Influences of removing linear and nonlinear trends from climatic variables on temporal variations of annual reference crop evapotranspiration in Xinjiang, China

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Abstract

Reference crop evapotranspiration (ET_o) is a key parameter in field irrigation scheduling, drought assessment and climate change research. ET_o uses key prescribed (or fixed or reference) land surface parameters for crops. The linear and nonlinear trends in different climatic variables (CVs) affect ET_o change. This research aims to reveal how ET_o responds after the related CVs were linearly and nonlinearly detrended over 1961-2013 in Xinjiang, China. The ET_o -related CVs included minimum (T_{min}), average (T_{ave}), and maximum air temperatures (T_{max}), wind speed at 2 m (U_2), relative humidity (RH) and sunshine hour (n). ET_o was calculated using the Penman-Monteith equation. A total of 29 ET_o scenarios, including the original scenario, 14 scenarios in Group I (ET_o was recalculated after removing linear trends from single or more CVs) and 14 scenarios in Group II (ET_o was recalculated after removing nonlinear trends from the CVs), were generated. The influence of U_2 was stronger than influences of the other CVs on ET_o for both Groups I and II either in northern, southern or the entirety of Xinjiang. The weak influences of increased T_{min} , T_{ave} and T_{max} on increasing ET_o were masked by the strong effects of decreased U_2 & n and increased RH on

decreasing ET_o . The effects of the trends in CVs, especially U_2 , on changing ET_o were clearly shown. Without the general decreases of U_2 , ET_o would have increased in the past 53 years. Due to the non-monotone variations of the CVs and ET_o , the results of nonlinearly detrending CVs on changing ET_o in Group II should be more plausible than the results of linearly detrending CVs in Group I. The decreasing ET_o led to a general relief in drought, which was indicated by the recalculated aridity index. Therefore, there would be a slightly lower risk of water utilization in Xinjiang, China.

Key words: reference crop evapotranspiration, temporal variation, climatic scenario, detrended climatic variable, Xinjiang

Abbreviations

CV-climatic variable; ET_o -reference crop evapotranspiration; T -air temperature; $T_{\min}$ -minimum T ; T_{ave} -mean T ; $T_{\max}$ -maximum T ; U -wind speed; U_2 - U at 2m; RH -relative humidity; n -sunshine hour; P -precipitation; NX-northern Xinjiang; SX-southern Xinjiang; EX-entire Xinjiang; EEMD-Ensemble empirical mode decomposition; MK-Mann-Kendall; MMK-modified MK; Z-MK statistic; Z_m -MMK statistic; SQMK-Sequential Mann-Kendall; S-scenario; b -Sen' s slope; LS -linear slope; Y_{AC} -year with an abrupt change; P_{sl} -significant level; G -soil heat flux; e_a - actual vapor pressure; e_s -saturation vapor pressure; Δ -slope of vapor pressure curve; γ -psychrometric constant; R_n -net radiation; SD-standard error, RMSE-root mean square error.

1. Introduction

The global average land surface temperature increased by 0.85 °C in the period from 1880 to 2012 (IPCC 2013). Faced with the challenges of global warming, it is crucial to know how the water availability and the agricultural water demands change, as a function of reference crop evapotranspiration (ET_o) variation (Espadafor et al. 2011). ET_o is widely used for water scheduling

of irrigation areas and uses key prescribed (or fixed or reference) land surface parameters for crops. Accurate estimation of ET_o is needed for field irrigation scheduling (Allen et al. 1998), drought assessment (Budyko 1974) and climate change research (Tabari and Hosseinzadeh Talaei 2014). The available models for estimating ET_o include temperature-based approaches (Blaney and Criddle 1952; Hargreaves and Samani 1985; Thornthwaite 1948), radiation-based approaches (Slatyer and McIlroy 1961) and combination approaches (Allen et al. 1998; Priestley and Taylor 1972). Following an extensive analysis of different ET_o methods in many world-wide locations, the Penman-Monteith (PM) approach was unanimously accepted as a standardized approach endorsed by the Food and Agricultural Organization (Allen et al. 1998; McVicar et al. 2007).

In the context of global warming, the trend of ET_o was found to have increased or decreased in different regions of the world. Increasing trends of ET_o were observed in Iran (Tabari et al. 2011, 2012) and southern Spain (Espadafor et al. 2011). However, a decreasing ET_o trend was reported for India (Chattopadhyay and Hulme 1997). ET_o at many places in China have decreased (see detail in Table 6 from McVicar et al. 2007). Trends in ET_o have decreased in northwest and southeast regions (Thomas 2000), the Yangtze River Basin (Xu et al. 2006), part of the Yellow River Basin (Liu and Yang 2010), Tibet Plateau (Liu et al. 2011), and the Haihe River Basin (Tang et al. 2011). The increase or decrease of ET_o were mainly caused by the increase or decrease of climatic variables (CVs), which are necessary for estimating ET_o . These variables include air temperature (T), wind speed (U), relative humidity (RH), and radiation or sunshine hour (n) in the absence of radiation. The influences of CVs on ET_o , which also potentially reflect the effects of climatic change on ET_o , have been investigated regionally or globally (McVicar et al. 2012; Xu et al. 2006).

There are different ways for assessing the influences of CVs on ET_o . One way is to conduct a sensitivity analysis. This is done by determining the corresponding changes of ET_o after adding

different percentages of the CVs or by calculating the sensitivity coefficient (Goyal 2004; Lenhart et al. 2002; McKenney and Rosenberg 1993). Because ET_o is a multi-factor parameter, its sensitivity varies with various CVs. Moreover, other factors, such as geological locations and the calculation models, also affect its sensitivity. Another way is to analyze the ET_o series re-estimated by the detrended CVs such as previous studies investigating the influences of detrended CVs on ET_o in the Changjiang River Catchment during 1970-2000 (Xu et al. 2006) and in northwestern China (Huo et al. 2013). However, their results only showed the influences of single CV on ET_o , not the simultaneous influences of multiple variables on ET_o . Because CVs change simultaneously, even the minimum, mean and maximum T ($T_{\min}$, T_{ave} and $T_{\max}$) increased with different patterns, not to mention the other CVs. It is not sufficient to only know the influences of single CV on ET_o . Previous research has not distinguished the ability of various T s ($T_{\min}$, T_{ave} and $T_{\max}$) on influencing ET_o . Moreover, not only removing linear trends from CVs is executable and referable, but also removing nonlinear trends in CVs is necessary because most CVs vary nonlinearly with time. There is limited research that compares the influences of removing linear trends and nonlinear trends from various CVs on ET_o .

The effects of climate change on ET_o in northwestern China have been studied by Huo et al. (2013) using data obtained from 23 weather stations. The linear trends of T , RH , solar radiation and U were removed, and the detrended CVs were used for re-estimating ET_o . Their results showed that the contribution of the decline in U to the decrease in ET_o is larger than that of other meteorological variables. This study investigates the effects of removing linear and nonlinear trends from the annual CVs (including $T_{\min}$, T_{ave} , $T_{\max}$, RH , U and n) on the temporal variations of annual ET_o in Xinjiang, China. Our aims are to: i) assess the importance of each CV to ET_o for northern (NX), southern (SX) and the entirety of Xinjiang (EX); ii) to compare the differences in removing the

trends from single, double and multi-CVs in various scenarios for each sub-region, and to distinguish the influences of various T -factors ($T_{\min}$, T_{ave} and $T_{\max}$) and non- T -factors (U_2 , RH and n) on changing ET_o ; and iii) to clearly show how the CVs affect ET_o in Xinjiang by comparing the original and recalculated ET_o series using the linear and nonlinear detrended CVs.

2. Data and Methodology

2.1 The study sites and the data sets

The Xinjiang Uygur Autonomous Region is located in inland area of northwestern China. Xinjiang is surrounded on three sides by mountains and is distant from any sea (Li et al. 2016). The multiyear mean ratio of precipitation (P) (147mm) to ET_o (1512mm) is 0.1 (Li and Sun 2016); therefore, the region was classified as an arid zone according to Erinc (1965). A total of 53 weather stations in Xinjiang, China were selected as study sites (Figure 1). The observed monthly weather data were collected from the Meteorological Data Sharing Service Network in China, with strict quality control. Elevations of the selected sites ranged between 30-3095 m. The data duration was from 1961 to 2013 with the completeness larger than 99.7%. Missing data were interpolated linearly with the neighboring months. The belt along Tuergate – Aheqi – Bayinbuluke – Urumqi – Qitai – Qijiaojing – Balikun – Zhuomaohu, which belongs to NX, was set as the border of NX and SX. There were 27 sites in NX and 26 sites in SX, respectively.

----- Figure 1-----

2.2 Estimation of reference crop evapotranspiration

The Penman-Monteith equation (Allen et al. 1998) is used here for estimating ET_o (mm):

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_{\text{ave}} + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where G is soil heat flux ($\text{MJ m}^{-2} \text{ day}^{-1}$), T_{ave} is for 2 m ($^{\circ}\text{C}$), U_2 is U at 2 m (m s^{-1}), e_s is saturation

vapor pressure (kPa), $e_s - e_a$ is saturation vapor pressure deficit (kPa), Δ is slope of vapor pressure curve (kPa °C⁻¹), γ is psychrometric constant (kPa °C⁻¹), R_n is net radiation (MJ m⁻² day⁻¹) and calculated with n following Allen et al. (1998). Monthly G is estimated by

$$G_M = 0.07(T_{M+1} - T_{M-1}) \quad (2)$$

where the subscripts $M+1$, M and $M-1$ are the numbers of month. Annual ET_0 is determined by monthly values.

2.3 Trend and abrupt change year analysis

The data series of the trend and abrupt change year (Y_{AC}) analysis include the T_{min} , T_{ave} , T_{max} , U_2 , n , RH , P and ET_0 . A trend test is conducted by the modified nonparametric Mann-Kendall (MMK) method (Yue and Wang 2002). The MMK method reflects the effects of autocorrelation in time series x_i ($i=1, 2, \dots, N_T$, where N_T is the total year number) based on the Mann-Kendall (MK) method (Kendall 1975; Mann 1945). In order to limit the influence of serial autocorrelation, the original standardized MK test statistic (Z) is modified to the new MMK statistic (Z_m) with a correction factor n^s (Li et al. 2010; Yue and Wang 2002), written as below:

$$Z_m = Z / \sqrt{n^s}, \text{ where } n^s = \begin{cases} 1 + \frac{2}{n} \sum_{j=1}^{n-1} (n-1)r_j & \text{for } j > 1 \\ 1 + 2 \frac{r_1^{n+1} - nr_1^2 + (n-1)r_1}{n(r_1-1)^2} & \text{for } j = 1 \end{cases} \quad (3)$$

where r_j is sample auto-correlation coefficient of x_i at lag j .

If Z (or Z_m) is positive (or negative), x_i has an upward (or downward) trend. When the lag j of autocorrelation functions r_j is > 0 and $|Z_m| \geq 1.96$, the trend is significant at a confidence level $\alpha=0.05$, and x_i is time-dependent. The slope of the trend (b) is estimated by the method of Sen (1968).

A sequential Mann-Kendall (SQMK) analysis is used for Y_{AC} detection (Partal and Kahya

2006). The SQMK is a sequential progressive $u(t)$ and backward $u'(t)$ analyses of the MK test. If the two series cross each other, the crossing point exhibits the Y_{AC} . If the two series cross and diverge from each other for a longer period of time, the beginning of the year of divergence exhibits the Y_{AC} . Its sequential behavior fluctuates close to zero. In the sequential progressive $u(t)$ analysis, the number of cases $x_j > x_K$ ($K=1, 2, \dots, j-1$), denoted by N_j , is counted at each comparison. The SQMK test statistic S_j is calculated by

$$S_j = \sum_j N_j \quad (4)$$

The mean and variance of the test statistic are calculated by

$$E(t) = \frac{N_T(N_T - 1)}{4} \quad (5)$$

and

$$Var(t_j) = \frac{j(j-1)(j-2)}{72} \quad (6)$$

Sequential progressive $u(t)$ is calculated by

$$u(t) = \frac{S_j - E(t)}{\sqrt{Var(S_j)}} \quad (7)$$

Sequential backward serial values $u'(t)$ are calculated similarly with the end of x_i being starting point.

2.4 Linear and nonlinear detrending approaches of climate variables

The trends in CVs of $T_{\min}$, T_{ave} , $T_{\max}$, U_2 , n , RH and ET_0 will be analyzed. A linear trend is obtained by linearly correlating x_i with the year. The ensemble empirical mode decomposition (EEMD) (Wu and Huang 2009), an adaptive and temporally local time series analysis method (Ji et al. 2014), is applied to obtain the nonlinear trends in the CVs. Its principle is to obtain the arithmetic mean of multiple observations by adding multiple white noise realizations to the target data to mimic a scenario of multi-trial observations for a single-trial one. After multi-step calculations, the raw data are decomposed into finite intrinsic mode functions and a nonlinear trend.

A detrended data series $x_{i,D}$ is generated by removing the linear or nonlinear trend from an observed time series x_i at each year. Then, a constant value is added to maintain $x_{i,D}$ at a similar variation range to x_i . For the linear trend analysis, the constant value is the multi-year average of x_i . For the nonlinear trend analysis, the constant value is x_1 .

2.5 Scenarios of ET_0 estimated using the detrended CVs

The total number of scenarios is $2(C_6^1 + C_6^1 + C_6^1 + C_6^1 + C_6^1 + C_6^1) = 114$. Despite all CVs change over a long time-period, and scenarios for different CV scenarios could be as many as 114 considering both linear and non-linear trend removal effects, this research can't cover all. Here we mainly focus on comparing the effects of detrending (i) different temperature-related factors (i.e., T -factor, $T_{\min}$, T_{ave} and $T_{\max}$), and (ii) T - and non- T factors (i.e., U_2 , RH and n) on changing ET_0 . In addition to the original scenario (S-1) of ET_0 , which is estimated by the observed CVs, 2 scenario groups are set, and both contain 14 different scenarios ('S-' below) of recalculated ET_0 using the different combinations of the observed and detrended CVs (Table 1). In Group I (or II), linear (or nonlinear) trends in one or more observed CVs are removed, and the detrended CVs with the other observed CVs are used for recalculating ET_0 . A total of 29 scenarios of ET_0 , including S-1, S-2 to S-15 in Group I and S-2 to S-15 in Group II, are applied. In scenarios 2 to 8, the effects of detrending single, bi-, or multi- T -factors on the recalculated ET_0 are compared step by step, while in scenarios 9 to 14, the effects of detrending single, or two non- T -factors are compared step by step. The influence extent between T - and non- T -factors could be shown by comparing scenarios 2 to 8 with scenarios 9 to 14 indirectly.

----- Table 1 -----

3. Results

3.1 Temporal variations of CVs and ET_0 and their trends

The temporal variations of annual CVs and their linear and nonlinear trends in NX, SX and EX over 1961-2013 are illustrated in Figure 2. The CVs differed between NX and SX, with the Tianshan Mountains as a division. Although the fluctuation patterns of $T_{\min}$, T_{ave} , $T_{\max}$, U_2 and RH between NX and SX were generally similar, distinctively different ranges were shown. $T_{\min}$, T_{ave} and $T_{\max}$ were higher but U_2 and RH were lower in SX than in NX. However, this was not the case for n , which had generally similar ranges for NX, SX and EX. The CV values in EX were between those in NX and SX. There were general increases in $T_{\min}$, T_{ave} and $T_{\max}$ but decreases in U_2 and n in NX, SX and EX, as shown by the linear trends. RH had very weak increasing trends either in NX, SX or EX. The linear trends of $T_{\min}$, T_{ave} and $T_{\max}$ after 1976 were generally similar to their nonlinear trends. However, the linear trends of $T_{\min}$, T_{ave} and $T_{\max}$ before 1976 and U_2 , RH and n over the whole study period were generally different from their nonlinear trends. These differences would result in different recalculated ET_0 in Groups I and II.

----- Figure 2 -----

The nonlinear variations of U_2 , RH and n contributed greatly to the nonlinear variations of ET_0 . The different fluctuations of the six observed CVs resulted in corresponding differences of ET_0 between NX, SX and EX (Figure 3). There were similar fluctuations of ET_0 in NX, SX and EX, but the ET_0 values in NX were generally smaller than those in SX for the entire study period. Similar values between ET_0 in NX and EX than between SX and EX were observed. ET_0 showed decreased linear trends but concave nonlinear and non-monotone trends with a sub-region order of $SX > EX > NX$. The difference between the linear and nonlinear ET_0 trends for each sub-region was prominent, which would cause differences between the subsequent regenerated ET_0 scenarios between Groups I and II.

----- Figure 3-----

The tested trends and abrupt change years, Y_{AC} , for the annual CVs and ET_o are presented in Table 2. The calculated sequential progressive $u(t)$ and backward $u'(t)$ curves are illustrated in Figure 4, from which the Y_{AC} could be visually discerned for each CV and sub-region. At the annual timescale, T_{min} increased significantly in NX and EX but insignificantly in SX; T_{max} increased significantly in NX but insignificantly in SX and EX; U_2 decreased but T_{ave} and RH increased, all insignificantly in NX, SX and EX; n decreased insignificantly in NX and EX but significantly in SX; and P increased insignificantly in NX and EX but significantly in SX. Under the interactions of the different CVs, annual ET_o decreased insignificantly in NX, SX and EX. Sen's slope b had an order of $T_{min} > T_{ave} > T_{max}$ for each sub-region. The values of b for the six CVs and ET_o differed slightly, but there were large differences for b values of P in different sub-regions. The sign of b agreed well with that of Z_m . The tested Y_{AC} happened in 1992 or 1993 for T_{min} , in 1993 or 1996 for T_{ave} , and in 1996 and 1997 for T_{max} for different sub-regions. The Y_{AC} in each sub-region had a CV order of $T_{min} < T_{ave} < T_{max}$. The Y_{AC} of U_2 occurred in 1980, 1977 and 1978 for NX, SX and EX, respectively. The Y_{AC} of RH was in 1974 for NX and 1975 for SX. The Y_{AC} of n was in 1978 for NX and 1971 for EX. No abrupt change occurred for RH in EX and for n in SX. The Y_{AC} of P occurred in 1986 and 1987. The Y_{AC} of ET_o were in 1979, 1975 and 1975 for NX, SX and EX, respectively. Overall, the climate change in Xinjiang was warmer and wetter in the recent 53 years.

-----Table 2-----

----- Figure 4-----

The Pearson correlation coefficients (r) shows the statistical relationship between annual ET_o and each related CV as well as the relative contribution of each CV to ET_o for NX, SX and EX (Table 3). The r values were positive for ET_o with T_{min} , T_{ave} , T_{max} , U_2 and n , but negative for ET_o with RH in NX, and negative for ET_o to T_{min} , T_{ave} and RH in SX and EX at different significant

levels. The absolute r values for ET_0 with RH and n in NX were larger than 0.5, which implied that from a statistical viewpoint, RH and n were the main factors that influenced ET_0 in NX. The absolute r values for ET_0 with $T_{\max}$ and U_2 in NX were 0.438 and 0.395, respectively, indicating the two next important factors that affected ET_0 in NX. In SX and EX, the absolute r values for ET_0 with U_2 , RH and n were larger than 0.5. The absolute r values for ET_0 with $T_{\min}$, T_{ave} and $T_{\max}$ were much smaller than for ET_0 with the other 3 CVs in NX, SX or EX. The absolute r values were used to rank the CVs to primarily and statistically assess the extent of their influence on ET_0 . The ranks of CVs were $RH > n > T_{\max} > U_2 > T_{\text{ave}} > T_{\min}$ for NX, $U_2 > n > RH > T_{\min} > T_{\text{ave}} > T_{\max}$ for SX, and $n > RH > U_2 > T_{\max} > T_{\min} > T_{\text{ave}}$ for EX. The generally larger roles of U_2 and n (with decreasing trends), as well as RH (with slightly increasing trends) than $T_{\min}$, T_{ave} and $T_{\max}$ on ET_0 may have contributed to the decreasing trends of ET_0 over 1961-2013 in Xinjiang, China.

-----Table 3-----

The r values for ET_0 with the related six CVs were only shown for S-1 in Table 3; r for ET_0 with the CVs in the other scenarios were not shown. The above results can be referenced in the other scenarios. In addition, although the Y_{AC} was detected for the CVs over 1961-2013, these values were only for primary investigations of their temporal variation characteristics. The following trend removal analysis of each CV would not be conducted in two (or more) time stages using the Y_{AC} as a division because there were only 53 years of this short study period. The nonlinear trends showed generalized temporal changes in the CVs, which also reflected the Y_{AC} to some extent.

There was a CV order affecting ET_0 for each sub-region through correlation analysis. This order only showed the possible effects of CV on ET_0 , which were static. When the correlation was conducted for scenario I, the static roles of each CV on ET_0 was shown. When scenarios changed,

the static roles of each CV on ET_0 changed because the detrended CVs would be applied to correlate with detrended ET_0 . Correlation analysis between the recalculated ET_0 and CVs were not conducted for scenarios II to XV because correlation analysis after detrending only reflected shared time series variation independent of any underlying trend. The correlation analysis only showed the connect extent between ET_0 and CVs from a statistical respect. When also considering the shared trend of each CV, its effects could be shown more clearly. It should be emphasized that when a slight trend occurs in the CVs, e.g., for n , its effects on changing ET_0 could be also slight for investigating detrending effects on ET_0 , although its r values with ET_0 is relatively high.

3.2 Effects of removing linear trends from the CVs on ET_0

The recalculated ET_0 series using the linearly detrended CVs in various scenarios of Group I over 1961-2013 are compared with S-1 (Figure 5). In Figure 5a of the recalculated values of ET_0 for NX, the ET_0 curves of S-2 (in which $T_{\min}$ was detrended) and S-4 ($T_{\max}$ was detrended) decreased, but that of S-3 (T_{ave} was detrended) increased slightly when compared to S-1. Larger differences existed after 2000. This caused the actual roles of increasing $T_{\min}$, T_{ave} and $T_{\max}$ on ET_0 to differ. Although the trends in $T_{\min}$, T_{ave} and $T_{\max}$ were all increasing, the increase of T_{ave} decreased ET_0 very slightly, whereas both the increases of $T_{\min}$ and $T_{\max}$ increased ET_0 . The increase of $T_{\min}$ on increasing ET_0 surpassed that of $T_{\max}$, because the Sen's slope of $T_{\min}$ (Table 2) was larger than that of $T_{\max}$ for each sub-region. For SX (Figure 5aa) and EX (Figure 5aaa), small differences were found between the ET_0 curves of S-1 and S-3 and between S-2 and S-4. There were greater effects of detrending $T_{\min}$ and $T_{\max}$ than detrending T_{ave} on changes in ET_0 in SX and EX. In Figure 5b of the recalculated values of ET_0 for NX, there were general decreases in ET_0 when the increasing trends in two or three of $T_{\min}$, T_{ave} and $T_{\max}$ were removed. Their decreasing effects on ET_0 ranked in a CV order of $(T_{\text{ave}} \& T_{\max}) < (T_{\min} \& T_{\text{ave}}) < (T_{\min}, T_{\text{ave}} \& T_{\max}) < (T_{\min} \& T_{\max})$, corresponding to a

scenario order of S-7<S-5<S-8<S-6. However, the differences between various scenarios were small.

For SX (Figure 5bb) and EX (Figure 5bbb), the ET_o curve of S-5 were very close to that of S-7, and the ET_o curve of S-6 were close to that of S-8. All four curves were below the ET_o curve of S-1, showing the effects of detrending multi- T -factors on decreasing ET_o . These decreasing effects on ET_o ranked with a CV order of $(T_{ave} \& T_{max})$ (or $T_{min} \& T_{ave}$)< $(T_{min} \& T_{max})$ (or $T_{min}, T_{ave} \& T_{max}$), corresponding to a scenario order of S-5(or S-7) <S-6 (or S-8)<S-1. Therefore, the increases in T_{min} , T_{ave} and T_{max} should have played some role in increasing ET_o in Xinjiang in the recent period of 53 years.

In Figures 5c, 5cc and 5ccc, the effects of removing the decreasing trend of U_2 in S-9 increased ET_o apparently, while the effects of removing the decreasing trends of n in S-10 or removing small increasing trends of RH in S-11 increased ET_o very slightly in NX, SX and EX. Provided there was no any decrease trend in U_2 , ET_o should have increased over the past 53 years. This also explained why the influences of detrending $U_2 \& RH$ in S-13 and detrending $U_2 \& n$ in S-14 surpassed that of detrending $n \& RH$ in S-12 on increasing ET_o (Figures 5d, 5dd and 5ddd). In addition, the effects of increasing U_2 on decreasing ET_o were much stronger than that of increasing T_{min} , T_{ave} and T_{max} on increasing ET_o . Overall, the effects of removing all the trends from the six CVs (S-15) caused the increases of ET_o in NX, SX and EX over 1961-2013. Provided without any trend in each CV, ET_o should have increased over the past 53 years.

----- Figure 5-----

3.3 Effects of removing nonlinear trends from the CVs on ET_o

The recalculation of ET_o by removing the nonlinear trends from the CVs for the 14 scenarios of Group II over 1961-2013 are shown in Figure 6. It also shows the effects of removing the

increasing trends in $T_{\min}$, T_{ave} & $T_{\max}$ on slight decreasing or increasing ET_0 , removing decreasing trends in U_2 on largely increasing ET_0 , removing the slight decreasing trend of n on tiny increasing ET_0 , and removing the increasing trend of RH on minute increasing ET_0 in each sub-region. The effects of detrending two, three or all CVs were connected with that of detrending a single CV on changes in ET_0 . Similar to Group I, the effects of detrending U_2 , n and RH on increasing ET_0 also surpassed the effects of detrending $T_{\min}$, T_{ave} & $T_{\max}$ on decreasing ET_0 for Group II, which resulted in a general increase of ET_0 after removing all the trends from the six CVs.

----- Figure 6-----

The results from Groups I and II explained why the actual ET_0 decreased over the studied period. The recalculated ET_0 in Groups I and II generally varied in similar patterns but with different scopes and values. Figures 5 and 6 showed temporal fluctuations of the recalculated ET_0 in different scenarios, but the r values in Table 3 only showed statistical (static) correlations between ET_0 and the CVs in S-1. The combined methods revealed the relationship between ET_0 and the CVs from two different respects.

3.4 D_{ET_0} variations for different scenarios of Groups I and II

There are differences between the ET_0 values of the various scenarios and S-1 (D_{ET_0}). Figure 7 illustrates how D_{ET_0} varies in different scenarios for Groups I and II in NX, SX and EX. In Figure 7a of Group I in NX, the four D_{ET_0} curves, in which the ET_0 values were recalculated using the detrended U_2 (S-9), the detrended U_2 & RH (S-12), the detrended U_2 & n (S-14), and the detrended six CVs (S-15), were generally positive and larger than the D_{ET_0} values of the other 10 scenarios over 1961-2013. These four D_{ET_0} curves showed larger recalculated ET_0 values than original ET_0 values in S-1 over time. The total D_{ET_0} reached 72.8 for S-14, 72.3 for S-9, 68.3 for S-12 and 36.2 for S-15 mm in 2013, respectively. The increases of the four D_{ET_0} curves generally followed a

scenario order of S-9>S-14>S-12>S-15. On the contrary, the other four D_{ET_0} curves, in which ET_0 values were recalculated using the detrended $T_{\min}$ & $T_{\max}$ (S-6), the detrended $T_{\min}$, T_{ave} & $T_{\max}$ (S-8), the detrended $T_{\min}$ (S-2) and the detrended $T_{\min}$ & T_{ave} (S-5), decreased over time. The decreases of D_{ET_0} curves ranked in a scenario order of S-5<S-2<S-8<S-6, and the total D_{ET_0} in 2013 reached -18.9, -20.2, -28.4 and -28.0 mm, respectively. The other six D_{ET_0} curves in S-3, S-4, S-7, S-10, S-11 and S-13 decreased a little over time, and their absolute D_{ET_0} values in 2013 were all below 7.8 mm. Therefore, there were generally three types of D_{ET_0} curves that resulted from detrended U_2 (or U_2 and RH or n), detrended $T_{\min}$, T_{ave} & $T_{\max}$, and detrended RH and n , respectively. These three types were also typical for the D_{ET_0} curves in SX (Figure 7b) and EX (Figure 7c), although the orders of scenarios for increased or decreased D_{ET_0} changed within each type. There were even larger D_{ET_0} curves of S-14, S-9, S-12 and S-15 in SX than in NX. The D_{ET_0} curves of various scenarios in EX were between those of NX and SX.

For Group II (Figures 7aa, 7bb and 7cc), the D_{ET_0} values increased (e.g., in S-9, S-14 and S-12), increased first and then decreased (in S-15), or decreased (in the other 10 scenarios of recalculated ET_0) over time, and the variations of D_{ET_0} values had a general sub-region order of SX>EX>NX. The main differences of D_{ET_0} curves between Groups I and II was that the D_{ET_0} values in the 14 scenarios of Group I generally increased linearly (although had some perturbations) as time increased, but most D_{ET_0} curves in Group II varied nonlinearly, they increased before 1996 but decreased after the year. This differed with the effects of linear or nonlinear trend removal from the CVs on the changes in ET_0 . Therefore, in Group I, especially for S-9, S-12, S-14 and S-15, the D_{ET_0} curves increased to larger values than those in Group II until 2013.

----- Figure 7-----

Figure 8 shows the statistical properties of D_{ET_0} for 14 scenarios of Groups I and II in NX, SX

and EX. In Figure 8a, the minimum D_{ET_0} values ranged between -40 and 14 mm for different scenarios, of which S-6 (detrending $T_{\min}$ & $T_{\max}$) and S-8 (detrending $T_{\min}$, T_{ave} & $T_{\max}$) had the smallest minimum D_{ET_0} in NX, SX and EX. The effects of detrending T -related-factors have surpassed that of detrending non- T -related-factors on decreasing the minimum D_{ET_0} . For NX, the minimum D_{ET_0} values from S-2 to S-8 in Group I were smaller than those in Group II but reversed for the other six scenarios. For SX and EX, the minimum D_{ET_0} values from S-2 to S-8 in Group I were larger than those values in Group II. In Figure 8b, the average D_{ET_0} values ranged between -18 and 57 mm for different scenarios. Generally, the average D_{ET_0} values were negative for S-2 to S-8 but positive for S-9 to S-15, of which, S-9, S-12, S-14 and S-15 had much larger average D_{ET_0} values than the other 11 scenarios, showing the strong effects of detrending U_2 (or U_2 with RH and n) on increasing the average D_{ET_0} . In Figure 8c, the differences among the maximum D_{ET_0} values of various scenarios were even more prominent than the minimum and average D_{ET_0} values. Similar to average D_{ET_0} , the maximum D_{ET_0} values were much larger for S-9, S-12, S-14 and S-15 (ranging from 40 to 118 mm) than for the other 11 scenarios (ranging from -5 to 20 mm). The maximum D_{ET_0} curves generally ranked with an order of “SX in Group II > EX in Group II > SX in Group I > EX in Group I > NX in Group I > NX in Group II”. Overall, the minimum D_{ET_0} values were small and negative, the average D_{ET_0} values varied in a larger scope than the minimum D_{ET_0} values, and the maximum D_{ET_0} values were generally positive and higher than the average and the minimum values. This implied that the trend removals from the CVs changed extreme values, especially the maximum values of ET_0 in Xinjiang.

----- Figure 8-----

3.5 Comparisons of ET_0 after trend removals from all of the six CVs

The ET_0 values of S-1 were generally smaller than the recalculated ET_0 values of S-15 after

removing all the linear (Group I) or nonlinear (Group II) trends from all of the six CVs over the period 1961-2013 in NX, SX and EX (Figure 9). There were larger differences in ET_o curves of S-15 for Groups II than for Group I over 1961-2010 for NX, and over 1961-2005 for SX and EX, respectively, using S-1 as the reference. It was shown that if there was no trend in the CVs, the annual ET_o should have been larger than the actual values over 1961-2013 in Xinjiang. ET_o in Xinjiang responded prominently to the changes in climate.

----- Figure 9-----

3.6 Different detection technologies that affect ET_o trends

Li et al. (2014) reported that the change of dominant factors in the ET_o trend has differences after 1993, and judged a Y_{AC} of 1993 by comparing the ET_o anomaly in northwestern China including Xinjiang. From our results, the Y_{AC} for NX, SX and EX happened in 1979, 1975 and 1975, respectively, which were earlier than the reported 1993 of Li et al. (2014). Our results were obtained using the SQMK change point analysis, which detected the Y_{AC} statistically. Figure 10 clearly shows the decadal averages and the periodical linear trends in ET_o for EX. In any case, both the decadal average and periodical linear lines showed that there were more than one Y_{ACS} over 1961-2013 in Xinjiang. Owing to the limitations of the method, the SQMK technique may have only detected the first significant Y_{AC} in the ET_o series in the study period, while the ET_o anomaly technique (Li et al. 2014) detected the most significant Y_{AC} . Different results were used for different research aims. Although Y_{AC} in this research was different from that of Li et al. (2014), it was only used to indicate the temporal variations of ET_o in Xinjiang, and the results didn't affect the further detrending analysis.

----- Figure 10-----

3.7 Consequences of decreased ET_o under global warming

The decrease of ET_0 in Xinjiang, China will result in different consequences for agriculture, hydrology, meteorology, society and the economy. There will be a smaller requirement of irrigation amounts corresponding to the decrease in ET_0 and actual evapotranspiration (which could be estimated by multiplying ET_0 with a crop coefficient) for field crops and plants. Decreased ET_0 and evapotranspiration would result in increased runoff, considering the increased P over the period of 1961-2013 (Li and Sun 2016). Consequently, it could possibly increase the risk of flooding in the summer when the snow on the alpine mountain areas melts rapidly under high temperatures.

ET_0 is used as a component of the aridity index I_A , which is the ratio of P to ET_0 (Budyko 1974; Li et al. 2016). I_A falls in the ranges of (0.05, 0.2), [0.2, 0.5), [0.5, 0.65), [0.65, 0.8), [0.8, 1.0) and [1.0, 2.0) for arid, semi-arid, dry sub-humid, semi-humid, humid and severe humid climates, respectively. Annual I_A values were estimated here for assessing the dry/wet conditions by using different ET_0 values obtained from the observed (S-1), the linearly detrended (S-15 in Group I) and the nonlinearly detrended six CVs (S-15 in Group II) in NX, SX and EX, respectively (Figure 10). Generally, there were slightly larger I_A values estimated using ET_0 in S-1 than I_A values estimated by using the ET_0 values in S-15 of Groups I and II over 1961-2013 in NX, SX and EX. This indicated (i) wetter conditions or relieved droughts in the region under the present global warming background, and (ii) drier conditions after detrending all of the six CVs and reassessing drought conditions. The larger I_A values implied decreased amounts of irrigation would be needed for crops. In this respect, a water crisis would be prevented in the region when only the effects of climate change are considered but the effects of human activity are not considered, which consequently results in more stable economic development to a certain extent, and therefore, a more stable life and society.

----- Figure 11 -----

4. Discussion

The Sen's slope (b) was used to estimate the trend magnitude. However, for linear detrending, a parametric method was applied which may not be suitable for the data with a non-normal distribution. To clearly investigate their similarity (or differences), Figure 12 quantifies and compares the differences between b and linear slope (LS) values of the related CVs. For most sites or sub-regions, LS values were close to b values for each CV. The deviations between b and LS values were small for different sites or sub-regions. There were two individual data-points in Figures 1a and 1d which deviated more than the other data-points, both occurred for the site Qijiaojing, where there was an infrastructure disturbance (station-moving in 1998, although not far away, T and U_2 both increased). The linear correlations showed very high similarity of b and LS values either for different sites or sub-regions ($0.971 < R^2 < 0.993$). For each CV, there were general very similar values of ranges, average, standard error (SD) for LS and b , and the root mean square error (RMSE) values were also small (Table 4). Although the Sen's slope estimator is non-parametric and the regression slope method a parametric method, both methods are linear. Therefore, the very slight differences between LS and b values (especially for NX, SX and EX) would lead to very similar results for analyzing detrending effects on ET_0 and confirmed the correctness of using LS values to detrend CVs.

----- Figure 12-----

----- Table 4-----

Except scenario 15, there are no other preset scenarios combining T -factor with non- T -factor because our results showed that: (1) The effects of simultaneously detrending the three T -factors on decreasing ET_0 were the largest when compared to the effects of detrending single or two T -factors; (2) The effects of detrending U_2 on increasing ET_0 was much larger than detrending RH , n , or single,

bi-, or multi- T -factors, which emphasized the most important role of U_2 on changing ET_0 . It was unnecessary to add extra scenarios to show the detrending effects of combining single, bi-, or multi- T s with RH or n because their effects on changing ET_0 would be small. Therefore, the scenario (S-15) containing both CVs of multi- T s and U_2 could comprehensively show the detrending CV effects on changing ET_0 .

With global warming, decreasing trends in ET_0 were detected not only in this research for Xinjiang, but also in other studies for many regions in China and around the world. Li et al. (2014) reported that the decreases in the diurnal T range and U may have led to a decrease of ET_0 during 1956–1993 in northwestern China, including Xinjiang. Using data from 65 stations over 1954–1993 in China, Thomas (2000) indicated that ET_0 had decreased in all seasons, and for south of 35°N , n was most strongly associated with changes in ET_0 , while U , RH and $T_{\max}$ were the primary factors in northwest, central and northeast China, respectively. Gao et al. (2006) found that n , U and RH had greater impacts on ET_0 than T over 1956–2000, and the declining tendencies of n and/or U were the major causes for the negative trend of ET_0 in most areas of China. Yin et al. (2010) applied a sensitivity analysis to ET_0 using data from 595 meteorological stations across China over 1961–2008 and concluded that the decreasing trend of ET_0 was primarily driven by a significant decline in U , especially in the northwest arid region. Huo et al. (2013) investigated temporal variations in ET_0 after linearly detrending the CVs over 1955–2008 in northwest China, including Xinjiang. They also found that the contribution of U to the decrease of ET_0 was larger than that of other CVs.

The previous studies generally agreed on emphasizing the importance of the decreased U on decreasing ET_0 . Our results of the original and the recalculated ET_0 values obtained with either linear or nonlinear detrended CVs in Xinjiang also supported this conclusion. Although the

correlations between ET_0 and n or between ET_0 and RH were large (absolute $r > 0.5$) in Xinjiang, their influences on the changes in ET_0 were small. This was mainly due to the results that the actual trend slopes in n and RH were small, being only -0.007 h/year and 0.024% /year for EX, respectively.

By comparing the effects of removing linear nonlinear trends from the CVs on ET_0 in Xinjiang, differences were found for the recalculated ET_0 scenarios between Groups I and II. Because of the non-monotone variations of the CVs and ET_0 , the results from Group II were more convincing for the assessment of the effects of climate change on ET_0 .

5. Conclusion

The climatic factors that drive ET_0 have been investigated in parts of or all of China, but the effects of removing linear and nonlinear trends from the related CVs on ET_0 have not been conducted before in Xinjiang, China. A total of 29 scenarios, including the non-detrended ET_0 scenario (S-1), the recalculated ET_0 scenarios in Groups I (by removing linear trends from single or more CVs) and II (by removing nonlinear trends from the related CVs), were set to analyze how the CVs affected ET_0 over 1961-2013 in Xinjiang. Among the six CVs, U_2 was the most important factor that affected ET_0 in NX, SX and EX because ET_0 increased the most when U_2 was detrended either linearly in Group I or nonlinearly in Group II. A decrease in U_2 caused a general decrease of ET_0 , which masked the effects of increased $T_{\min}$, T_{ave} & $T_{\max}$ on increasing ET_0 . The decreases of n and a slight increase of RH also contributed to the tiny decrease of ET_0 . The different roles of the CVs caused the overall decrease of ET_0 . The statistical properties, including the minimum, the average and the maximum D_{ET_0} , were generally within the scopes of -40 to 14 mm, -18 to 57 mm, and -5 to 118 mm, respectively.

The effects of simultaneously removing the existed trends in U , $T_{\min}$, T_{ave} , $T_{\max}$, n and RH on

increasing ET_o were more significant for Group I than for Group II in NX, SX and EX. However, the results from Group II were more convincing than those from Group I because ET_o in Xinjiang exhibited non-monotone variations and changes in trends at different time stages. The thorough step-by-step comparisons of removing trends from single or multiple CVs (either linearly or nonlinearly) on changing ET_o explained why ET_o decreased in Xinjiang under global warming conditions. Consequently, the annual aridity index I_A increased, which indicated wetter conditions in Xinjiang. A water utilization crisis would be relieved slightly considering the decrease of ET_o .

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Table 1 The combinations of detrended or observed climatic variables (CVs) in the preset 15 scenarios. $\surd$ - the CV was detrended in the scenario and used for recalculating ET_o .

CV	Scenario														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$T_{\min}$ ($^{\circ}\text{C}$)		$\surd$			$\surd$	$\surd$		$\surd$							$\surd$
T_{ave} ($^{\circ}\text{C}$)			$\surd$		$\surd$		$\surd$	$\surd$							$\surd$
$T_{\max}$ ($^{\circ}\text{C}$)				$\surd$		$\surd$	$\surd$	$\surd$							$\surd$
U_2 (m/s)									$\surd$				$\surd$	$\surd$	$\surd$
RH (%)										$\surd$		$\surd$	$\surd$		$\surd$
n (h)											$\surd$	$\surd$		$\surd$	$\surd$

Table 2 Results of trend test and abrupt changes of the CVs in Xinjiang. Z_m -MMK test statistic, * -pass the 95% significance level, b -Sen's slope, Y_{AC} -year with an abrupt change, P_{sl} -significant level, NX-north Xinjiang, SX-south Xinjiang, EX-entire Xinjiang, P -precipitation.

Sub-region	NX			SX			EX		
	Z_m	b	Y_{AC}	Z_m	b	Y_{AP}	Z_m	b	Y_{AC}
$T_{min}(^{\circ}C)$	1.99*	0.056	1993	1.92	0.047	1992	2.03*	0.053	1993
$T_{ave}(^{\circ}C)$	1.89	0.038	1993	1.88	0.030	1996	1.91	0.036	1996
$T_{max}(^{\circ}C)$	3.12*	0.024	1996	1.63	0.022	1996	1.68	0.024	1997
$U_2(m/s)$	-1.61	-0.015	1980	-1.31	-0.014	1977	-1.37	-0.015	1978
$RH(\%)$	0.161	0.015	1974	0.667	0.031	1975	0.652	0.024	-
$n(h)$	-1.50	-0.009	1978	-2.45*	-0.007	-	-1.28	-0.007	1971
$P(mm)$	1.62	0.106	1987	2.42*	0.040	1986	1.69	0.072	1987
$ET_o(mm)$	-1.76	-0.970	1979	-1.16	-1.77	1975	-1.11	-1.28	1975

Table 3 Pearson correlation coefficients (r) between ET_o and the involved CVs at different significant levels (P_{sl}) in S-1.

Region	NX		SX		EX	
CV	r	P_{sl}	r	P_{sl}	r	P_{sl}
T_{min} (°C)	0.027	0.846	-0.291	0.034	-0.159	0.254
T_{ave} (°C)	0.243	0.080	-0.133	0.341	-0.105	0.452
T_{max} (°C)	0.438	0.001	0.056	0.689	0.227	0.103
U_2 (m/s)	0.395	0.003	0.751	<0.001	0.596	<0.001
RH (%)	-0.856	<0.001	-0.666	<0.001	-0.764	<0.001
n (h)	0.742	<0.001	0.691	<0.001	0.810	<0.001

Table 4 The statistical properties of LS and b for the studied CVs. SD-standard error, RMSE-root mean square error.

CV	Range _{LS}	Range _{b}	Average _{LS}	Average _{b}	SD _{LS}	SD _{b}	RMSE
$T_{\min}$ (°C)	[-0.026, 0.116]	[-0.025, 0.133]	0.049	0.048	0.025	0.026	0.004
T_{ave} (°C)	[-0.009, 0.084]	[-0.009, 0.085]	0.032	0.032	0.017	0.017	0.001
$T_{\max}$ (°C)	[-0.001, 0.071]	[-0.001, 0.070]	0.023	0.022	0.011	0.011	0.001
U_2 (m/s)	[-0.061, 0.071]	[-0.060, 0.070]	-0.015	-0.014	0.017	0.019	0.004
RH (%)	[-0.161, 0.238]	[-0.160, 0.238]	0.005	0.002	0.079	0.081	0.010
n (h)	[-11.1, 9.14]	[-12.1, 9.65]	-1.74	-1.67	4.25	4.28	0.596

Figure Captions

Figure 1 Geological information of the study sites in Xinjiang, China. The color legend represents the elevation (m above sea level).

Figure 2 The observed CVs and their linear and nonlinear trends in NX, SX and EX.

Figure 3 Temporal variations of annual ET_0 and their trends in NX, SX and EX over 1961-2013.

Figure 4 Curves of $u(t)$ and $u'(t)$ for the involved CVs and ET_0 in NX, SX and EX over 1961-2014.

Figure 5 Variations of annual ET_0 estimated with linearly detrended CVs (Group I) in NX, SX and EX over 1961-2013.

Figure 6 Variations of annual ET_0 estimated with nonlinearly detrended CVs (Group II) in NX, SX and EX over 1961-2013.

Figure 7 Variations of annual D_{ET_0} for scenarios 2 to 15 of Groups I and II in NX, SX and EX over 1961-2013.

Figure 8 Statistical properties of D_{ET_0} for S-2 to S-15 in Groups I and II in NX, SX and EX over 1961-2013.

Figure 9 Variations of annual ET_0 for S-1, S-15 in Group I and S-15 in Group II over 1961-2013 for NX, SX and EX.

Figure 10 Decadal averages and periodical linear trends of ET_0 in EX. $Y_{AC,1}$, $Y_{AC,2}$, $Y_{AC,3}$ and $Y_{AC,4}$ represent the 1st, 2nd, third, and the forth abrupt change years.

Figure 11 Variations of annual I_A using ET_0 in S-1 and S-15 in Groups I and II for NX, SX and EX over 1961-2013.

Figure 12 Comparison between linear slope (LS) and Sen's slope (b) for the related CVs at each site and sub-region of Xinjiang, China. Site numbers 54, 55 and 56 referred to NX, SX, and EX, respectively.

Figure 1 Geological information of the study sites in Xinjiang, China. The color legend represents the elevation (m above sea level).

Figure 2 The observed CVs and their linear and nonlinear trends in NX, SX and EX.

Figure 3 Temporal variations of annual ET_0 and their trends in NX, SX and EX over 1961-2013.

Figure 4 Curves of $u(t)$ and $u'(t)$ for the involved CVs and ET_0 in NX, SX and EX over 1961-2014.

Figure 5 Variations of annual ET_0 estimated with linearly detrended CVs (Group I) in NX, SX and EX over 1961-2013.

Figure 6 Variations of annual ET_0 estimated with nonlinearly detrended CVs (Group II) in NX, SX and EX over 1961-2013.

Figure 7 Variations of annual D_{ET0} for scenarios 2 to 15 of Groups I and II in NX, SX and EX over 1961-2013.

Figure 8 Statistical properties of D_{ETo} for S-2 to S-15 in Groups I and II in NX, SX and EX over 1961-2013.

Figure 9 Variations of annual ET_0 for S-1, S-15 in Group I and S-15 in Group II over 1961-2013 for NX, SX and EX.

Figure 10 Decadal average and periodical linear trends of ET_o in EX. $Y_{AC,1}$, $Y_{AC,2}$, $Y_{AC,3}$ and $Y_{AC,4}$ represent the 1st, 2nd, third, and the forth abrupt change years.

Figure 11 Variations of annual I_A using ET_o in S-1 and S-15 in Groups I and II for NX, SX and EX over 1961-2013.

Figure 12 Comparison between linear slope (LS) and Sen's slope (b) for the related CVs at each site and sub-region of Xinjiang, China. Site numbers 54, 55 and 56 referred to NX, SX, and EX, respectively.

Graphical abstract