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Key Points:
- China experiences the recent warming hiatus
- The temperature changes have increased the likelihood of extreme events
- These are correlated with increases in solar radiation and dryness

Supporting Information:
- Text S1

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China experiencing the recent warming hiatus

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Abstract Based on the homogenized data set, we analyze changes in mean temperature and some extreme temperature indices over China since 1961 and especially during the recent warming hiatus period (1998–2012) in a global average context. The result shows that the decrease of annual mean maximum has contributed most to the decreases in overall mean temperature and in diurnal temperature range (DTR) during the warming hiatus period. In most parts of China except the southwest, the summer mean maximum temperature (T_{xS}) shows the largest increase, while the winter mean minimum temperature (T_{nW}) indicates slight cooling trends. These changes have augmented the seasonal cycle and increased the likelihood of extreme warm and cold events. Further analyses reveal that the increases in T_{xS} are significantly correlated with concurrent increases in solar radiation. In southwest China, the annual mean temperature, T_{xS}, T_{nW}, and DTR increased during 1998–2012, possibly related to increased dryness in this region during the hiatus period.

1. Introduction

The global surface air temperature data show an increase of about 0.89°C over 1901–2012 and about 0.72°C over 1951–2012 when described by a linear trend [*Hartmann et al.*, 2013]. The global and regional temperature changes from the second half of the twentieth century (since 1951) can be regarded as occurring with high confidence [*Brohan et al.*, 2006; *H. Li et al.*, 2010; *Q. Li et al.*, 2010; *Trenberth et al.*, 2007; *Hartmann et al.*, 2013]. Further, Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5) pointed out that during the recent 15 year period (1998–2012), although the surface air temperature (SAT) has not decreased, the warming rate has slowed down. This period has been discussed in a number of papers [*Easterbrook*, 2008; *Easterling and Wehner*, 2009; *Kaufmann et al.*, 2011] and has become known as "hiatus" [*Fyfe et al.*, 2013], "global slowdown" [*Guemas et al.*, 2013], or "pause" [*Slingo et al.*, 2013]. Although different results have been obtained between different researchers, recent studies indicate that the recent "warming hiatus" is also found in Chinese SAT changes [*H. Li et al.*, 2010; *Q. Li et al.*, 2010; *Cao et al.*, 2013; *J. Wang et al.*, 2014].

The analyses of extreme temperatures and DTR have attracted attention in recent years (*Easterling et al.* [1997], *Alexander et al.* [2006], *Zhai and Ren* [1997], IPCC AR4: *Trenberth et al.* [2007], *Zhou et al.* [2009], and IPCC: *Hartmann et al.* [2013]). Previous studies had systematically focused on the maximum temperature, minimum temperature, and DTR changes and their attributions (e.g., to greenhouse gases forcing) [*Karl et al.*, 1991; *Easterling et al.*, 1997; *Zhou et al.*, 2009; *Li et al.*, 2014]. *Karl et al.* [1993] and *Zhai and Ren* [1997] found that at the global land and national/regional scales, mean minimum temperatures increased faster than mean maximum temperature during 1951–1990 and referred to this as an "asymmetric change." It is generally believed that the increases of cloud amount, soil humidity, and precipitation cause the decrease in DTR, and vice versa [*Karl et al.*, 1993; *Dai et al.*, 1997, 1999]. Extreme indices like summer mean maximum temperature (T_{xS}) and winter mean minimum temperature (T_{nW}) encapsulate many impacts of temperature changes [*Li and Huang*, 2013; *Li et al.*, 2014].

Proposed mechanisms for the recent warming hiatus at the global scale are still under debate, including changes in deep-ocean heat uptake, anthropogenic aerosols, solar variations, volcanoes, and sea surface temperature [*Solomon et al.*, 2010, 2011; *Meehl et al.*, 2011; *Kaufmann et al.*, 2011; *Kosaka and Xie*, 2013]. At regional and local scales, other factors may also play a significant role, which makes attribution challenging. The amount of solar energy reaching the surface is a major component of the surface energy balance and governs a large number of diverse surface processes, as well as the diurnal and seasonal course of surface temperatures [*Wild*, 2009]. Recent studies have suggested correlations between surface solar radiation (SSR) associated with global "dimming" and "brightening" changes and long-term temperature variations [*Shi et al*., 2008; *Wild*, 2009; *Yang et al*., 2013].

This paper analyzes changes in several extreme temperature indices over China since 1961 and particularly during the recent global warming hiatus period 1998–2012. The changes will be assessed in the context of variations in T_{xS}, T_{nW}, and DTR and their associations with the changes in SSR, aerosols, and precipitation during the same period.

2. Data and Methods

It is important in observational studies that the data used are homogeneous [*Jones et al*., 1985; *Peterson et al*., 1998; *Li et al*., 2009; *Trewin*, 2010; *X. L. Wang et al*., 2014]. The National Meteorological Information Center of China Meteorological Administration (NMIC, CMA) has developed the first national homogenized temperature data set [*Li et al*., 2009] and its updated version [*Xu et al*., 2013]. Comparisons indicated that it is much superior to the raw data for climate change detection, especially for extreme event detection [*Xu et al*., 2013, and Figure S1 in supporting information]. In this study, daily maximum and minimum temperature records from 825 stations in China were selected for trend analysis by seasons. The SSR data are also quality controlled and processed by NMIC. There are about 130 sites with SSR observations over mainland China, and the sparse station distribution makes it difficult to construct reference series for SSR from nearby stations when homogenizing the temporal series. To minimize the SSR data inhomogeneities, we focus on the records during 1998–2012 using 90 stations with higher SSR data completeness than earlier records [*Yang et al*., 2013, and Figure S2 in supporting information]. The Climate Anomaly Method [*Jones and Hulme*, 1996] is applied to gridded deviations from climatological average ("anomalies") to construct a regional average time series over the entire China. The seasons are defined as follows: December to February for winter; March to May for spring; June, July, and August for summer; and September to November for autumn.

As extreme temperatures are not normally distributed, we used the Kendall's slope estimator developed by *Wang and Swail* [2001] to estimate linear trends and test for their statistical significance at the 5% level. This method accounts for the effect of first-order autocorrelation and has been found to perform best, especially for short time series in comparison with other approaches [*Zhang and Zwiers*, 2004]. Kendall's slope estimation [*Kendall and Gibbons*, 1981] is a nonparametric estimation method and can be used for any type of data including extreme indices. It is insensitive to missing data and is more robust against outliers than the traditional least squares linear trend estimator because its use of ranking rather than absolute values limits the influence of extreme events.

3. Results

3.1. Trend of National Average Temperature

Table 1 shows trends in seasonal and annual mean maximum (T_x) and minimum temperatures (T_n) and DTR averaged across China. Evidently, there is a warming trend in the national average temperatures (see also Figure S3 in the supporting information) during 1961–2012. For T_x, the annual mean warming rate was 0.20°C/decade; seasonally, winter had the largest warming trend, 0.25°C/decade, followed by 0.22°C/decade in fall and 0.19°C/decade in spring, and summer had the weakest warming trend of 0.15°C/decade. For T_n, the annual mean warming rate was about 0.37°C/decade, significantly greater than that of the annual mean T_x; seasonally, the greatest warming rate of 0.52°C/decade occurred in winter, followed by a smaller but still considerable warming rate of 0.37°C/decade in spring and 0.36°C/decade in fall, while summer had the least warming rate of 0.31°C/decade. Taking T_x and T_n together indicates a reduction in DTR of −0.18°C/decade annually. The seasonal DTR trends show the greatest decline in winter, −0.24°C/decade, followed by −0.17°C/decade in spring, −0.15°C/decade in summer, and −0.12°C/decade in fall.

Trends in maximum and minimum temperatures and DTR had different characteristics during the warming hiatus period (1998–2012). The annual mean T_x declined by −0.39°C/decade, primarily due to the

Table 1. Trends (°C per Decade) in Seasonal and Annual Mean T_x, T_n, and DTR Over Mainland China for Different Periods

Duration	Variables	Spring	Summer	Fall	Winter	Annual
1961–2012	DTR	−0.166*	−0.150*	−0.118*	−0.237*	−0.178*
	T_x	0.185*	0.153*	0.224*	0.245*	0.196*
	T_n	0.367*	0.313*	0.361*	0.519*	0.370*
1961–1997	DTR	−0.292*	−0.185*	−0.099	−0.300*	−0.250*
	T_x	−0.074	−0.024	0.103	0.335*	0.081
	T_n	0.224*	0.167*	0.216*	0.615*	0.327*
1998–2012	DTR	−0.058	−0.076	−0.501	−0.348*	−0.257
	T_x	−0.044	0.178	−0.068	−0.805	−0.392
	T_n	−0.055	0.267	0.329	−0.572	−0.131

*The trends are statistically significant at the 5% level.

pronounced (though statistically insignificant) decline of −0.81°C/decade in winter. On the other hand, the reduction of the annual mean T_n, −0.13°C/decade, was much weaker and insignificant. The greatest reduction in T_n was during the winter, −0.57°C/decade, but two of the other seasons had warming trends, 0.27°C/decade in summer and 0.33°C/decade in fall, while there was little change (−0.06°C/decade) in spring. In summary, for both T_x and T_n, the greatest decline in 1998–2012 was in winter, while other seasons showed warming or weak cooling trends. This contrasts markedly with 1961–1997, when the annual mean warming trends were 0.08°C/decade in T_x and 0.33°C/decade in T_n, with the greatest warming trends of 0.34°C/decade and 0.62°C/decade in winter, respectively. The other three seasons had significant warming trends for T_n but insignificant trends for T_x.

Generally, DTR trends should be roughly the difference in the trends between T_x and T_n. We notice that this rule works well for the period 1961–2012 and 1961–1997 but not as well for the shorter period 1998–2012 (Table 1 and Figure S3). This is at least in part due to greater uncertainties in estimating trends for shorter time series. Although the trends during 1998–2012 are not statistically significant, the positive trends in summer and negative trends in winter (both for T_x and T_n) are impressive (Table 1 and Figure S3).

3.2. Spatial Distributions of Maximum and Minimum Temperature Trends

3.2.1. 1961–2012

Figure 1 shows the spatial patterns of trends in time series of annual means of T_x, T_n, and DTR during the period 1961–2012. We also show the trends in T_{xS} and T_{nW}, given that their changes are more likely to have potential impacts on society in coping with a changing climate.

The annual mean daily T_x clearly shows warming trends across the whole country. Five hundred thirty-seven stations have significant warming trends, most of which are located east of 95°E and north of 35°N (Figure 1a). In the areas east of 95°E and south of 35°N, most of the regions show insignificant warming trends, although significant warming trends are identified from the middle Yangtze River valley to the southeast coast. In addition, a weak cooling trend is estimated for 11 sites in local mountainous regions in Sichuan and Yunnan provinces, but none is significant at the 5% level. For the summer mean T_x (Figure 1b), the warming trends are weaker than for the annual mean T_x and are mainly located in the northern, western, and southern coastal regions of China. Cooling trends are mainly identified from the Yangtze River to Huanghe basins, which is related to the weakening trend of East Asian summer monsoon circulation and the associated excessive precipitation along the Yangtze River basin [*Yu and Zhou*, 2007; *Zhou et al.*, 2013]. The weakening trend of East Asian summer monsoon circulation is driven by internal variability mode of Pacific Decadal Oscillation rather than global warming [*H. Li et al.*, 2010; *Q. Li et al.*, 2010].

Similarly, positive trends in annual mean T_n are observed at almost all locations across the country; the warming rate in the northern regions is greater than that in the southern regions (Figure 1c). Seven hundred sixty stations show significant increasing trends with many warming trends exceeding 0.8°C/decade in the northeast, Yellow River, and Yangtze River regions. A negative trend is estimated for eight sites, but none of them is significant at the 5% level. For T_{nW} (Figure 1d), positive trends are also observed at almost all locations across the country, and the greatest warming trends occurred during this season. Only one station shows a cooling but insignificant trend. Seven hundred sixty-six stations have significant increasing trends, with the

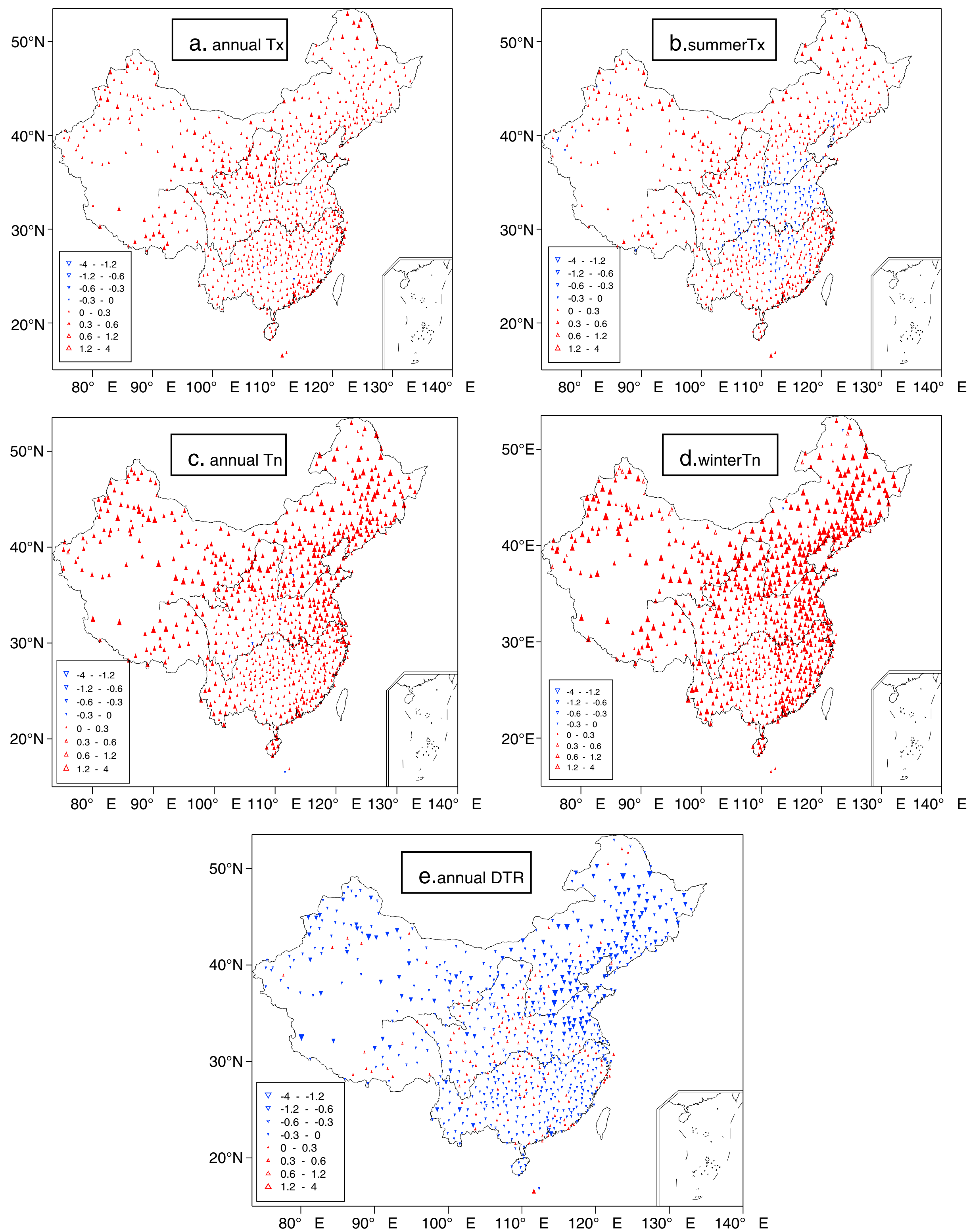

Figure 1. Trends of (a) annual T_x,(b) summer T_x, (c) annual T_n, (d) winter T_n, and (e) annual DTR during 1961–2012. Red upward pointing triangles indicate increasing trends and blue downward pointing triangles decreasing trends. Filled triangles indicate trends that are significant at the 5% level. The triangle size is proportional to the trend magnitude. Units: °C/decade.

greatest warming rates exceeding 0.9°C/decade in high-latitude regions, such as Xinjiang, Mongolia, northwest, and northeast regions.

The annual mean DTR shows decreasing trends in most regions (Figure 1e). Most stations with significantly decreasing trends at the 5% level are located in the northeast, northern, western, Jianghuai, and Yunnan regions. Other regions, such as Yangtze River, southern, and southwest China, mainly show insignificant trends.

3.2.2. 1998–2012

The recent 15 year period, 1998–2012, has been recognized as having little warming in the global surface temperature series. IPCC [*Hartmann et al*., 2013] gives a warming magnitude of only 0.05 (−0.05 ~ 0.15 in 95% confidence interval) °C/decade in this period, compared to the magnitude of 0.12 (0.08 ~ 0.14 in 95% confidence interval) °C/decade during the years 1951–2012. In China during the 15 year period, the annual mean trends are −0.39°C/decade in T_x and −0.13°C/decade in T_n (Table 1). Therefore, the mean temperature change is about −0.26°C/decade, and a negative trend of −0.26°C/decade is observed for annual mean DTR.

The patterns of trends of annual mean T_x and T_n, as well as T_{xS} and T_{nW}, differ in 1998–2012 (Figure 2) from 1961 to 2012 (Figure 1). For T_x (Figure 2a), there were positive trends in the southwest, the Yangtze River, and far northeastern China, while negative trends were observed in other regions, with the largest decreases mainly located near northern and southeast coasts. For T_n (Figure 2c), the regions with significantly decreasing trends are mainly located in northern China, while the regions with significantly increasing trends are mainly distributed across the Tibetan Plateau.

For T_{xS} (Figure 2b), there were positive trends at many locations across the country but with negative trends near the Bohai Sea, the Yellow River Loop, northern Xinjiang, and northeastern Tibetan Plateau regions. Thus, during the hiatus, the T_{xS} shows significant warming trends in many regions in China. On the other hand, T_{nW} (Figure 2d) exhibits significant cooling trends in most regions in China, although some southwestern regions (Yunnan-Guizhou Plateau (100–110°E, 23–27°N) and the southern and eastern Tibetan Plateau) have warming trends.

Finally, the annual mean DTR has decreased almost everywhere across the country except for the Yangtze River and the southern Tibetan Plateau (Figure 2e). Compared with the trends of annual mean DTR during 1961–2012 (Figure 1e), there are more stations showing significantly increasing trends in southwestern China, while negative trends are observed in other regions, such as central China, the southeastern coast, the northeast, and parts of the Tibetan Plateau.

It can be concluded that in the recent 15 years, the difference between the winter nighttime and summer daytime mean temperatures has been widening in most regions of China except for the southwest. Summer days have become warmer and winter nights cooler—a unique and interesting characteristics of climate change in mainland China during the warming hiatus. These features are much different from those during 1961–2012, especially for T_{nW}, which showed negative trends in most regions of China, except for some southwestern regions, during 1998–2012. These two indices are most likely to influence public feeling about climate change.

4. Possible Linkage Between Temperature Change and SSR, Aerosol Forcing, and Precipitation During the Hiatus

Next we attempt to explain the particular temperature change features in China during 1998–2012 in terms of variations in SSR and regional aerosol forcing along with precipitation. *Kühn et al*. [2014] found that recent changes (1996–2010) in aerosol forcing over China are positive (warming) due to increasing black carbon concentrations, especially in the north (see their Figure S1). However, this forcing cannot explain the cooling patterns shown in Figure 2 for winter or summer. Furthermore, some recent summer daytime warming trends are seen on southern rather than northern China (Figure 2b). On the contrary, *Lovejoy* [2014] believes that the pause (warming hiatus) is no more than natural variability. Without using surface air temperature and aerosols, the Twentieth Century Reanalysis (20CR) [see also *Compo et al*., 2013] closely reproduced SAT change features in Figures 1 and 2 (see Figure S4), particularly during the winter season. This leads us to consider that the immediate cause of the winter cooling must be changes in atmospheric circulation, i.e., an increase in winds from the north responding to the assimilated atmospheric pressure data.

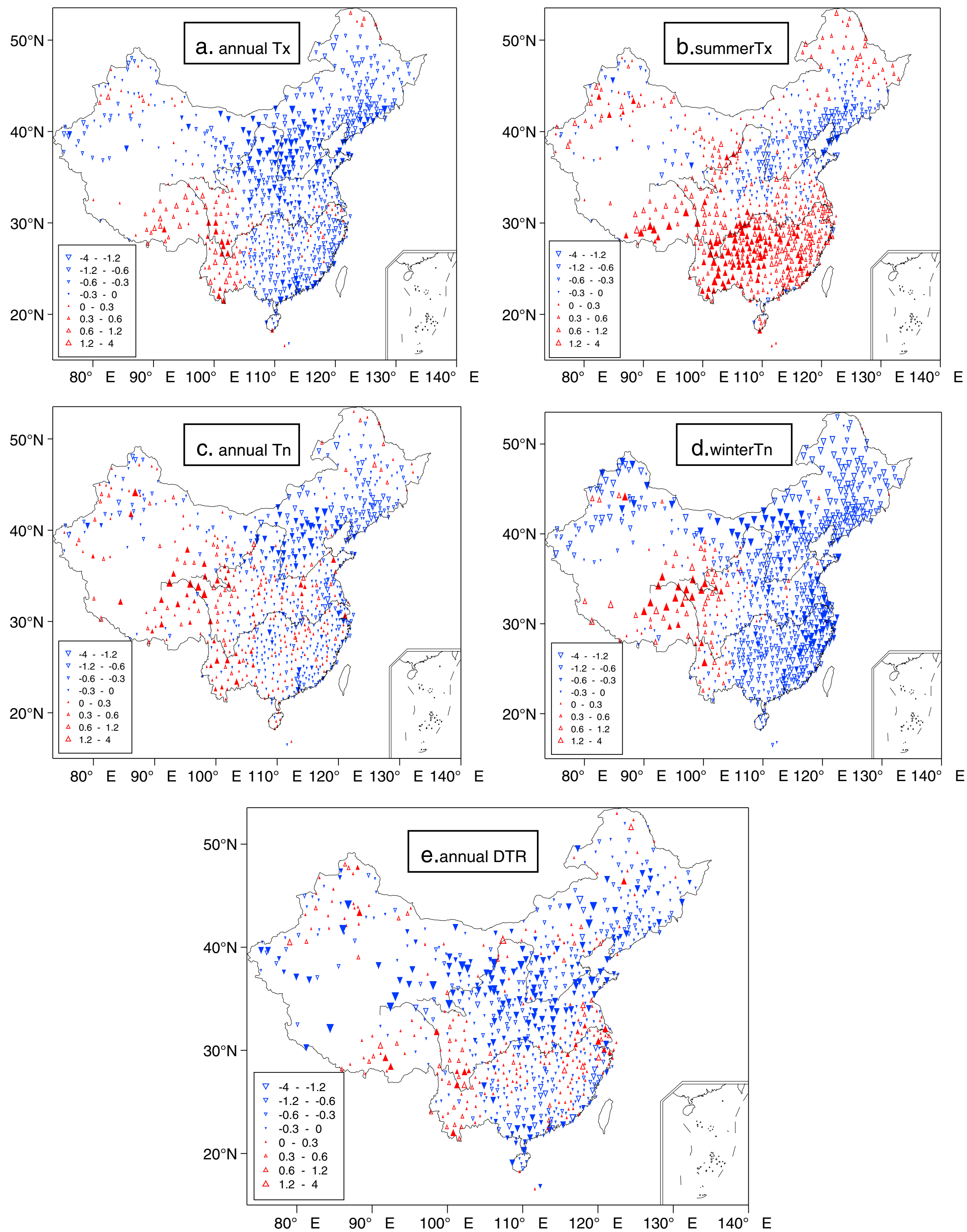

Figure 2. Same as in Figure 1 but for the period 1998–2012.

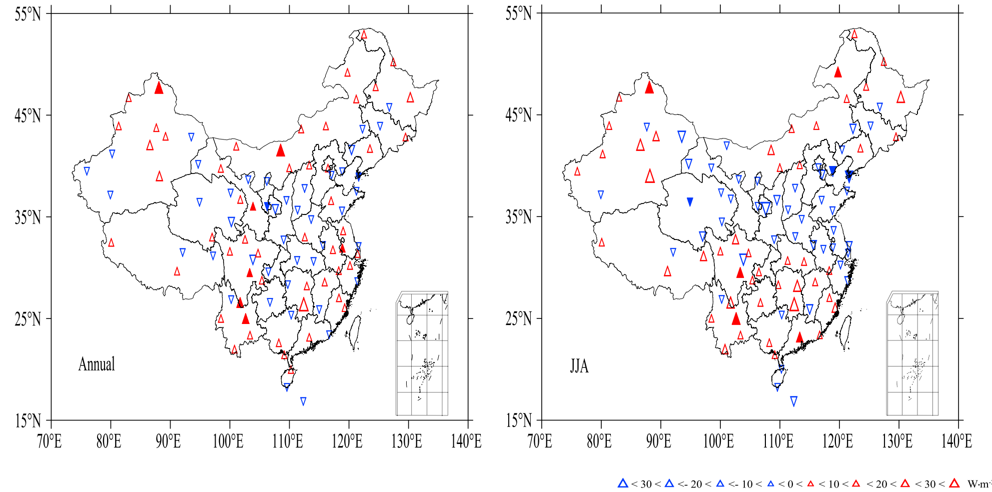

Figure 3. Trends of (left) annual and (right) summer SSR during 1998–2012. Units: W/m^2 decade^{-1}.

4.1. Consistency Between SSR and Maximum Temperature

In general, SSR is expected to have a high correlation with DTR or T_x [*Liu et al*., 2004; *Yang et al*., 2013; *Zhou et al*., 2009]. In this paper, we calculated the correlation coefficient (r) between SSR and seasonal T_x during 1998–2012 and found that the values of T_x are significantly correlated with SSR during winter (December-January-February (DJF)) and summer (June-July-August (JJA)) during this period ($r = 0.57$ and 0.47, respectively), suggesting possible causes of T_x changes.

Figures 1 and 2 indicate that trends of DTR in 1998–2012 differed substantially from those in 1961–2012 (and therefore 1961–1997); the trends in annual mean T_x and T_n show similar marked changes, particularly in T_{xS} and T_{nW}. So in this section, we examine how SSR has changed and its relationship with DTR. In 1998–2012, there has been brightening in SSR annually (Figure 3, left) in the southern Qinghai-Tibet Plateau, the southwest, far northwest, and northeast of China, possibly due to increasing clear sky over these regions. The SSR declined in a zone around 35°N, where a significant decrease in DTR was observed. In summer (Figure 3, right), the regions with decreasing SSR around 35°N are more coherent and the overall pattern of SSR trends resembles that of T_{xS} trends in Figure 2b, except for the Yangtze and Huaihe River valleys, north of Xinjiang, and west of Hetao in Inner Mongolia. The spatial correlation between the trends in Figures 3 (left) and 2a (annual mean) is only −0.01, whereas that between Figures 3 (right) and 2b (summer) is 0.34 ($n = 90$), which is statistically significant at the 0.1% level. The weak correlation in the annual means between SSR and T_x (−0.01) or DTR (0.20) agrees well with previous results [*Wang and Dickinson*, 2013], which indicate that the temperature change has not been more closely related to SSR since the 1970s, while on seasonal scales, there are still significant correlations between summer SSR and T_x (0.34) or DTR (0.35).

4.2. Distinctive Temperature Change in Southwest China

T_x and T_n in the southwest region (Figure 2) showed continued warming trends during the warming hiatus period, but DTR changed differently relative to the earlier period (1961–1997). As shown in Figure 4 (we plot the results before 1998 in grey to stress the unreliability of the SSR data and to highlight the recent 15 years), this region has become drier in winter since 1998, and the relative humidity has decreased about 10% during the last 15 years. The winter T_x has increased by about 2°C from 1998 to 2012, inconsistent with the slight decrease in SSR during the same time. Similar characteristics were also found in summer where precipitation showed a more obvious, though statistically insignificant, decline than in winter. Possibly, the ongoing warming in the southwest region may have been facilitated by the low thermal capacity of the arid surface [*Ji et al*., 2014] leading to an even drier surface [*Yang et al*., 2011] and reduced evaporative cooling due to less soil moisture.

5. Main Conclusions

Surface air temperatures across China behaved in similar ways to global SAT during 1961–2012 as a whole but have had distinct features since the warming hiatus started in the late 1990s.

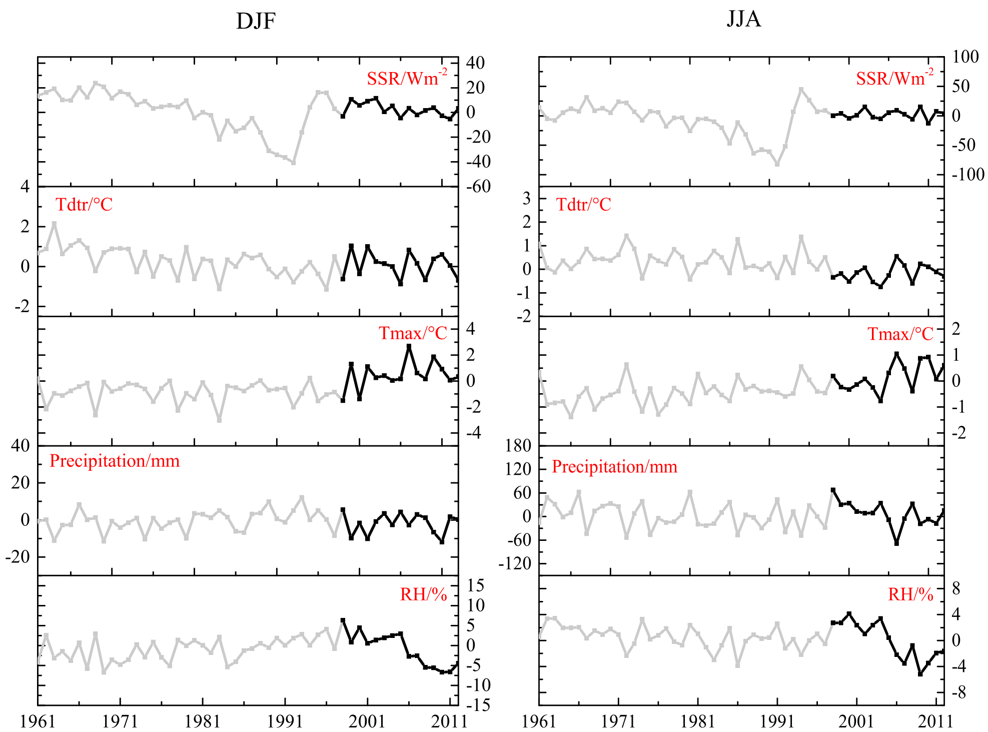

Figure 4. Regional mean time series of SSR, DTR, T_x, precipitation, and relative humidity (RH) in southwest China in (left column) winter (DJF) and (right column) summer (JJA) during the period 1998–2012 (1961–1997 series are given in grey line to show comparisons). Regional mean series is calculated from the arithmetical average of the station series in the region.

During 1961–2012, there was a marked decline of DTR in northern China (Figure 1e) with weak trends elsewhere in China. Minimum temperatures warmed most in winter, and maximum temperatures warmed less than the minima and least in summer, implying a more equable climate with, in particular, fewer cold nights.

During 1998–2012, the national climate warming trend was replaced by a decrease of mean maximum temperature, while the mean minimum temperature was static. On seasonal timescales, T_{xS} continued to increase significantly except in the southern parts of north and northeast China, and T_{nW} decreased quickly except for the plateau area. In other words, during the warming hiatus period, the summer became warmer, and the winter colder, giving a less equable climate.

In general, SSR is expected to have a high correlation with DTR and surface air temperature. However, *Wang and Dickinson* [2013] recently found that at global scales, such a relationship was insignificant during the rapid warming period since the mid-1970s and during the recent warming hiatus period. Nevertheless, this study shows that the spatial patterns of large-scale T_{xS} increase are in accord with observed SSR changes, implying that enhanced summer insolation is an important reason for the T_{xS} increase.

The continuing warming of annual mean temperature, T_{xS} and T_{nW}, and increasing DTR in southwest China may be connected to the recent droughts in this region. The winter cooling in eastern China results likely from atmospheric circulation change, i.e., an increase in winds from the north in accord with atmospheric pressure patterns as shown in the Twentieth Century Reanalysis [*Compo et al*., 2013].

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