A_i (km^2)	S_i	T_i
Tangnaihai 34823.3	Maduo	803.84	0.02	Mean annual and seasonal values for each station
	Dari	1044.61	0.03	
	Xinghai	9030.92	0.26	
	Jiuzhi	152.81	0.004	
	Maqu	2041.77	0.06	
	Henan	15051.92	0.43	
	Maqing	6697.43	0.19	
Maqu 41635.7	Dari	9564.36	0.23	Mean annual and seasonal values for each station
	Jiuzhi	11053.23	0.27	
	Maqu	4208.52	0.10	
	Ruergai	6698.81	0.16	
	Hongyuan	8390.50	0.20	
	Henan	237.01	0.01	
	Maqing	1483.24	0.04	
Jimai 22229	Maduo	5084.18	0.23	Mean annual and seasonal values for each station
	Dari	6251.43	0.28	
	Maqing	9495.70	0.43	
	Qingshuihe	1397.71	0.06	
Huangheyan 23284	Maduo	11917.78	0.51	Mean annual and seasonal values for each station
	Qumalai	5736.85	0.25	
	Qingshuihe	5629.49	0.24	

that of the nearest station and allows a graphical depiction of the relative influence of each station on a given area or sub-basin. Since some of the sub-basins such as Huangheyan have only one station, so the stations from surrounding area have been included. The polygons shown in Figure 3, are graphically weight point values (such as temperature, provided in Table 1) over an area. Moreover, to keep the originality in annual and seasonal regional temperature time series, the elevation effect was not considered. Finally, 300 time series were obtained ($3 \times 4 \times 5 \times 5 = 300$, where 3 represents the numbers of periods, 4 represents the number of temperature variables, 5 represent the seasons and annum and 5 represents the number of basins including sub-basins).

c. Methods

In this study two analyses were performed. First, absolute temperature change was analyzed to evaluate if patterns in absolute change exist or not. Second, trend analysis was performed to evaluate if the trends are statistically significant and if patterns in trends across the basin area can be identified. Parametric or nonparametric statistical tests can be used to decide whether there is a statistically significant trend or not. The application of these tests simultaneously and non-simultaneously were found to be useful in various previous studies, such as the studies of Colorado River Basin (Miller and Piechota, 2008), Mangla Watershed in Pakistan (Yaseen et al., 2014) and Calabria region in Southern Italy (Caloiero et al., 2011). For trend analysis nonparametric Mann Kendall test has been used often for this region while other tests Spearman (nonparametric) and Pearson (parametric) were also used in this study.

(1) Evaluation of absolute temperature changes

Absolute changes were evaluated in the 2nd period (1990-2014) compared to 1st period (1965-1989) for annual and seasonal air temperature series. Statistical tests such as *F*-test and Student's *t* test (parametric) and Mann Whitney (MW) test (nonparametric) were applied to determine the difference between two sub periods either significant or not at 0.05 significance level. According to equal or unequal variances (i.e., *F*-test), test statistics of student's *t* test for differences between means of the datasets of two sub periods was computed. The null hypothesis, H_o means difference = 0, was rejected or absolute change in the 2nd period was considered statistical significant if the computed test statistic *t* is higher than the t_{crit} or $P < 0.05$, i.e. significance level with degree of freedom $2n - 2$, where n is number of participants of each period. MW test is often used to determine whether medians are different or not between datasets (Nachar, 2008). Mathematically, the Mann-Whitney U statistics are defined by the following formulas, for each dataset:

$$U_1 = n_1 n_2 + \frac{n_1(n_1+1)}{2} - R_1 , \tag{1}$$

$$U_2 = n_1 n_2 + \frac{n_2(n_2+1)}{2} - R_2 , \tag{2}$$

Here n_1 is the number of observations or participants in the first period, n_2 is the number of observations or participants in the second period, $R1$ is the sum of the ranks assigned to the first period and $R2$ is the sum of the ranks assigned to the second period. Here for statistical significance, the null hypotheses $H_{o,}$ median difference = 0, was rejected if P resultant to (U_1, U_2) (the smallest value of U both calculated) is smaller than $\alpha = 0.05$ i.e. significance level or threshold. {Reject H_o if P of min (U_1, U_2) < α}. Furthermore, decadal absolute changes were also evaluated and compared to 1st decade using annual temperature series.

(2) Trend diagnosis of the air temperature

Trend analysis was performed on the regional annual and seasonal time series to identify the trends and also to verify whether the trends are statistically significant or not. The steps which necessarily require; checking the serial correlation effect, trends detection by Mann Kendall (M-K) test, Spearman test and Pearson test, and trend magnitude estimation by Sen's estimator. Before applying statistical test, the existence of positive or negative serial correlation is essential to consider as it increases or decreases the chance of detecting the significance trend using MK test. Among all considered temperature variables time series, 16% time series have been found serially correlated. In the Tangnaihai sub-basin, more than 60% serial correlated temperature time series were found for different variables as well as for different periods. As to develop regional annual and seasonal temperature time series for the Tangnaihai sub-basin, the Xinghai, Henan, Hongyuan, Jiuzhi, Dari, Maqing and Maqu stations data and their contributing areas to sub-basin and most of these stations temperature time series have already been found serially correlated e.g., Xinghai, Henan, Hongyuan and Jiuzhi annual mean minimum temperature series are serially correlated (Hu et al., 2012). Von Storch (1995) has suggested a pre whitening technique to limit the effect of serial correlation from time series such as lag-1 autoregressive process. This pre-whitening also removes a part of the trend which may cause to accept the null hypothesis of no trend whereas this hypothesis might be wrong as revealed by Yue et al. (2002b). To detect a trend accurately, a trend-free pre-whitening (TFPW) technique that is widely applied by many researchers in different fields (Cao and Ma, 2009; Ahmad et al., 2015) has been used before using the MK test. Thus, the true trend is preserved in time series and is no more affected by the serial correlation effect.

Mann Kendall test (Mann, 1945; Kendall, 1975) and Theil-Sen estimator (Sen, 1968) have been regarded as excellent tools for the detection and magnitude of trends in climatic and hydrologic time series (Nalley, 2013; Tabari et al., 2012; Gu et al., 2012; Mavromatis and Stathis, 2011; Bhutiyani et al., 2007). MK test and Sen's method have advantages comparative to linear regression that the data do not need to be confirmed by any particular distribution and also allowed to missing values.

The null hypothesis (H_o) assuming no trend was established against the alternate hypothesis (H_1) of continuous increasing or decreasing trend using the MAKESENS programme developed by Salmi et al. (2002). MAKESENS programme has been widely used by many researches to detect trends and its magnitude in climatic parameters such as temperature and precipitation (Safeeq et al., 2013; Abbas et al., 2014). The details of the MAKESENS programme can be obtained in the literature (Salmi et al., 2002). Warming (increasing) and cooling (decreasing) trends were detected by positive and negative value of standardized statistics Z and for statistically significance of trend, H_o is rejected when absolute value of Z is larger than $Z_{1-\alpha/2}$ in a two-tailed test at significance level $\alpha = 0.05$ (Safeeq et al., 2013).

Spearman's test same as the MK test, since it is rank based non-parametric test to observe trends in time series. But, unlike the MK test, it defines the correlation of the data with time instead of the other values within the time series (Miller and Piechota, 2008). The correlation coefficient r_s or test statistic and the standardized test statistic Z_{SR} are described by:

$$r_s = 1 - \frac{6\sum_{k=1}^{n}(D_k - i)}{n(n^2-1)} \tag{3}$$

$$Z_{SR} = r_s\sqrt{\frac{n-2}{1-r_s^2}} \tag{4}$$

Here D_k is the rank of kth observation X_k in the time series data and n is the total length of the temperature time series. Z_{SR} is student's t-distribution with degree of freedom ($n - 2$). Like the MK test, Z_{SR} can be compared to a normal probability table to derive level of significance.

A parametric linear trend test (Pearson t test) analog of the Spearman test was also used in this study. Like Spearman's test, it also defines the correlation between data and time. Pearson's coefficient and standardized test statistic same as Spearman rank test are as follows:

$$r = \frac{\Sigma xy - N\bar{x}\bar{y}}{\sqrt{(\Sigma x^2 - N\bar{x}^2)}\sqrt{(\Sigma y^2 - N\bar{y}^2)}} \tag{5}$$

$$Z_{SR} = r\sqrt{\frac{n-2}{1-r^2}} \tag{6}$$

Here x represents the year and y represents the temperature value of that year. Like Spearman's test, the test statistics Z_{SR} can be compared to a normal probability table to derive level of significance.

Above applied statistical tests provide information about the trend without any quantify the magnitude. If a linear trend exists in time series, then true slope of the trend can be computed by non-parametric method established by Sen (1968) using the MAKENSENS programme. Sen's slope for consistently decreasing and increasing time series $f(t)$ is computed as:

$$f(t) = Qt + B \tag{7}$$

Here B and Q are intercept and slope of linear trend $f(t)$, respectively. To determine Q, first slope estimates of each data pair are determined by following equation:

$$Q_i = \frac{x_j - x_k}{j-k} \quad if\ j>k \tag{8}$$

If the time series contain n values of x_j, then slope estimates Q_i will be$[N = n\ (n-1)/2]$. N values Q_i can be ranked from smallest to largest to get the median for Q_i. If N is odd number, then Sen's estimator slope is

$$Q_{med} = Q_{\left(\frac{N+1}{2}\right)}\,. \tag{9}$$

If N is even number, in that case Sen's estimator slope is

$$Q_{med} = \frac{1}{2}[Q_{\frac{N}{2}} + Q_{\frac{N+2}{2}}]\,. \tag{10}$$

3. Results

a. Absolute temperature changes in the SRYR and its sub-basins

The magnitude of absolute changes for Tmax, Tmin, Tavg and DTR in the 2nd period compared with the 1st period and their significance obtained by Mann Whitney U test, Student's t test and F test at the 95% confidence level- presented in different signs showed in Table 2. Most of the absolute changes were significant, especially for Tmax, Tmin and Tavg. Annual Tmax, Tmin, and Tavg increased by 0.63°C, 0.92°C and 0.77°C respectively, while annual DTR decreased by 0.29°C in the SRYR. Tmin has higher magnitude of absolute changes than the other temperature variables on both annual and seasonal scale. The highest absolute changes magnitude of Tmax, Tmin and Tavg were found in winter followed in order by autumn, summer and spring, while those for DTR were observed in spring followed in order by winter, summer and autumn. In addition, more absolute changes of Tmax, Tmin and Tavg took place within Huangheyan, Jimai and Maqu sub-basins. The highest magnitude of Tmax was found within Huangheyan followed in order by Jimai and Maqu on both annual and seasonal scales except in summer where observed change was more in Jimai. The highest magnitude of Tmin happened within Huangheyan followed in order by Maqu and Jimai in winter and autumn, while in spring and autumn Tmin change magnitude was more happened within Maqu followed in order by Jimai and Huangheyan. The highest magnitude of Tavg happened within Huangheyan followed in order by Maqu and Jimai during spring and autumn, and in winter followed in order by Jimai and Maqu, and within Maqu followed in order by Huangheyan and Jimai during summer. The highest magnitude of DTR was found within Maqu followed by Tangnaihai on both annual and seasonal scales. The significant decrease of DTR's absolutes in winter and spring was higher because that increased absolute changes of Tmin's more than Tmax's in these seasons.

Figure 4 depicted the decadal absolute changes of Tmax, Tmin and Tavg and DTR in the SRYR and its sub-basins. Decadal change revealed that Tmax, Tmin and Tavg were increased continuously for the SRYR and its sub-basins and their values were rapidly increased nearly as an exponential curve. The annual average temperature was decreasing in the SRYR and its sub-basins from 1975 to 1984 but shifted toward increasing from 1995 while the values of last decade from 2005 to 2014 were nearly two times as those of the decade from 1995 to 2004. Last two decades results of Tmax and Tmin for the SRYR and its sub-basins demonstrated that both Tmax and Tmin have presented of increasing changes with the higher rate in Tmin than Tmax. Hence, the observed decrease in DTR is mainly because of the increase in Tmin (Fig. 4d). In high altitude sub-basins Huangheyan and Jimai, last decade changes for Tmax and Tmin were higher as compared to other sub-basins, even almost two times of recent decade (1995-2004). DTR decadal change towards decreasing remains consistent and its magnitude in the SRYR, Jimai and Huangheyan decreased decade by decade from 1975 to 2004, and increased rapidly in the decade from 2005 to 2014 with nearly the same magnitude in the decade of 1975-1984. In Tangnaihai, Tmax

Table 2. Absolute Changes (°C) of temperature in the SRYR and sub-basins during the 2nd period (1990-2014) compared to the 1st period (1965-1989).

Basins	Annual	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)
Tmax					
SRYR	*___0.63___	*__0.90__	0.15	*__0.69__	*__0.77__
Tangnaihai	0.23	0.26	–0.24	*__0.49__	0.40
Maqu	*___0.61___	*__0.86__	0.10	*__0.73__	__0.76__
Jimai	*__0.86__	*__1.23__	0.43	*__0.83__	*__0.95__
Huangheyan	*__1.01__	*__1.58__	0.53	*__0.79__	*__1.16__
Tmin					
SRYR	*__0.92__	*__1.19__	*__0.73__	*__0.89__	*__0.85__
Tangnaihai	0.21	–0.10	0.18	*__0.49__	0.25
Maqu	*__1.27__	*__1.73__	*__1.15__	*__1.14__	*__1.05__
Jimai	*__1.05__	*__1.49__	*__0.78__	*__0.96__	*__0.98__
Huangheyan	*__1.16__	*__1.79__	*__0.69__	*__0.92__	*__1.24__
Tavg					
SRYR	*__0.77__	*__1.01__	*__0.47__	*__0.79__	*__0.82__
Tangnaihai	0.22	0.003	0.02	*__0.55__	0.30
Maqu	*__0.95__	*__1.27__	*__0.66__	*__0.91__	*__0.94__
Jimai	*__0.91__	*__1.32__	*__0.56__	*__0.82__	*__0.93__
Huangheyan	*__1.12__	*__1.69__	*__0.67__	*__0.89__	*__1.23__
DTR					
SRYR	–0.29	–0.29	__–0.58__	–0.19	–0.08
Tangnaihai	0.02	0.35	–0.42	0.001	0.15
Maqu	*__–0.66__	*___–0.87___	*__–1.05__	–0.41	–0.30
Jimai	–0.19	–0.26	–0.36	–0.13	–0.03
Huangheyan	–0.15	–0.22	–0.17	–0.13	–0.08

*, Bold and italic showed significant change with Mann Whitney U test, Student's t test and F test respectively at 95% confidence level

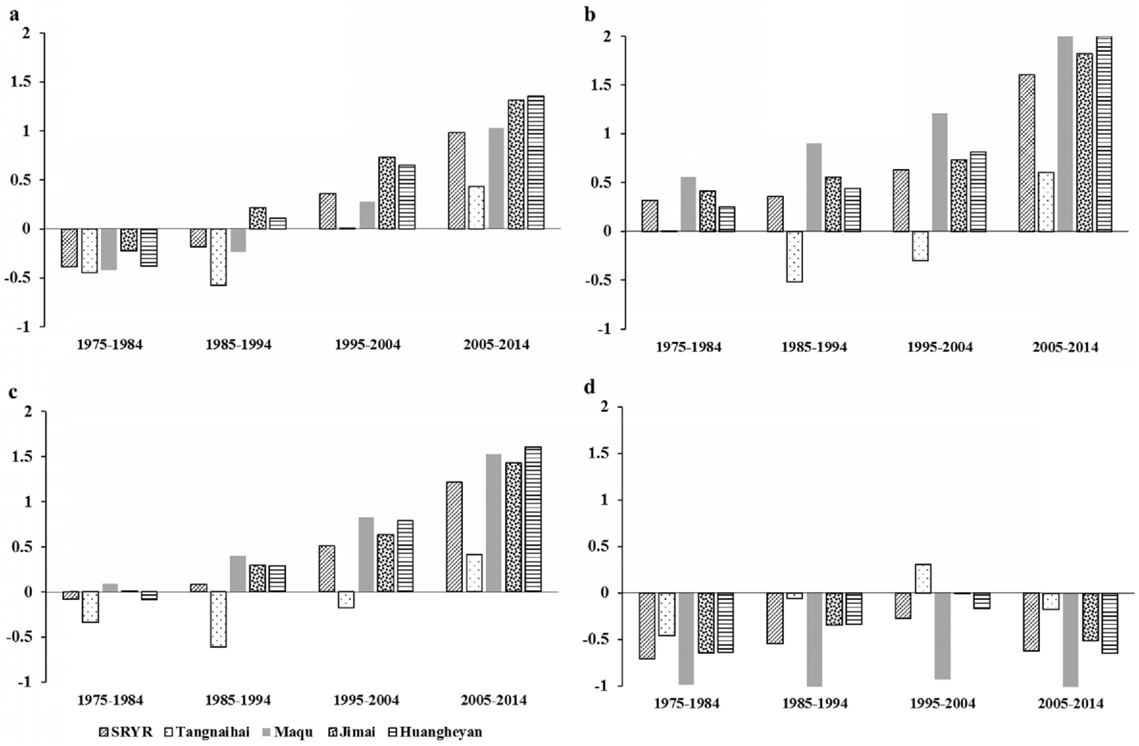

Fig. 4. Decadal Absolute changes (°C) of Annual (a) Tmax (b) Tmin (c) Tavg and (d) DTR compared to their values in the decade of 1965-1974.

and Tmin had the opposite trends in the decades of 1985-1994 and 1995-2004, and DTR had opposite trend in the decade 1995 to 2004 as compared to the other sub-basins.

b. Trend changes

Annual and seasonal time series of Tmax, Tmin, Tavg and DTR for the SRYR and sub-basins are showed in Fig. 5 and linear trends for each time series superimposed in the figure. Tmax, Tmin and Tavg showed increasing while DTR presented decreasing trends however Tmin had higher increasing gradient compared to the others temperature variables. This higher increasing gradient of Tmin over Tmax could lead to the decreasing trend of DTR time series. These statuses occurred in the SRYR and its all sub-basins.

The magnitude of trends (the true slopes) of annual and seasonal Tmax, Tmin, Tavg and DTR for the SRYR and its sub-basins were calculated by Sen's slope method, and their significance were examined by MK test, Pearson t test, and Spearman test at the 95% confidence level (Table 3). The significant trends were marked by showing the results of corresponding Sen's slope results with *, bold and italic symbols. The analyses were carried out for the three study periods have been already explained.

Annual Tmax, Tmin and Tavg showed a positive significant trend in the SRYR basin at the rate of 0.28°C, 0.36°C and 0.31°C $(10\,\mathrm{yr})^{-1}$ respectively, while annual DTR showed a negative insignificant trend at the rate of 0.05°C $(10\,\mathrm{yr})^{-1}$ during the period of 1965-2014. The trends for the SRYR were much higher in the 2nd period for Tmax, Tmin and Tavg than the 1st period.

For sub-basins, annual Tmax, Tmin and Tavg presented the significant increasing trends for the whole and 2nd period as well. Trends in sub-basins during the 2nd period were more pronounced with high rates than that of whole and 1st period. The greatest increase of trend magnitude in annual temperature variables, was the trend for Tmin (0.86°C decade^{-1}) that occurred in Huangheyan during the 2nd period. Annual Tmax, Tmin and Tavg were consistent to keep warming trends in Maqu, Jimai and Huangheyan while consistent cooling trends observed during the 1st period in Tangnaihai. In the 1st period, DTR showed significant decreasing trends in all sub-basins except Tangnaihai which exhibited insignificant decreasing trend, while in 2nd period DTR showed increasing trends in Maqu and Jimai.

On seasonal scale, all temperature variables except DTR showed increasing trends during the whole and the 2nd periods while increasing or decreasing trends during the 1st period over the SRYR and its sub-basins. Mostly changes in Tmax and Tmin were noticed in winter during the 2nd period but the rates of trends were significant and higher for Tmin than Tmax. In contrast to the 2nd period, Tmax showed insignificant decreasing trend during the 1st period in the SRYR and its all sub-basins except spring Tmax in Tangnaihai, while it presented significant increasing trends in the 2nd period except Tangnaihai sub-basin. Consistently significant increase

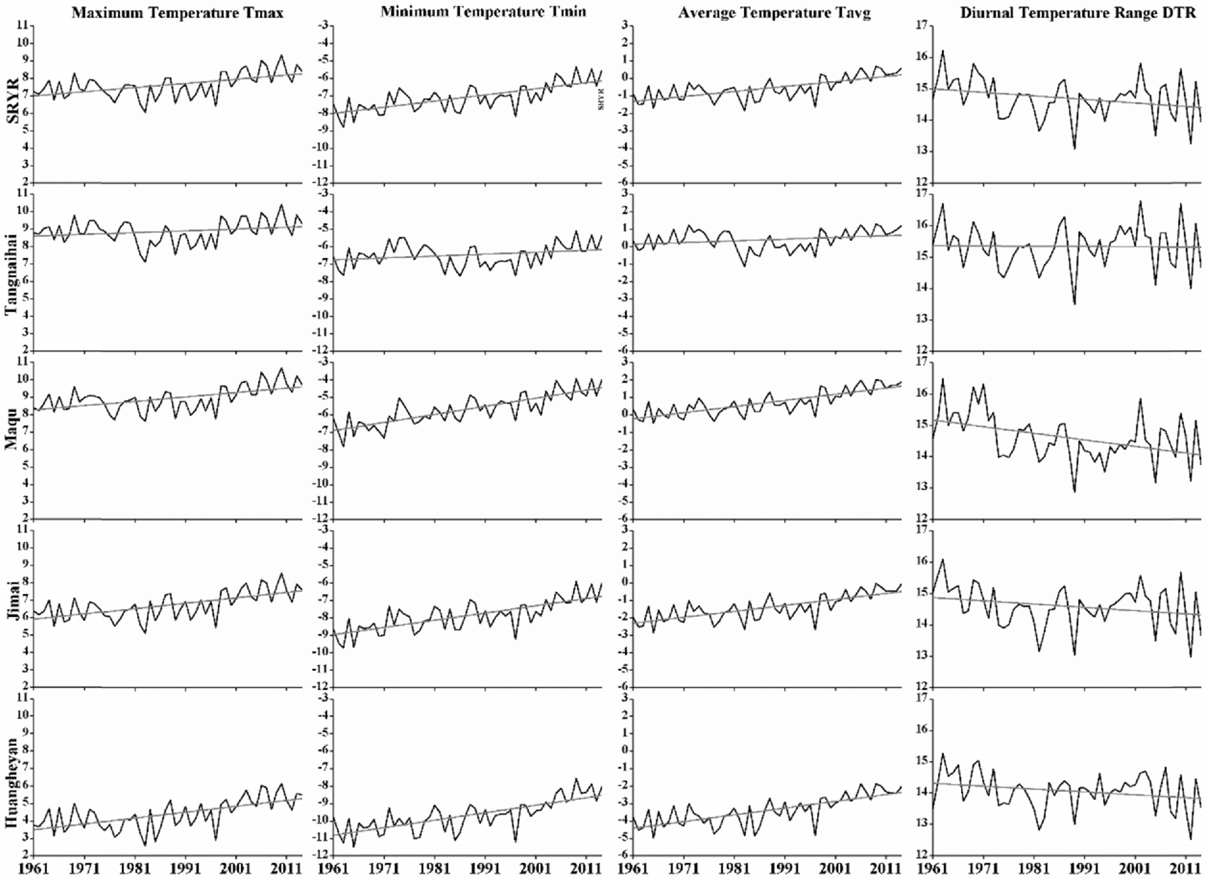

Fig. 5. Time series of annual Tmax, Tmin, Tavg and DTR (°C) for the SRYR and its sub-basins and their linear trends.

of Tmin in all seasons during the 1st period was observed in Maqu and Jimai sub-basins, which caused the increase in Tmin during this period for the SRYR. With remarkable increase in the 2nd period, the trend analysis for winter temperatures in the period of 1965-2014 depicted that Tmax, Tmin and Tavg in the SRYR were increasing at the rate of 0.35, 0.46 and 0.37°C, respectively and DTR was decreasing at the rate of 0.09°C $(10\,\mathrm{yr})^{-1}$. Winter Tmax, Tmin and Tavg were also increased in all sub-basins and the highest increasing trends at the rate of 0.52°C, 0.63°C and 0.56°C $(10\,\mathrm{yr})^{-1}$ respectively, occurred in Huangheyan (a high altitude sub-basin). Spring Tmax presented higher rates of trends than Tmin and Tavg during the 2nd period which was contrary to winter. Overall during the 1st period, Tmax and Tmin in spring followed the same trend as in winter except that Tmax showed significant decrease (−0.81°C decade^{-1}) in Tangnaihai and Tmin showed an increase in Maqu and Jimai. The analysis of the 1st period for summer and autumn temperature depicted that Tmax, Tmin and Tavg increased in all sub-basins except Tangnaihai.

Tmax, Tmin and Tavg in all seasons except spring Tmin displayed significant increasing trends during the 2nd period in the SRYR and its sub-basins. In winter and summer, the highest trends of Tmin and Tavg occurred in Jimai followed by Huangheyan, while the highest trend of Tmax happened in Huangheyan followed by Maqu. In spring and autumn, the highest trends of Tmax and Tavg occurred in Maqu, and the highest trend of Tmin happened in Huangheyan. The largest decreasing trends of DTR in the winter, spring and summer all occurred in Maqu, while that in autumn occurred in Huangheyan.

To ascertain the warming rates in particular sub-basins were uniform throughout the last decades or not, decade-to-decade rates were figured.

Tmax trends in the SRYR, Jimai and Huangheyan were higher in the decade from 1995 to 2004 as compared to other decades. While in last decade from 2005 to 2014, Tmax showed decreasing trend in the SRYR and its all sub-basins with significant decrease in Tangnaihai sub-basin at the rate of 0.07°C yr^{-1} (Fig. 6a). The change per year in Tmin was positive in the SRYR and its sub-basins except Tangnaihai, and Maqu showed negative trends in the 2nd and 5th decades. The decadal trends in Tmin were positive and largest in the SRYR and its sub-basins from 1965 to 1974 and after that, magnitudes of decadal trends in Tmin were smaller and in some sub-basins became negative (Fig. 6b). The trends of Tavg showed increase in the 1st decade from 1965 to 1974 in the SRYR and its sub-basins as compared to other decades. The trends of Tavg during the last decade from 2005 to 2014 were

Table 3. Annual and seasonal trends of temperatures (°C decade^{-1}) in the SRYR and sub-basins for three periods: 1965-2014, 1965-1989 and 1990-2014 by using Sen's slope.

Basins	**Maximum Temperature**			**Minimum Temperature**			**Mean Temperature**			**Diurnal Temperature Range**		
	1965-2014	1965-1989	1990-2014	1965-2014	1965-1989	1990-2014	1965-2014	1965-1989	1990-2014	1965-2014	1965-1989	1990-2014
Annual (J-D)												
SRYR	***0.28****	–0.09	***0.65****	***0.36****	**0.32**	***0.71****	***0.31****	0.10	***0.63****	–0.05	***-0.38****	0.08
Tangnaihai	0.11	–0.23	***0.54****	**0.07**	–0.18	***0.72****	***0.11***	***-0.28***	***0.57****	0.06	–0.22	–0.07
Maqu	***0.26****	–0.07	***0.72****	***0.48****	***0.58****	***0.64****	***0.39****	***0.27***	***0.62****	***-0.19****	***-0.57****	0.24
Jimai	***0.38****	0.16	***0.65****	***0.41****	***0.49****	***0.79****	***0.37****	0.27	***0.65****	–0.01	–**0.34**	0.08
Huangheyan	***0.41****	–0.01	***0.64****	***0.47****	0.38*	***0.86****	***0.44****	0.20	***0.65****	–0.06	–**0.35**	–0.07
Winter (DJF)												
SRYR	***0.35****	–0.17	***0.73****	***0.46****	0.23	***0.99****	***0.37****	0.04	***0.80****	–0.09	–0.43	–0.04
Tangnaihai	0.10	–0.30	***0.68****	*–0.01*	–0.38	***0.91****	0.01	–0.26	***0.76****	0.17	0.24	–0.15
Maqu	***0.34****	–0.05	***0.88****	***0.60****	***0.66****	***0.75****	***0.47****	0.42	***0.79****	***-0.32****	***-0.60***	0.16
Jimai	***0.45****	0.18	***0.82****	***0.61****	0.49	***1.24****	***0.52****	0.28	***0.96****	–0.06	–0.42	–0.22
Huangheyan	***0.52****	–0.11	***0.90****	***0.63****	0.20	***1.18****	***0.56****	0.07	***0.89****	–0.08	***-0.53***	–0.08
Spring (MAM)												
SRYR	0.13	–0.60	***0.57****	***0.24****	0.19	0.29	***0.21****	–0.24	***0.45****	–0.08	***-0.64****	0.42
Tangnaihai	0.02	–**0.81***	***0.59****	0.02	–0.13	0.23	0.04	***-0.54****	***0.42****	0.00	***-0.45***	0.48
Maqu	0.14	–0.49	***0.62****	***0.39****	***0.36****	0.33	***0.27****	–0.09	***0.50****	***-0.23****	***-0.73****	0.42
Jimai	***0.24****	–0.34	***0.59****	***0.25****	***0.29***	0.31	***0.24****	–0.08	***0.46****	–0.02	***-0.52****	0.38
Huangheyan	***0.25****	–0.35	***0.50****	***0.27****	0.31*	***0.54****	***0.28****	–0.03	***0.37***	–0.03	***-0.60****	0.13
Summer (JJA)												
SRYR	***0.27****	–0.05	***0.46****	***0.40****	0.35	***0.86****	***0.34****	0.16	***0.63****	–0.09	–0.29	–0.30
Tangnaihai	***0.17****	–0.23	**0.36**	***0.25****	0.07	***0.85****	***0.24****	–0.03	***0.57****	–0.05	–0.30	–0.33
Maqu	***0.29****	0.06	***0.47****	***0.49****	***0.56****	***0.84****	***0.40****	0.32	***0.62****	–**0.15**	***-0.37****	–0.11
Jimai	***0.31****	0.14	***0.44****	***0.44****	0.44	***0.96****	***0.36****	0.23	***0.68****	–0.09	–0.27	–0.34
Huangheyan	***0.30****	0.07	***0.52****	***0.44****	0.23	***0.93****	***0.38****	0.15	***0.67****	–0.10	–0.22	–0.26
Autumn (SON)												
SRYR	***0.39****	0.34	***0.44****	***0.39****	0.55	***0.71****	***0.39****	0.27	***0.55****	–0.01	–0.21	–0.23
Tangnaihai	***0.21****	–0.05	***0.37***	0.16	0.05	***0.80****	***0.18****	–0.11	***0.54****	0.06	–0.16	–0.50
Maqu	***0.42****	0.28	***0.59****	***0.45****	***0.72****	***0.53****	***0.45****	0.32	***0.57****	–0.03	–0.43	0.08
Jimai	***0.46****	**0.62***	0.37	***0.42****	***0.77****	***0.73****	***0.42****	0.48	***0.50****	0.04	–0.17	–0.31
Huangheyan	***0.49****	0.74*	0.29	***0.57****	0.73	***0.95****	***0.51****	*0.70**	***0.55****	–0.06	–0.04	***-0.57****

*, Bold and italic showed significant trend with Mann Kendall, Pearson t test and Spearman test respectively at 95% confidence level.

smallest than other decades (Fig. 6c). The decadal trends of DTR were quite different from Tmax, Tmin and Tavg trends. The DTR decreased from 1965 to 1994 and then increased significantly in the 4th decade while decreased again in last decade in all sub-basins. Moreover, decadal trends of DTR were smaller in 2nd and 5th decade compared to others decades (Fig. 6d).

4. Discussion

a. Results of statistical tests

Parametric trend tests are more powerful than non-parametric ones; however, they require data to be independent and normally distributed. On the other hand, non-parametric trend tests require only data to be independent and can tolerate outliers in the data (Shadmani et al., 2012). In Table 2, Mann Whitney U test, Student's t test and F test all agree over the significances of absolute changes for Tmax, Tmin, Tavg and DTR during the period of 1990-2014 compared to 1965-1989. It examined that total 63 out of 100 values were marked as significant at the 95% confidence level. The analogous values for absolute change of temperature variables by Mann Whitney U and student t tests were 61% and 63%, respectively. Therefore, these tests had almost similar performance at the 95% confidence level and use of F test seems very strict with only 3% of significant values.

Mann Kendall test, Spearman test and Pearson t test used to

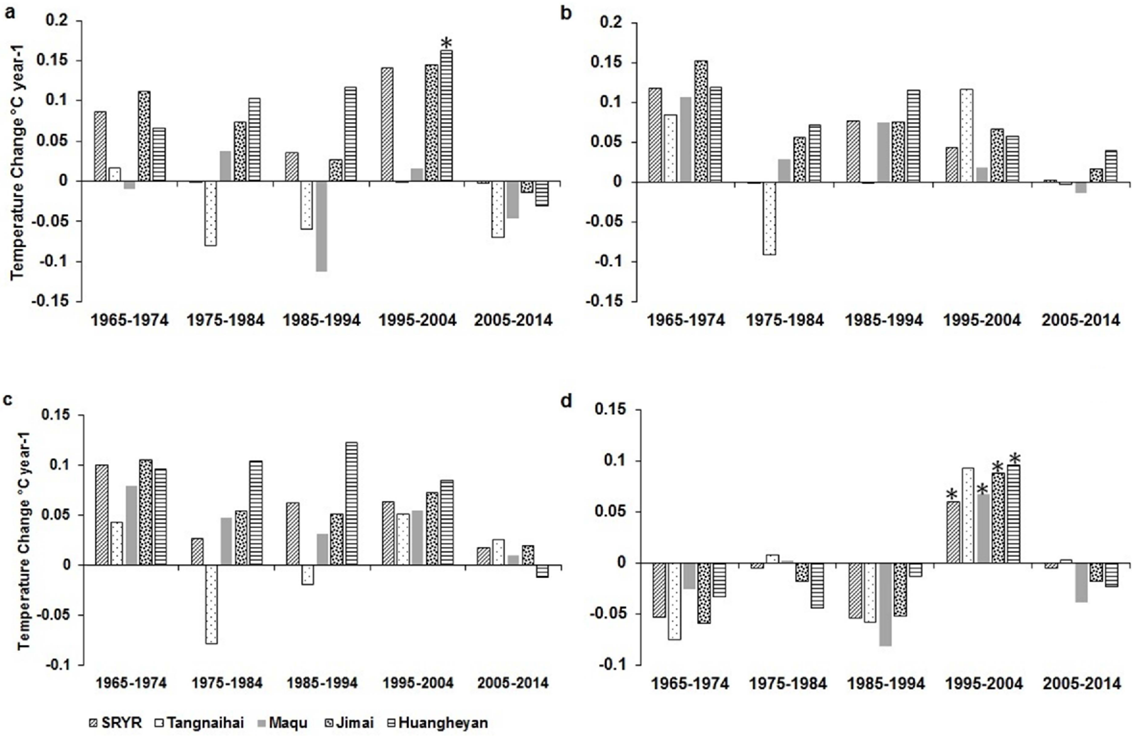

Fig. 6. Decadal trends in annual (a) Tmax, (b) Tmin (c) Tavg and (d) DTR. * Sign on bars showed trend are significant by Mann Kendall test at 5% significant level.

check the significant trends of Tmax, Tmin, Tavg and DTR (Table 3). Total 170 out of 300 values were detected significant at 95% confidence level while 148 out of these 170 values passed all the significance tests of these three methods. Individually 154, 158 and 165 values passed the significance tests by MK, Spearman and Pearson tests, respectively. The weighted values of Mann Kendall, Spearman and Pearson tests for detection of trends were 51%, 52% and 55% respectively. Therefore, Mann Kendall and Spearman tests had comparable performance at the 5% significant level for the analysis of trends. In situations where the detection of significance by two tests was not similar, values of confidence level of trend acceptance presented low difference. Similar behavior of Mann Kendall and Spearman tests for trends analysis was also confirmed by Yue et al. (2002a).

b. Spatial and temporal features of temperature variables in the SRYR and Sub-basins

The increasing trend of annual Tavg found for the SRYR was 0.31°C decade^{-1}, nearly the same as found by Lan et al. (2010). But they concluded that the lower elevation sub-region, experienced the larger rising extent of temperature. This conclusion is quite different from the results in our study as it was found that the rising extent of annual Tavg for sub-basins during 1965-2014 were 0.11, 0.39, 0.37 and 0.44°C decade^{-1} for Tangnaihai, Maqu, Jimai and Huangheyan respectively. The elevation in Huangheyan sub-basin is the highest, followed in order by Jimai, Maqu and Tangnaihai. This may be because Lan et al. (2010) simply divided the three sub-regions according to the different underlying surfaces in the SRYR, while we attracted four sub-basins considering the four hydrological stations as catchment outlets. Another reason may be the use of Thiessen polygon method to obtain the areal average temperature for every sub-basin, while there is no clear explanation on how they obtained the average temperature for regions.

It is very clear that most of the changes of Tmax, Tmin and Tavg occurred in the 2nd period in our analysis, and the increasing trends of Tmax, Tmin and Tavg were varying with sub-basins and seasons. The Huangheyan and Jimai sub-basins experienced higher seasonal variations and this result is in agreement with Wang et al. (2015). The temperature in mountains with snow cover has higher seasonal increasing trends than the global land average due to free-thaw cycle (Rangwala and Miller, 2012). However, winter and summer experienced higher increasing trend than spring and autumn. Continuous positive and high temperatures in winter and summer were also observed for the SRYR in the study conducted by Wang et al. (2015) but without pointing out the sub-basins which had higher trends in winter and summer. In winter and summer, the highest increasing trends of Tmax occurred in Huangheyan followed by Maqu whereas the highest increasing trends of Tmin and Tavg occurred in Jimai followed by Huangheyan. In spring and autumn, Tmax and Tavg had the highest increasing trends in Maqu while Tmin had the highest increasing trend in

Huangheyan followed by Maqu/Tangnaihai. Therefore, we tend to deduce that the larger magnitudes of increasing trends for Tmax, Tmin and Tavg in winter and summer were found in high elevated sub-basins named Huangheyan and Jimai, while they were found in spring and autumn in Maqu sub-basin which has low elevation. The sub-basins of Huangheyan and Jimai might be dominated by southwest monsoon from the Indian Ocean, which is strong in summer and weak in winter. In these sub-basins with higher elevation, there are more glacier, snow cover, and frozen soils which are mainly affected by temperature. If the temperature in winter and summer increases rapidly in a long time period, the runoff in these basins will decrease significantly due to the strong evapotranspiration in lake areas of Huangheyan sub-basin, and due to less accumulated solid water resources in winter and more consumed solid water resources in summer in the mountain areas. Additionally, an increasing temperature tendency in summer may lead to increase extreme high temperature intense and frequency, which may have bad impacts on human health (Yin et al., 2012) and livestock. This phenomenon requires the local government attentions to mitigate the related disasters.

DTR over Maqu sub-basin was decreasing from 1965 to 2014 though there was a little fluctuation in the process, which depicts good agreement with the results of Hu et al. (2012). The largest decreasing trends of DTR in the winter, spring and summer all were occurred in Maqu during the 1st period, while those in autumn occurred in Huangheyan during the 2nd period. Generally, except autumn, DTR in Maqu which is the wettest sub-basin in the SRYR, was decreasing more rapidly than in the other sub-basins during the period from 1965 to 2014 (Table 3). If DTR decreases, the evaporation capacity weakens, resulting in less precipitation. For wet sub-basin like Maqu, precipitation is an important source of runoff, when the precipitation decreases, the runoff in this sub-basin also decreases.

In addition, much larger increasing magnitude of Tmax, Tmin and Tavg were found after 1990. There might be two causes for the increasing trends of these temperature variables. 1) Decline in solar radiation up to 1990 and a widespread brightening since the 1990 (Martin et al., 2005), 2) dramatic land-cover changes along with rapid economic development in the past 30 years (Yin et al., 2015), which could be another reason to explain the results from sub-basin's environment point. The increasing trends of temperature variables imply that the runoff might decrease rapidly after the mentioned year. This deduction is consistent with the results found by Yuan et al. (2015) that the runoff in the SRYR is decreasing rapidly since 1990. Though the relationship between runoff and temperature is complicated, this can support the results we found in this study.

The absolute values of Tmax, Tmin and Tavg were increasing rapidly with decades but the trends in the last ten years (2005-2014) slowed down and even reversed, such as Tmax in the SRYR and all its sub-basins, and Tavg in Huangheyan (Figs. 4 and 6). It implies that there were obvious decadal fluctuations in these temperature variables, consequently runoff in this basin might have correlated decadal fluctuations.

5. Conclusions

The main purpose of this study was to comprehensively understand the temperature variations in the Source Region of Yellow River and its sub-basins that would provide effective information for the water resources planning, development and its management under the climate change. This study was conducted by using temperature data of typical located meteorological stations during the period of 1965-2014. The whole period was divided into two periods i.e. 1965-1989 and 1990-2014 on the basis of previous findings. Tmax Tmin and Tavg data were aggregated to get mean annual and seasonal temperature time series of Tmax, Tmin, Tavg and DTR for the SRYR and sub-basins. Annual and seasonal changes of the absolute values of the temperature as well as the trends of temperature were analyzed during three periods: 1965-2014, 1965-1989 and 1990-2014. Decadal changes of annual temperature were also analyzed for the SRYR and its sub-basins. The following are some important conclusions.

Broadly, the results indicate warming temperatures during 1965-2014 in the SRYR. Both mean annual and seasonal temperatures (Tmax, Tmin and Tavg) experienced a significant increasing change in the SRYR. On the annual scale, the absolute change of Tmin towards increasing is highest in Maqu (1.27^{o}C) and lowest in Tangnaihai (0.21^{o}C) sub-basins. On the seasonal scale, the absolute change towards increase of winter Tmin (1.79^{o}C) is highest in Huangheyan (a high altitude sub-basin) and winter Tavg (0.003^{o}C) is lowest in Tangnaihai (a low altitude sub-basin). With the greatest variation from -0.66^{o}C to 0.02^{o}C between Maqu and Tangnaihai, the annual and seasonal DTR change remained toward decreasing in the SRYR and sub-basins except for Tangnaihai. The change towards an increase in summer seems more significant than those in the other three seasons. The greatest magnitudes of the increase in temperature occurred in winter while smallest in spring. As a whole, among sub-basins Maqu and among seasons, summer have more significant changes.

Trend analysis revealed that trends of Tmax, Tmin and Tavg changed prominently during the 2nd period from 1990 to 2014. The larger magnitudes of increasing trends for Tmax, Tmin and Tavg were found in sub-basins which have high elevation in winter and summer, while they were found in sub-basins which have low elevation in spring and autumn. DTR's decreasing trends in winter, spring, summer mainly occurred in the 1st period, while that in autumn mainly occurred in the 2nd period. The largest decreasing trends of DTR in the winter, spring, and summer all occurred in Maqu, while that in autumn occurred in Huangheyan. It indicates that in winter and summer, high-altitude climate in the SRYR such as Huangheyan and Jimai, warming to a greater extent than climate at low-altitude sub-basins and vice versa in spring and autumn.

Though the absolute values of Tmax, Tmin and Tavg increased rapidly with decades nearly as an exponential curve, but the trends in the latest ten years (2005-2014) slowed down and even reversed for Tmax in the SRYR, Tangnaihai, Maqu, Jimai and Huangheyan sub-basins with the rate of −0.002, −0.07, −0.05, −0.01 and −0.03°C yr^{-1}, and Tavg in Huangheyan with the rate of −0.02°C yr^{-1}. The absolute values of annual DTR in the SRYR, Tangnaihai, Jimai, and Huangheyan were decreasing gradually from 1975 to 2004 compared to the decade of 1965-1974, and increased rapidly in the decade from 2005 to 2014 with almost the same magnitude in the decade of 1975-1984.

Thence, changes of temperature variables differ with sub-basin due to its different catchment characteristics and have significant seasonal variations. It implies that runoff also might have great seasonal and spatial variations. Therefore, to provide scientific knowledge for water resource and hazard management in the SRYR the relationship between temperature and runoff needs to be studied in detail on sub-basins as well as seasonal scales.

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References

Abbas, F., A. Ahmad, M. Safeeq, S. Ali, F. Saleem, H. M. Hammad, and W. Farhad, 2014: Changes in precipitation extremes over arid to semiarid and subhumid Punjab, Pakistan. *Theor. Appl. Climatol.*, **116**, 671-680, doi:10.1007/s00704-013-0988-8.

Ahmad, I., D. Tang, T. F. Wang, M. Wang, and B. Wagan, 2015: Precipitation trends over time using Mann-Kendall and spearman's rho tests in swat river basin, Pakistan. *Adv. Meteorol.*, **2015**, 431860, doi:10.1155/2015/431860.

Beniston, M., 2003: Climatic change in mountain regions: A review of possible impacts. *Climatic Change*, **59**, 5-31.

______, H. F. Diaz, and R. S. Bradley, 1997: Climatic change at high elevation sites: An overview. In *Climatic Change at High Elevation Sites*, H. F. Diaz et al. Eds., Springer, 233-251.

Bhutiyani, M. R., V. S. Kale, and N. J. Pawar, 2007: Long-term trends in maximum, minimum and mean annual air temperatures across the Northwestern Himalaya during the twentieth century. *Climatic Change*, **85**, 159-177.

Brassel, K. E., and D. Reif, 1979: A procedure to generate Thiessen polygons. *Geogr. Anal.*, **11**, 289-303.

Buishand, T. A., 1982: Some methods for testing the homogeneity of rainfall records. *J. Hydrol.*, **58**, 11-27.

Caloiero, T., R. Coscarelli, E. Ferrari, and M. Mancini, 2011: Trend detection of annual and seasonal rainfall in Calabria (Southern Italy). *Int. J. Climatol.*, **31**, 44-56, doi:10.1002/joc.2055.

Cao, Z., and J. Ma, 2009: Summer severe-rainfall frequency trend and variability over ontario, Canada. *J. Appl. Meteorol. Clim.*, **48**, 1955-1960.

Christensen, N. S., and D. P. Lettenmaier, 2007: A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River basin. *Hydrol. Earth Syst. Sci.*, **11**, 1417-1434.

______, A. W. Wood, N. Voisin, D. P. Lettenmaier, and R. N. Palmer, 2004: The effects of climate change on the hydrology and water resources of the Colorado River basin. *Climatic Change*, **62**, 337-363.

Fowler, H. J., and D. R. Archer, 2005: Conflicting signals of climatic change in the Upper Indus Basin. *J. Climate*, **19**, 4276-4293.

Gu, Y., J. Lin, X.-L. Wang, and X.-J. Zhang, 2012: Trend of annual runoff for major rivers in China under climate change. *Procedia Engineer.*, **28**, 564-568, doi:10.1016/j.proeng.2012.01.769.

Hu, Y., S. Maskey, S. Uhlenbrook, and H. Zhao, 2011: Streamflow trends and climate linkages in the source region of the Yellow River, China. *Hydrol. Process.*, **25**, 3399-3411, doi:10.1002/hyp.8069.

______, ______, and ______, 2012: Trends in temperature and rainfall extremes in the Yellow River source region, China. *Climatic Change*, **110**, 403-429, doi:10.1007/s10584-011-0056-2.

IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* T. F. Stocker et al., Eds., Cambridge University Press, 1535 pp.

Kendall, M. G., 1975: *Rank Correlation Methods*. Charles Griffin, 202 pp.

Lan, Y., G. Zhao, Y. Zhang, J. Wen, X. Hu, J. Liu, M. Gu, J. Chang, and J. Ma, 2010: Response of runoff in the headwater region of the Yellow River to climate change and its sensitivity analysis. *J. Geogr. Sci.*, **20**, 848-860, doi:10.1007/s11442-010-0815-4.

Li, L., S. Yang, Z. Wang, X. Zhu, and H. Tang, 2010: Evidence of warming and wetting climate over the Qinghai-Tibet Plateau. *Arct. Antarct. Alp. Res.*, **42**,449-457, doi:10.1657/1938-4246-42.4.449.

Li, Z., X. Liu, T. Ma, D. Kejia, Q. Zhou, B. Yao, and T. Niu, 2013: Retrieval of the surface evapotranspiration patterns in the alpine grassland-wetland ecosystem applying SEBAL model in the source region of the Yellow River, China. *Ecol. Model.,* **270**, 64-75, doi:10.1016/j.ecolmodel.2013.09.004.

Li, Z. W., Z. Wang, and B. Z. Pan, 2016: Wetland ecosystems of the Yellow River source zone. In *Landscape and Ecosystem Diversity, Dynamics and Management in the Yellow River Source Zone*, G. J. Brierley et al. Eds., Springer Berlin, 183-207.

Mann, H. B., 1945: Nonparametric test against trend. *Econometrica*, **13**, 245-259.

Martin, W., and Coauthors, 2005: From dimming to brightening: Decadal changes in solar radiation at Earth's surface. *Science*, **308**, 847-850.

Mavromatis, T., and D. Stathis, 2011: Response of the water balance in Greece to temperature and precipitation trends. *Theor. Appl. Climatol.*, **104**, 13-24, doi:10.1007/s00704-010-0320-9.

Meng, F., F. Su, D. Yang, K. Tong, and Z. Hao, 2016: Impacts of recent climate change on the hydrology in the source region of the Yellow River basin. *J. Hydrol.*, **6**, 66-81, doi:10.1016/j.ejrh.2016.03.003.

Miller, W. P., and T. C. Piechota, 2008: Regional analysis of trend and step changes observed in hydroclimatic variables around the Colorado River Basin. *J. Hydrometeorol.*, **9**, 1020-1034.

Nachar, N., 2008: The Mann-Whitney U: A test for assessing whether two independent samples come from the same distribution. *Tutorials Quant. Meth. Psychol.*, **4**, 13-20, doi:10.20982/tqmp.04.1.p013.

Nalley, D., J. Adamowski, B. Khalil, and B. Ozga-Zielinski, 2013: Trend detection in surface air temperature in Ontario and Quebec, Canada during 1967-2006 using the discrete wavelet transform. *Atmos. Res.*, **132**, 375-398, doi:10.1016/j.atmosres.2013.06.011.

Payne, J. T., A. W. Wood, A. F. Hamlet, R. N. Palmer, and D. P. Lettenmaier, 2004: Mitigating the effects of climate change on the water resources of the Columbia River basin. *Climatic Change*, **62**, 233-256.

Qi, L., and Y. Wang, 2012: Changes in the observed trends in extreme temperatures over China around 1990. *J. Climate*, **25**, 5208-5222.

Ran, Y., J. Xie, and X. Li, 2016: Socio-economic development and its effects on the ecological environment of the Yellow River Source Zone. In *Landscape and Ecosystem Diversity, Dynamics and Management in the Yellow River Source Zone*, G. J. Brierley et al. Eds., Springer Berlin, 331-351.

Rangwala, I., and J. R. Miller, 2012: Climate change in mountains: A review of elevation-dependent warming and its possible causes. *Climatic Change*, **114**, 527-547, doi:10.1007/s10584-012-0419-3.

Safeeq, M., A. Mair, and A. Fares, 2013: Temporal and spatial trends in air temperature on the Island of Oahu, Hawaii. *Int. J. Climatol.*, **33**, 2816-2835, doi:10.1002/joc.3629.

Salmi, T., A. Määttä, P. Anttila, T. Ruoho-Airola, and T. Amnell, 2002: Detecting trends of annual values of atmospheric pollutants by the Mann-Kendall test and Sen's slope estimates: The Excel template application MAKESENS. Publications on Air Quality No. 31, Report code FMI-AQ-31, Finnish Meteorological Institute, 35 pp.

Sen, P. K., 1968: Estimates of the regression coefficient based on Kendall's tau. *J. Am. Stat. Assoc.*, **63**, 1379-1389, doi:10.1080/01621459.1968.10480934.

Shadmani, M., S. Marofi, and M. Roknian, 2012: Trend analysis in reference evapotranspiration using Mann-Kendall and Spearman's Rho tests in arid regions of Iran. *Water Resour. Manage.*, **26**, 211-224, doi:10.1007/s11269-011-9913-z.

Shi, H., T. Li, J. Wei, W. Fu, and G. Wang, 2016: Spatial and temporal characteristics of precipitation over the Three-River Headwaters region during 1961-2014. *J. Hydrol.*, **6**, 52-65, doi:10.1016/j.ejrh.2016.03.001.

Singh, P., V. Kumar, T. Thomas, and M. Arora, 2008: Basin-wide assessment of temperature trends in northwest and central India. *Hydrolog. Sci. J.*, **53**, 421-433.

Su, B. D., T. Jiang, and W. B. Jin, 2006: Recent trends in observed temperature and precipitation extremes in the Yangtze River basin, China. *Theor. Appl. Climatol.*, **83**, 139-151.

Tabari, H., B. S. Somee, and M. R. Zadeh, 2011: Testing for long-term trends in climatic variables in Iran. *Atmos. Res.*, **100**, 132-140, doi:10.1016/j.atmosres.2011.01.005.

______, P. Talaee, A. Ezani, and B. S. Somee, 2012: Shift changes and monotonic trends in autocorrelated temperature series over Iran. *Theor. Appl. Climatol.*, **109**, 95-108, doi:10.1007/s00704-011-0568-8.

Thiessen, A. H., 1911: Precipitation averages for large areas. *Mon. Wea. Rev.*, **39**, 1082-1089, doi:10.1175/1520-0493(1911)39<1082b:PAFLA>2.0.CO;2.

von Storch, H., 1995: Misuses of statistical analysis in climate research. In *Analysis of Climate Variability: Applications of Statistical Techniques*, H. von Storch et al. Eds., Springer Berlin, 11-26.

Wang, Y., X. Wang, C. Li, F. Wu, and Z. Yang, 2015: Spatiotemporal analysis of temperature trends under climate change in the source region of the Yellow River, China. *Theor. Appl. Climatol.*, **119**, 123-133, doi:10.1007/s00704-014-1112-4.

Yaseen, M., T. Rientjes, G. Nabi, H. Rehman, and M. Latif, 2014: Assessment of recent temperature trends in Mangla watershed. *J. Himalayan Earth Sci.*, **47**, 107-121.

Yin, J. F., Y. F. Zheng, R. J. Wu, J. G. Tan, D. X. Ye, and W. Wang, 2012: An analysis of influential factors on outdoor thermal comfort in summer. *Int. J. Biometeorol.*, **56**, 941-948, doi:10.1007/s00704-014-1112-4.

______, ______, X. Zhan, C. R. Hain, Q. Zhai, C. C. Duan, R. Wu, J. Liu, and L. Fang, 2015: An assessment of impacts of land-cover changes on root-zone soil moisture. *Int. J. Remote Sens.*, **36**, 6116-6134, doi:10.1080/01431161.2015.1111539.

Yuan, F., R. Berndtsson, L. Zhang, C. B. Uvo, Z. Hao, X. Wang, and H. Yasuda, 2015: Hydro climatic trend and Periodicity for the Source Region of the Yellow River. *J. Hydrol. Eng.*, **20**, 05015003, doi:10.1061/(ASCE):HE.1943-5584.0001182.

Yue, S., P. Pilon, and G. Cavadias, 2002a: Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *J. Hydrol.*, **259**, 254-271.

______, ______, B. Phinney, and G. Cavadias, 2002b: The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrol. Process.*, **16**, 1807-1829.

Zhang, Q., C.-Y. Xu, Z. Zhang, G. Ren, and Y. D. Chen, 2008: Climate change or variability? The case of Yellow river as indicated by extreme maximum and minimum air temperature during 1960-2004. *Theor. Appl. Climatol.*, **93**, 35-43.