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Key Points:

- The DTR decreased in the past 50 years as Tmin increased faster than Tmax
- Decreasing trends of DTR reduced from the north to south of China
- The decline of SD is one of the most important reasons for the DTR decrease

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Spatiotemporal change of diurnal temperature range and its relationship with sunshine duration and precipitation in China

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Abstract We examined the spatiotemporal variation in diurnal temperature range (DTR) and discussed the reasons for the changes of DTR in China based on data from 479 weather stations from 1962 to 2011. Results showed that DTR decreased rapidly (0.291°C/decade) from 1962 to 1989 due to slightly decreased T_{max} and significantly increased T_{min}, but the decrease in DTR has stopped since 1990 as T_{max} and T_{min} kept pace with each other. During 1990–2011, DTR remained trendless, with slight increase in the 1990s and slight decrease after 2000. During the whole study period from 1962 to 2011, DTR decreased at a rate of 0.157°C/decade nationally. Spatially, decreases in DTR were greatest in Northeast China and lowest in Southwest China with a transect running from northeast to southwest showing the decreasing trends change from high to low. Seasonally, DTR decreases were greatest in winter and lowest in summer, and the magnitudes of decrease reduced from the north to south of China. The changes in DTR were closely correlated with changes in sunshine duration (SD) in China except the Tibetan Plateau, suggesting that SD decrease is an important contributor to the decrease of DTR through its influence on T_{max}. In addition to the contribution of SD decrease, the increasing of precipitation played an important role in DTR decrease in Northwest China, the most arid region of China. It appeared that changes of cloud cover (CC) were not the reasons for DTR changes in the past 50 years as CC has decreased during the study period.

1. Introduction

The diurnal temperature range (DTR), defined as the difference between the daily maximum temperature (T_{max}) and minimum temperature (T_{min}), is considered as a suitable measure of climate change due to its sensitive to radiative energy balance changes [*Dai et al.*, 1999; *Sun et al.*, 2006; *Makowski et al.*, 2008]. In most parts of the world, T_{min} have increased at a faster rate than T_{max} since the 1950s, resulting in the decrease of DTR [*Karl et al.*, 1993; *Horton*, 1995; *Easterling et al.*, 1997; *Zhou et al.*, 2009]. However, in a few regions such as India, DTR has increased in recent decades [*Rupa Kumar et al.*, 1994].

DTR variation has regional and seasonal characteristics due to complicated interactions of local climatic and anthropogenic factors [*Karl et al.*, 1991, 1993; *Easterling et al.*, 1997]. Many scholars have studied the variation of DTR in China, showing that DTR decreased significantly in China over the past several decades [e.g., *Karl et al.*, 1991, 1993; *Kukla and Karl*, 1993; *Dai et al.*, 1997, 1999; *Liu et al.*, 2004; *Ye et al.*, 2010; *Zhou and Ren*, 2011; *Wang and Dickinson*, 2013; *Xia*, 2013; *Wang et al.*, 2014], but most of them focused on DTR changes at the national scale. *Chen and Chen* [2007] analyzed the spatial variation of DTR in China, but they mainly studied the declining trends of DTR during the whole study period. Similar to many other regions of the world, China experienced an obvious dimming from the 1960s to the 1980s, but it did not persist thereafter [*Pinker et al.*, 2005; *Wild et al.*, 2005, 2007]. Many studies found that radiation in China changed from dimming to brightening during the early 1990s [*Liang and Xia* [2005]; *Shi et al.*, 2008; *Ye et al.*, 2010], but *Tang et al.* [2011] indicated that the solar radiation reached a stable level since the 1990s. Consistent with the transition of solar radiation, *Liu et al.* [2004] found that the DTR in China decreased rapidly between 1960 and 1990 but leveled off in the 1990s. Considering the rapid climate changes in the 1990s [*Liu et al.*, 2004], the new data set including data from 2000 onward should be added to further understand present and future climate dynamics.

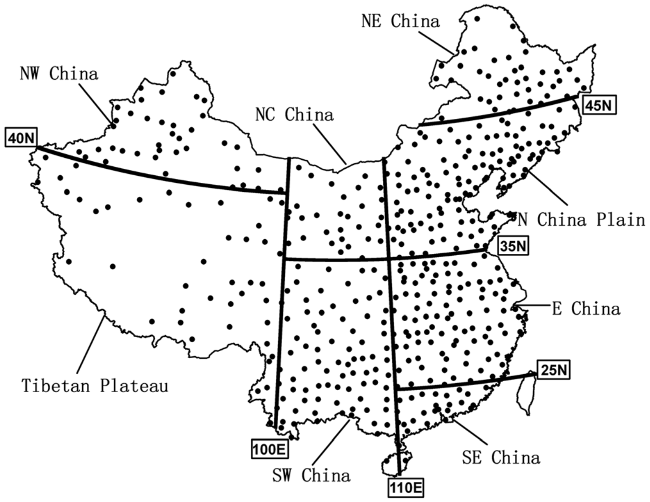

Figure 1. Geographical distribution of the 479 weather stations from eight climatic regions in China.

Cloud cover and precipitation have significant effects on the surface energy and hydrological balance and thus are widely identified as the main causes for DTR reduction [*Karl et al.*, 1993; *Dai et al.*, 1997, 1999; *Stone and Weaver*, 2002]. Clouds can reduce T_{max} through reducing incident shortwave solar radiation to the Earth's surface during the day and increase T_{min} through intercepting outgoing longwave radiation at night, thereby having a negative effect on DTR [*Campbell and Vonder Haar*, 1997; *Dai et al.*, 1997, 1999; *Zhou et al.*, 2009]. Precipitation, on the other hand, can reduce T_{max} and thus DTR through evaporative cooling [*Dai et al.*, 1999; *Zhou et al.*, 2009]. Other factors, such as atmospheric circulations, greenhouse gases, aerosols, and land cover/land use, could also have impacts on DTR [*Karl et al.*, 1993; *Stenchikov and Robock*, 1995; *Hansen et al.*, 1995; *Collatz et al.*, 2000; *Zhou et al.*, 2004; *Dai et al.*, 2006; *Huang et al.*, 2006]. For example, aerosols may have a cooling effect on T_{max} by reflecting solar radiation and influencing cloud properties [*Dai et al.*, 1997]. Greenhouse gases may change the surface energy and hydrological balance, hence affecting DTR [*Zhou et al.*, 2009]. As the complexity of the climatology [*Dai et al.*, 1997, 1999; *Sun et al.*, 2006], further investigations on the possible reasons of DTR change are needed.

In the current study, we collected data from 479 weather stations in China from 1962 to 2011. By analyzing the daily observation data in the past 50 years, we examined the spatial and temporal trends of DTR and its relationships with other climate variables such as precipitation, sunshine duration (SD), and cloud cover (CC). This study focuses on the spatial and temporal changes of DTR and explores possible reasons for the changes of DTR, particularly for the period from 2000 to 2011.

2. Materials and Methods

2.1. Data Sources

Data were sourced from the China Meteorological Administration, including daily measurements of T_{max}, T_{min}, precipitation, CC, and SD from more than 800 national reference climatic and basic meteorological stations across China. Most weather stations of China were established in the early 1950s. However, data in the earlier years contain more gaps due to instrument malfunctions. Thus, in this study we exclude the data from 1951 to 1961 and rely only on data reported from 1962 to 2011. According to the criteria that the series length is no less than 50 years and no more than 2% of the data are missing, the data of 479 stations were selected for analysis. Figure 1 shows the distribution of 479 stations in this study and the division of China into eight climatic regions by latitude and longitude, as defined by previous studies [*Shen and Varis*, 2001; *Liu et al.*, 2005, 2008, 2009, 2011]. The eight climatic regions reflect climatic and landform conditions in China [*Liu et al.*, 2011], coinciding roughly with the country's socioeconomic macroregions [*Qi et al.*, 2004]. In the aspects of climate conditions, temperatures generally increase from north to south [*Liu et al.*, 2011], whereas precipitation decreases from the southeastern coastal areas to the northwestern inland areas [*Qian and Leung*, 2007]. The annual total rainfall is more than 1500 mm in Southeast China but less than 100 mm in Northwest China [*Qian et al.*, 2009]. As such, we adopted these eight subdivisions which reflect the differences of climatic, landform, and socioeconomic conditions between different regions and also facilitate comparisons with studies published about other climatic phenomena [*Shen and Varis*, 2001; *Liu et al.*, 2005, 2008, 2009, 2011].

2.2. Data Processing

We adopted the method used by *Wang and Gaffen* [2001] to assure the quality and consistency of the selected data. First, the outlier data were identified by visual inspection of those data exceeding 3 standard deviations, and these data were dealt with as missing values. Second, we identified another type of erroneous data involving an abrupt shift in mean values, associated with station relocation. Based on this approach, there were 92 stations requiring data adjustments due to relocation. For these data, we adjusted the time series through shifting the earlier part of the time series by the difference in the mean values before and after the relocation [*Wang and Gaffen*, 2001]. With this vigorous data assurance policy, the quality and consistency of the data were guaranteed.

Missing data are inevitable for the most weather stations with long-term monitoring. In our study, most temperature data gaps were no more than 3 days. To supply the missing data, we used a simple linear interpolation algorithm when the data were missing for up to seven consecutive days for the temperatures and up to three consecutive days for the other variables. When the data were missing for more than seven consecutive days for the temperatures and more than 3 consecutive days for other variables, we used a stepwise regression to fill the gaps [*Liu et al*., 2004]. We performed the stepwise regression every 5 years, with all the stations that had no missing data as the variable and missing stations as the dependent variable. The stepwise regression showed a minimum coefficient of determination R^2 of 0.986 and 0.995 for $T_{\max}$ and $T_{\min}$, respectively.

The methods we used to fill the data gaps cannot substantially affect our results in analyzing China's climate changes. Missing data accounted for less than 0.35% of the total records from 1962 to 2011 in this study. Comparing the original data set (with missing data) with the gap-filled data set, we found that the difference (means and the trends) between two data sets was not statistically significant ($P > 0.05$). In this study, we used the gap-filled data set because the missing data were not distributed along the time series randomly but mainly concentrated in the early years [*Liu et al*., 2004].

In order to eliminate the presence of autocorrelation in our data, we tested the time series autocorrelation and employed prewhiting approach to exclude serial autocorrelation for the original data [*Hu et al*., 2012]. The monthly, seasonal, and annual mean variable values were computed from the daily climate data. Then regional average variable values were computed by the Thiessen polygon method [*Nicholls et al*., 1996]. In addition, the trend in temperatures and other climate factors was estimated by Mann-Kendall test and simple linear regression [*Mann*, 1945; *Kendall*, 1975].

In order to analyze temporal variation of DTR and main influence factors, we applied a nine-point binomial filter which can smooth out the year-to-year variations in a time series and show the longer-term trend. The time series of DTR was compared with other variables to estimate the influence of climate variables on DTR. Finally, we also calculated partial correlation coefficients between the variables and DTR to eliminate the effects of any interaction among variables on DTR.

3. Results and Discussion

3.1. Annual Change

Results from the time series analysis of temperatures showed that there was a great difference of temperature changes before and after 1990 (Figure 2). At the national scale, $T_{\max}$ declined modestly and $T_{\min}$ increased significantly before 1990, whereas both $T_{\max}$ and $T_{\min}$ increased significantly during the 1990s (Figure 2). These trends were consistent with previous findings [*Karl et al*., 1991, 1993; *Easterling et al*., 1997; *Liu et al*., 2004]. After 2000, however, we found that the increase of $T_{\max}$ and $T_{\min}$ slowed down (Figure 2) and both of them showed no significant change from 2000 to 2011. Over the whole study period from 1962 to 2011, $T_{\max}$ and $T_{\min}$ increased by 0.221°C/decade and 0.378°C/decade, respectively.

At the regional scale, the changes of $T_{\max}$ and $T_{\min}$ were similar to that on the nationwide scale, but with some differences in eight climatic regions (Table 1). For example, both $T_{\max}$ and $T_{\min}$ decreased slightly in Northeast China from 1990 to 2011, which was different from other regions. Over the whole study period, both $T_{\max}$ and $T_{\min}$ increased significantly in all eight climatic regions of China (Table 1). The warming trends became slower as we moved from Northeast China to Southeast China. This is also true as we move from north central China to Southwest China (Table 1), indicating that temperature change is closely related with the latitude. The minimum temperature increased at a faster rate than $T_{\max}$ at both national and regional scales, resulting in the decrease of DTR in our study.

For the DTR, it decreased significantly across China at a rate of 0.291°C/decade from 1962 to 1989 ($P < 0.01$, Figure 2), due to slightly decreased $T_{\max}$ and significantly increased $T_{\min}$. The DTR showed a slight and

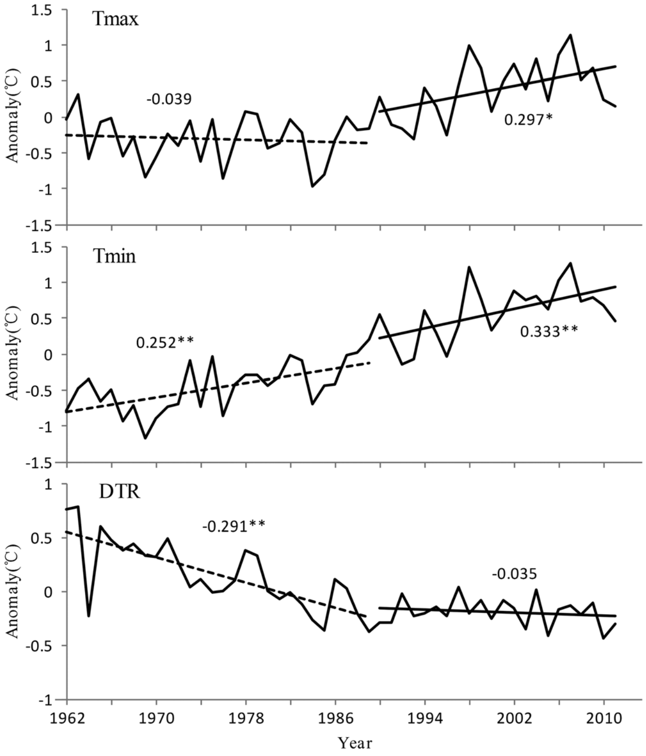

Figure 2. Linear trends and anomalies from annual means of daily T_{max}, T_{min}, and DTR for China. Linear trends: 1962–1989 (dashed lines) and 1990–2011 (solid lines). Values along the trend lines are the rate of change (°C/decade). Single asterisk: $P < 0.05$; double asterisk: $P < 0.01$.

nonsignificant increase in the 1990s when the T_{max} and T_{min} increased rapidly but with comparable rate (data not shown). After 2000, however, we found a slight and nonsignificant decrease of DTR (−0.098°C/decade) between 2000 and 2011 due to no significant change of T_{max} and T_{min}. As a result, DTR decreased slightly at the rate of 0.035°C/decade from 1990 to 2011 (Figure 2), indicating that DTR has reached a stable stage since 1990 in China.

During the entire study period, DTR for China as a whole decreased at a rate of 0.157°C/decade from 1962 to 2011. This is lower than the result of *Liu et al.* [2004] (−0.202°C/decade between 1955 and 2000) but higher than that for the Northern Hemisphere (−0.089°C/decade between 1950 and 1993) [*Easterling et al.*, 1997]. Excluding the data after 2000, the trend in DTR was −0.208°C/decade between 1962 and 2000, which was identical to that reported by *Liu et al.* [2004]. These indicate that the relative lower decrease rate of DTR for our study comes from the fact that the comparable changes of T_{max} and T_{min} in the 1990s continued after 2000, muting the overall trends of DTR. Our study further confirmed that the decrease of DTR in China did not extend to the period after 1990.

At the regional scale, similar to the national average trend, DTR decreased significantly before 1989 and showed no significant change from 1990 to 2011 for all the climate regions (Table 1). However, the decrease of DTR stopped a little early in Northeast China, East China, and Southeast China (Figure 3). Over the whole study period, DTR decreased in eight climatic regions due to the significant decline of DTR before 1989.

Spatially, the decrease of DTR was greatest in Northeast China and lowest in Southwest China, and the decrease rate became slower from the north to south of China (Table 1). The spatial pattern of changes in DTR

Table 1. Annual Trends (°C/Decade) of T_{max}, T_{min}, and DTR in Eight Climatic Regions of China

	1962–2011			1962–1989			1990–2011		
	T_{max}	T_{min}	DTR	T_{max}	T_{min}	DTR	T_{max}	T_{min}	DTR
Northeast China	0.279**	0.552**	−0.273**	0.132	0.560**	−0.427**	−0.036	−0.046	0.010
North China Plain	0.249**	0.440**	−0.190**	0.083	0.391**	−0.309**	0.083	0.159	−0.076
East China	0.186**	0.303**	−0.117**	−0.208	0.097	−0.305**	0.396**	0.412**	−0.015
Southeast China	0.159**	0.240**	−0.080*	−0.164	0.138	−0.302**	0.261	0.200	0.061
North central China	0.308**	0.496**	−0.187**	0.043	0.423**	−0.376**	0.347*	0.460**	−0.113
Southwest China	0.132**	0.198**	−0.067*	−0.129	0.056	−0.186**	0.431**	0.333**	0.098
Northwest China	0.249**	0.475**	−0.226**	−0.026	0.288*	−0.314**	0.316	0.517**	−0.202
Tibetan Plateau	0.260**	0.450**	−0.190**	−0.004	0.321**	−0.325**	0.604**	0.644**	−0.041

*Significant at $P < 0.05$.
**Significant at $P < 0.01$.

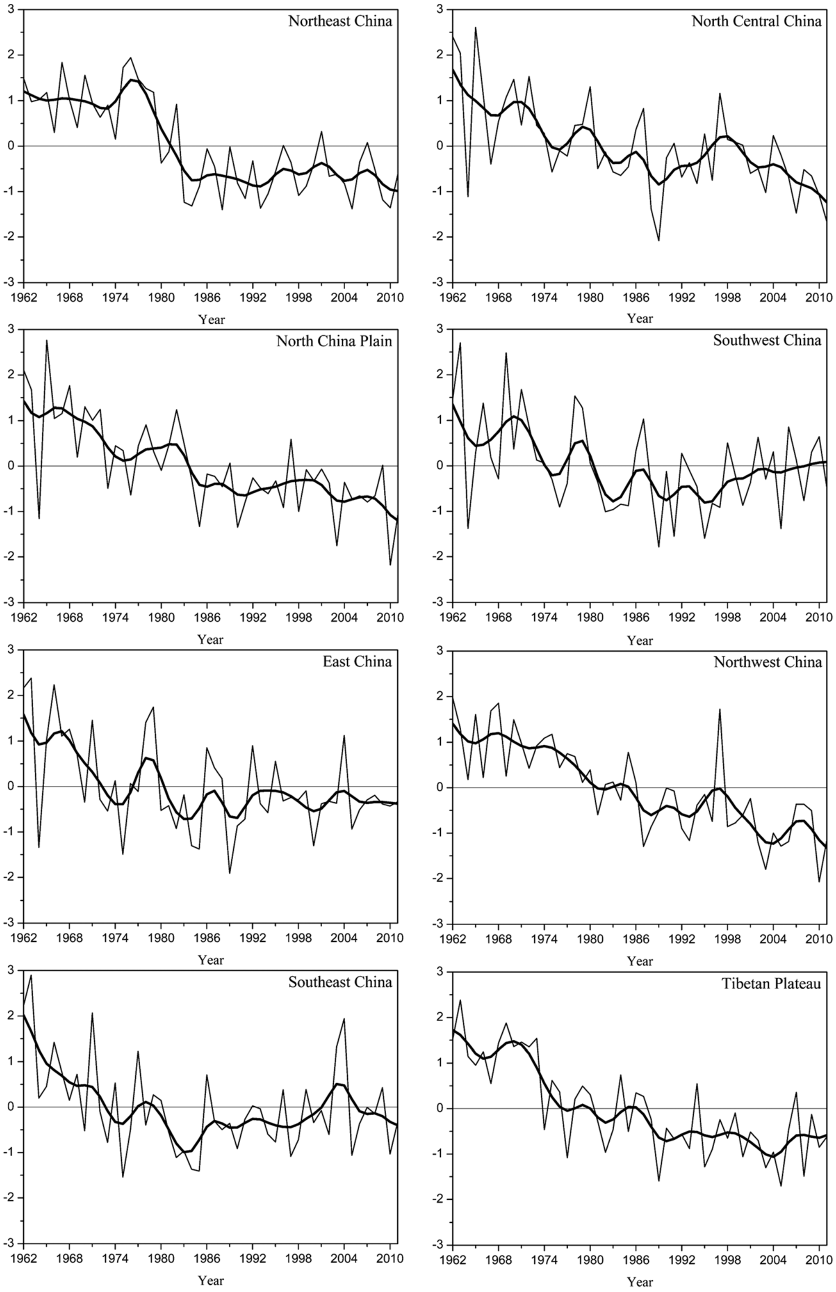

Figure 3. Time series of regional normalized (by standard deviation) DTR from 1962 to 2011. The heavy line is the result of smoothing with a 9 year binomial filter with reflected ends.

was not obvious in previous studies that based on the stational trend [*Karl et al*., 1991; *Liu et al*., 2004]. *Liu et al*. [2004] examined the spatial pattern of DTR changes in China from 1955 to 2000 by using DTR trends of each meteorological station and found no obvious spatial character. Excluding the data after 2000, based on the regional trend, however, we also found that the decreasing rates of DTR reduced from the north to south of China between 1962 and 2000. *Nicholls* [2001] pointed out that increased spatial scale could be an effective way to reduce the unexplainable variability (or "noise") and enhance the signal-to-noise ratio. In the current study, we grouped 479 stations across China into eight regions which possibly reduced noise and enhanced the signal in temperature time series. This is likely to account for the obvious spatial pattern of changes in DTR in our analysis.

Table 2. Seasonal Trends (°C/Decade) of T_{max}, T_{min}, and DTR in China and the Eight Climatic Regions

		Winter			Spring			Summer			Autumn		
		T_{max}	T_{min}	DTR	T_{max}	T_{min}	DTR	T_{max}	T_{min}	DTR	T_{max}	T_{min}	DTR
	1962–2011	0.287**	0.523**	−0.236**	0.202**	0.349**	−0.147**	0.145**	0.281**	−0.136**	0.246**	0.355**	−0.109
Nationwide	1962–1989	0.148	0.547**	−0.398**	−0.166	0.127	−0.293**	−0.119	0.120	−0.239**	−0.026	0.208	−0.235**
	1990–2011	−0.023	0.026	−0.050	0.475*	0.333	0.142	0.406**	0.424**	−0.019	0.318	0.533**	−0.215*
Northeast China		0.341	0.671**	−0.326**	0.224	0.604**	−0.380**	0.259**	0.451**	−0.192*	0.293**	0.488**	−0.195*
North China Plain		0.356**	0.621**	−0.264**	0.237*	0.456**	−0.218**	0.182**	0.301**	−0.119*	0.220*	0.380**	−0.160**
East China		0.207	0.429**	−0.222*	0.334**	0.297**	0.037	−0.003	0.186**	−0.191**	0.207**	0.299**	−0.091
Southeast China	1962–2011	0.200	0.373**	−0.173*	0.089	0.140*	−0.051	0.150**	0.185**	−0.035	0.198**	0.262**	−0.063
North central China		0.426**	0.686**	−0.260**	0.240**	0.398**	−0.157*	0.221**	0.453**	−0.225**	0.334**	0.439**	−0.105
Southwest China		0.170	0.307**	−0.137*	0.045	0.140**	−0.095*	0.107*	0.153**	−0.046	0.205**	0.192**	0.012
Northwest China		0.294*	0.642**	−0.349**	0.173*	0.370**	−0.198**	0.193**	0.391**	−0.197**	0.333**	0.495**	−0.162
Tibetan Plateau		0.334**	0.562**	−0.228**	0.155*	0.405**	−0.250**	0.247**	0.379**	−0.132**	0.305**	0.456**	−0.151**

*Significant at $P < 0.05$.
**Significant at $P < 0.01$.

3.2. Seasonal Change

Seasonally, similar to the annual trends, T_{max} in China decreased slightly before 1989 and increased after 1990; T_{min} increased during both two periods in all seasons (Table 2). But in winter, T_{max} increased slightly (0.148°C/decade) before 1989 and decreased slightly (−0.023°C/decade) after 1990. Over the whole study period, both T_{max} and T_{min} increased significantly in all seasons (Table 2). Increases of T_{max} and T_{min} on the nationwide scale were greatest in winter (0.287 and 0.523°C/decade) and lowest in summer (0.145 and 0.281°C/decade) (Table 2). This is consistent with previous studies of China [*Karl et al.*, 1991, 1993] but different from reports for the globe and the Northern Hemisphere [*Easterling et al.*, 1997], where changes were greatest in winter but lowest in autumn. We attribute this difference to China's monsoon-driven climate, which concentrates more precipitation in summer. *Liu et al.* [2004] suggested that the high moisture content in summer effectively slowed down changes in temperature. At the regional scale, both T_{max} and T_{min} increased in all seasons during the study period. The minimum temperature and T_{max} in eight climatic regions also showed greatest changes in winter except for the T_{max} in East China, Southwest China, and Northwest China and lowest changes in summer except for the T_{min} in north central China, Southwest China, and Northwest China (Table 2). This implies that other factors may influence the trends of temperature change in different regions apart from the precipitation.

Spatially, similar to the annual trends, both the seasonal trends of T_{max} and T_{min} became slower from the north to south of China, except for T_{max} in some regions (Table 2). For example, T_{max} of North China Plain increased faster than Northeast China in winter and T_{max} of East China decreased slightly in summer. The magnitude of changes for T_{max} increased from Northeast China to East China in spring, which is opposite to the spatial pattern of annual changes.

For the DTR, it decreased significantly across China in all seasons during 1962–1989 but showed no significant change during 1990–2011 except in autumn when it decreased significantly (−0.215°C/decade) (Table 2). At the regional scale, similar to the national average trend, DTR in eight climatic regions decreased in all seasons during 1962–1989 and decreased in autumn and showed no significant change in other seasons during 1990–2011. During the whole study period from 1962 to 2011, DTR decreased significantly in all seasons in eight climatic regions of China (Table 2). The reductions of DTR were lowest in summer both on the nationwide and regional scales and greatest in winter

Table 3. Correlation Coefficients Between Temperature Variables (T_{max}, T_{min}, and DTR) and Other Climatological Variables: Total Cloud Cover (CC), Precipitation (P), and Sunshine Duration (SD)

		CC	P	SD	CC	P	SD	CC	P	SD
			(1962–2011)			(1962–1989)			(1990–2011)	
Nationwide	T_{max}	−0.393	−0.073	0.501*	−0.246	−0.224	0.585**	−0.044	−0.035	0.372
	T_{min}	−0.346	0.084	−0.064	−0.208	0.152	−0.203	0.165	0.065	−0.064
	DTR	−0.174	−0.291	0.924**	−0.025	−0.393*	0.936*	−0.400	−0.308	0.738**
Northeast China	T_{max}	−0.418	−0.288	0.487*	−0.422*	−0.485**	0.438**	−0.135	−0.150	0.245
	T_{min}	−0.511*	−0.003	−0.109	−0.523**	−0.011	−0.139	0.091	0.130	−0.123
	DTR	0.188	−0.432	0.694**	0.308	−0.708**	0.700**	−0.294	−0.626**	0.600**
North China Plain	T_{max}	−0.316	−0.489*	0.430	−0.351	−0.522**	0.460**	−0.384	−0.261	0.229
	T_{min}	−0.200	−0.125	−0.282	−0.407	−0.165	−0.238	0.230	0.088	−0.288
	DTR	−0.137	−0.377	0.911**	−0.2 99	−0.494**	0.910**	−0.214	−0.710**	0.810**
East China	T_{max}	−0.449	−0.201	0.725**	−0.466*	−0.486**	0.758**	−0.208	−0.078	0.408
	T_{min}	−0.283	0.154	−0.285	−0.032	0.201	−0.367	0.041	0.030	−0.176
	DTR	−0.239	−0.457*	0.869**	−0.327	−0.575**	0.926**	−0.410	−0.221	0.785**
Southeast China	T_{max}	−0.430	−0.227	0.570**	−0.241	−0.376*	0.614**	−0.302	−0.308	0.411
	T_{min}	0.129	0.236	−0.375	0.248	0.251	−0.443*	0.098	0.027	−0.143
	DTR	−0.436	−0.416	0.902**	−0.409	−0.723**	0.951**	−0.342	−0.549**	0.892**
North central China	T_{max}	−0.356	−0.307	0.486*	−0.478*	−0.522**	0.475*	−0.015	−0.131	0.475*
	T_{min}	−0.138	0.015	0.038	0.028	−0.165	−0.384*	0.271	0.123	0.028
	DTR	−0.291	−0.500*	0.869**	−0.331	−0.494**	0.902**	−0.279	−0.455*	0.809**
Southwest China	T_{max}	−0.485*	−0.292	0.680**	−0.482**	−0.304	0.713**	−0.360	−0.175	0.664**
	T_{min}	−0.325	−0.236	0.397	−0.220	−0.207	−0.025	−0.073	−0.129	0.378
	DTR	−0.343	−0.137	0.847**	−0.342	−0.215	0.888**	−0.397	−0.177	0.870**
Northwest China	T_{max}	−0.291	−0.528*	0.535*	−0.035	−0.532*	0.543**	−0.227	−0.414	0.438*
	T_{min}	−0.209	0.207	0.155	0.047	0.120	−0.148	0.155	−0.001	0.150
	DTR	−0.061	−0.806**	0.793**	−0.140	−0.751**	0.838**	−0.310	−0.734**	0.542*
Tibetan Plateau	T_{max}	−0.454	0.164	0.217	−0.267	0.073	0.195	−0.492*	−0.065	0.170
	T_{min}	−0.433	0.401	−0.028	−0.069	0.314	−0.094	−0.451*	0.124	−0.076
	DTR	0.191	−0.491*	0.572**	−0.166	−0.452*	0.266	−0.197	−0.485*	0.648**

*Significant at $P < 0.05$.
**Significant at $P < 0.01$.

with the exception of changes in Northeast China and the Tibetan Plateau (Table 2). In Northeast China and the Tibetan Plateau, although the changes of T_{max} and T_{min} were greatest in winter, the greatest reductions of DTR occurred in spring since the differences between T_{max} and T_{min} were the largest (Table 2).

Spatially, similar to the spatial pattern of annual trends, the decreasing trends of seasonal DTR reduced from the north to south of China, with the exception in East China in spring and summer (Table 2). The spatial pattern of seasonal trends of DTR was generally consistent with that of T_{min} (Table 2), indicating that the change of T_{min} is the dominate factor that drives the change of DTR seasonally.

3.3. Possible Factors Contributing to DTR Change

3.3.1. Effect of Sunshine Duration on DTR

Solar irradiance (SR) is an important variable for analyzing climate change which is closely related to the change of DTR as reported by *Liu et al*. [2004]. In this study we use sunshine duration (SD) as a proxy for exploring changes of SR as suggested by a number of researches [*Stanhill and Cohen*, 2005; *Wang et al*., 2012]. Some previous studies suggested that SD not only affect pan evaporation but may also influence DTR [*Liu et al*., 2010; *Xia*, 2013].

There was large positive correlation between DTR and SD in all the climatic regions of China (Table 3 and Figure 4). The DTR was also strongly correlated with SD in all the seasons during the study period (Table 4). This is consistent to the work conducted in Northeast China [*Wang et al*., 2014], Northeast India [*Jhajharia and Singh*, 2011], and lower elevation sites in the Swiss Alps [*Rebetez and Beniston*, 1998]. The similarities in temporal patterns of national DTR and SD (Figures 2 and 5) suggest that the declines in SD could be one of the causes for the decline of DTR. Results from the time series analysis of annual SD in eight climatic regions also showed consistent temporal changes with DTR, except for the Tibetan Plateau prior to 1980 (Figures 3 and 6). Similar to the trends of DTR, the decrease of SD stopped a little early in Northeast China, East China, and Southeast China as well (Figure 6).

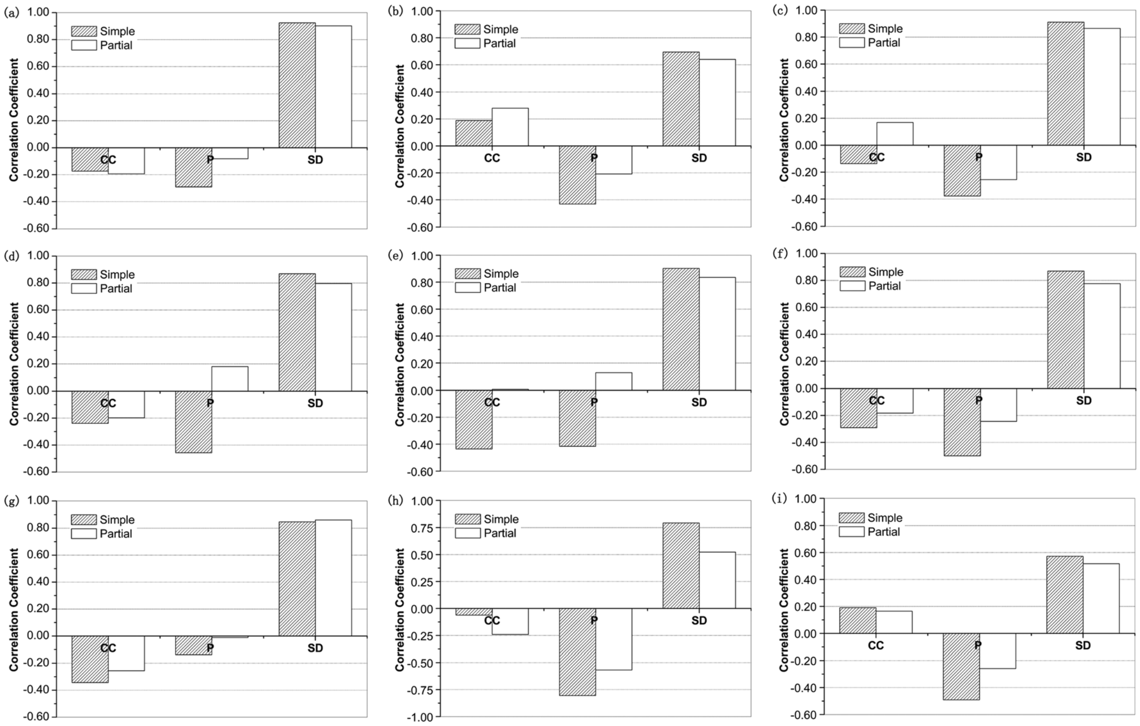

Figure 4. Simple and partial correlation coefficients between DTR and total cloud cover (CC), precipitation (*P*) and sunshine duration (SD): (a) Nationwide, (b) Northeast China, (c) North China Plain, (d) East China, (e) Southeast China, (f) North central China, (g) Southwest China, (h) Northwest China, and (i) Tibetan Plateau. Correlation coefficients of approximately 0.46 are statistically significant at the 0.05 level.

Table 4. The Correlation Coefficients Between DTR and SD by Season

		Winter	Spring	Summer	Autumn
Nationwide	1962–2011	0.930**	0.891**	0.881**	0.918**
	1962–1989	0.923**	0.892**	0.850**	0.946**
	1990–2011	0.886**	0.889**	0.855**	0.913**
Northeast China	1962–2011	0.565**	0.599**	0.896**	0.805**
	1962–1989	0.394*	0.526**	0.880**	0.780**
	1990–2011	0.673**	0.730**	0.939**	0.870**
North China Plain	1962–2011	0.805**	0.876**	0.847**	0.866**
	1962–1989	0.767**	0.856**	0.876**	0.869**
	1990–2011	0.718**	0.835**	0.876**	0.872**
East China	1962–2011	0.950**	0.937**	0.921**	0.924**
	1962–1989	0.942**	0.931**	0.931**	0.939**
	1990–2011	0.965**	0.964**	0.855**	0.964**
Southeast China	1962–2011	0.963**	0.920**	0.849**	0.915**
	1962–1989	0.965**	0.956**	0.906**	0.949**
	1990–2011	0.953**	0.826**	0.873**	0.918**
North central China	1962–2011	0.921**	0.775**	0.893**	0.923**
	1962–1989	0.908**	0.775**	0.917**	0.912**
	1990–2011	0.921**	0.862**	0.896**	0.945**
Southwest China	1962–2011	0.974**	0.894**	0.846**	0.855**
	1962–1989	0.972**	0.918**	0.921**	0.886**
	1990–2011	0.976**	0.799**	0.880**	0.897**
Northwest China	1962–2011	0.882**	0.724**	0.719**	0.839**
	1962–1989	0.823**	0.731**	0.738**	0.905**
	1990–2011	0.797**	0.845**	0.790**	0.756**
Tibetan Plateau	1962–2011	0.579**	0.629*	0.656**	0.705**
	1962–1989	0.281	0.228	0.313	0.301
	1990–2011	0.814**	0.885**	0.933**	0.738**

*Significant at $P < 0.05$.
**Significant at $P < 0.01$.

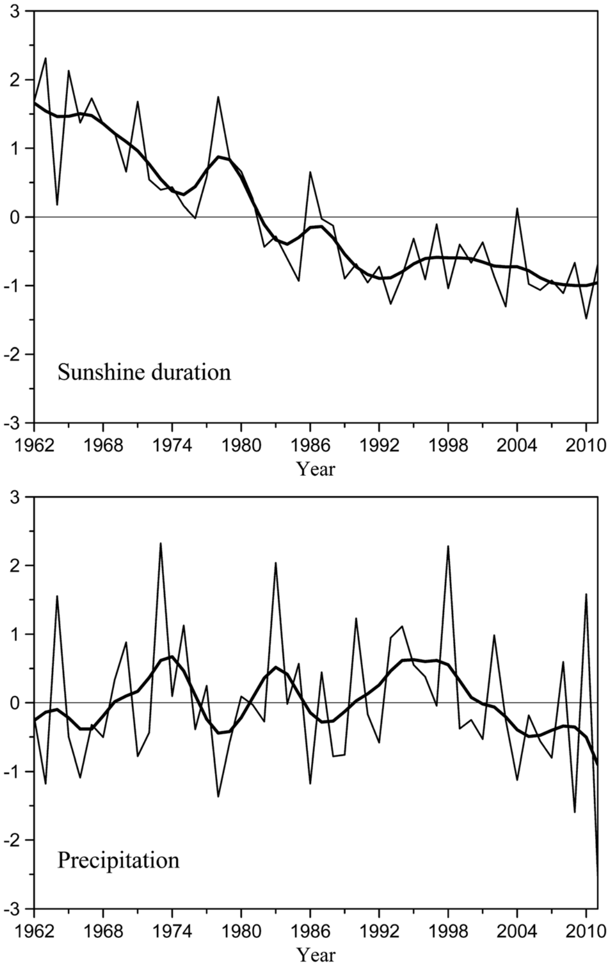

Figure 5. Time series of national normalized (by standard deviation) sunshine duration and precipitation from 1962 to 2011. The heavy line is the result of smoothing with a 9 year binomial filter with reflected ends.

Sunshine duration is directly related to downward shortwave radiation (Rsw,d), which had unbalanced effect on T_{max} and T_{min} [*Liu et al.*, 2004]. The effect of SD or Rsw,d on daytime T_{max} is greater than nighttime T_{min}, which is reflected at the results of correlation analysis (Table 3). The increase of global air temperature over the last century was largely attributed to the increasing greenhouse gas concentrations [*Wang and Dickinson*, 2013]. Greenhouse gases could affect T_{max} during the daytime as well as T_{min} during the night. Results showed that SD in China has decreased during the study time (Table 5). Effects of increasing greenhouse gases and declining Rsw,d on T_{max} may cancel each other out, resulting in the relatively small increase of T_{max}. Since Rsw,d is in effect only during daytime, the greenhouse effect takes major responsibility for the rapid increase in T_{min}. Thus, the decrease in Rsw,d resulted in a smaller increase in T_{max} than T_{min} and hence a lower DTR [*Liu et al.*, 2004; *Wang and Dickinson*, 2013].

In the Tibetan Plateau, the correlation between DTR and SD during the study period was relatively weak both from the annual and seasonal results (Figure 4 and Table 4) with the lowest decline trend of SD in China (Table 5). This is probably due to very low aerosol loads in the Tibetan Plateau [*Cong et al.*, 2009] where human activities are still limited. Aerosols can scatter and absorb a substantial amount of solar radiation [*Li*, 1998; *Ramanathan et al.*, 2007], and heavy loading of aerosols can lead to a significant cooling of the surface [*Li et al.*, 2010]. It was reported that the increased atmospheric aerosols was one of the reasons for the decrease in SD or SR in China [*Liu et al.*, 2004; *Liang* et al., 2005; *Wang et al.*, 2014]. During the study period, we also found that correlation coefficients between DTR and SD were the lowest for the winter seasons in the Tibetan Plateau and Northeast China, which usually receive large amounts of snowfall. It may be reasonable because snow cover could cause a significant cooling in the surface and reduce the amount of outgoing radiation emitted by the surface [*Cohen and Rind*, 1991], thereby reducing the effect of change in sunshine duration on T_{max}.

Results showed that DTR decreased rapidly from 1962 to 1989 but has leveled off since the 1990s in China. Interestingly enough, SD in China also has the same trend (Figure 5). SD showed an obvious decline (−0.019 h/d) from 1962 to 1989 but showed no significant increase (0.008 h/d) in the 1990s. Our result (from dimming since the 1960s to steady in the 1990s) is different from that (from dimming since the 1960s to brightening in the 1990s) addressed in many previous studies [*Liang and Xia*, 2005; *Shi et al.*, 2008; *Ye et al.*, 2010] but consistent with *Tang et al.* [2011] who indicated the solar radiation in China reached a stable level since the 1990s. The quality of solar radiation data obtained in China is often doubted [*Shi et al.*, 2008], and the above difference may be attributed to the inconsistent quality of solar radiation data used in the previous studies [*Tang et al.*, 2011].

After 2000, SD in China decreased slightly (−0.010 h/d) from 2000 to 2011, partly explaining why the increase of T_{max} and T_{min} slowed down during this period. As a result, similar to the DTR, SD showed no significant

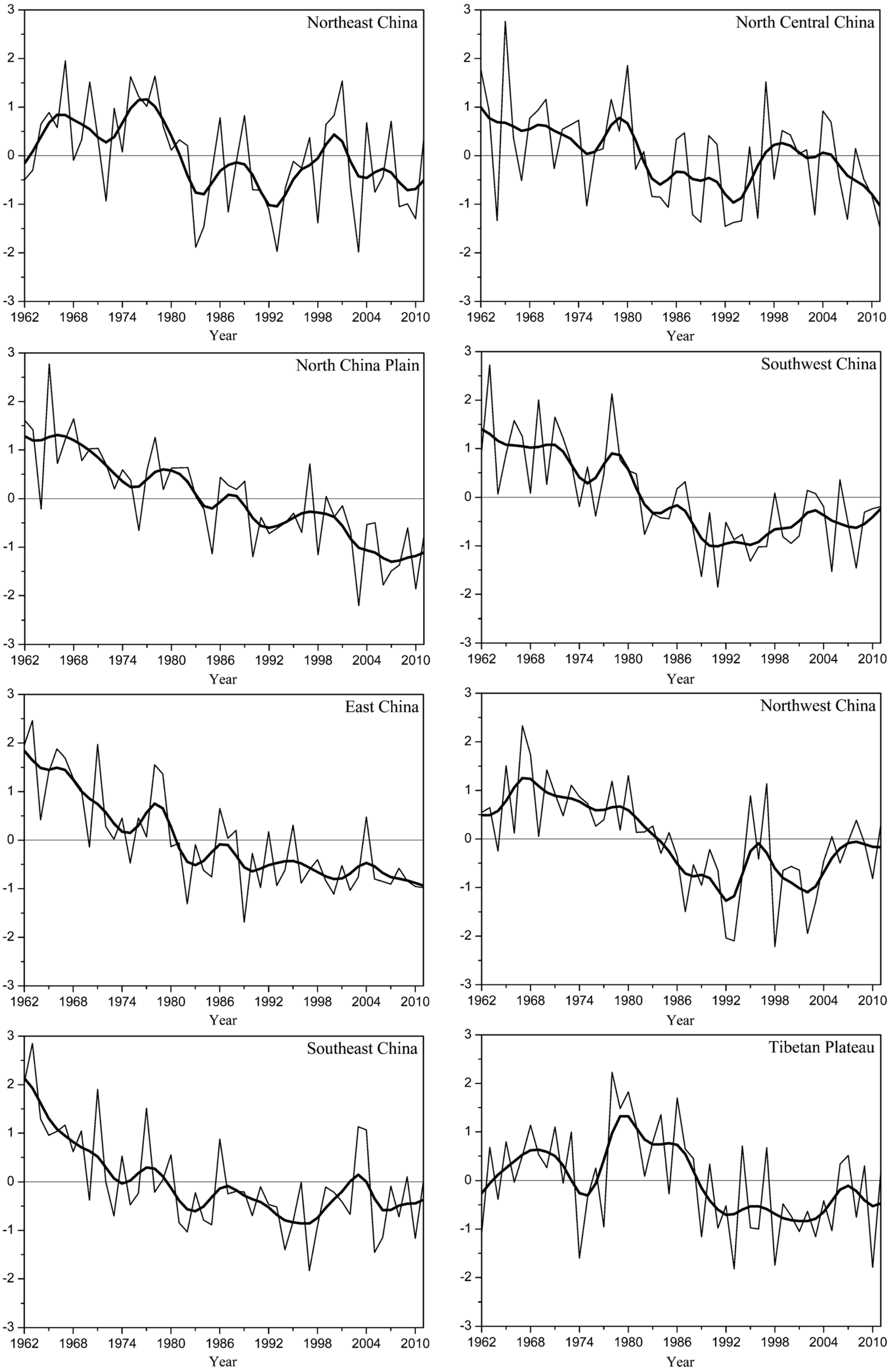

Figure 6. Time series of regional normalized (by standard deviation) sunshine duration from 1962 to 2011. The heavy line is the result of smoothing with a 9 year binomial filter with reflected ends.

Table 5. The Trends of Annual Average Precipitation, CC, and SD in China and the Eight Climatic Regions

	CC	*P* (mm)	SD (h)	CC	*P* (mm)	SD (h)	CC	*P* (mm)	SD (h)
		1962–2011			1962–1989			1990–2011	
Nationwide	−0.036*	−0.162	−0.013**	−0.024	−0.145	−0.019**	0.035	−2.953	−0.002
Northeast China	−0.053*	−0.387	−0.007**	−0.086**	0.894	−0.008*	0.019	−4.314	0.005
North China Plain	−0.021	−1.055	−0.018**	−0.037	−2.627	−0.018**	0.186**	−1.590	−0.013
East China	−0.042*	0.816	−0.020**	−0.020	1.468	−0.035**	0.055	−4.736	−0.008
Southeast China	−0.043*	2.006	−0.017**	0.023	6.041	−0.037**	−0.099	5.519	0.008
North central China	−0.023	−0.170	−0.007**	−0.013	−0.247	−0.014*	0.139**	−0.499	−0.003
Southwest China	−0.035	−1.605*	−0.011**	0.003	−2.075	−0.018**	−0.045	−5.502	0.007
Northwest China	−0.023	0.864**	−0.009**	−0.029	0.838	−0.014**	0.062	0.337	0.009
Tibetan Plateau	−0.043*	0.634*	−0.003**	−0.042*	0.948	0.002	−0.053*	−0.098	0.001

*Significant at $P < 0.05$.
**Significant at $P < 0.01$.

decrease (−0.002 h/d) from 1990 to 2011. So we can conclude that both the DTR and SD continued to level off from 1990 to 2011. But DTR and SD revealed slight increases in the 1990s and slight decreases from 2000 to 2011. Based on the transition of SD (dimming to steady) and DTR (decrease to steady), we also divided the whole period into two subperiods (1962–1989 and 1990–2011) to further investigate the effect of SD on DTR.

There were strong positive correlations between DTR and SD during two different periods (Table 3), which further confirmed that the decline of SD is one of the major reasons for DTR decrease in China. From 1962 to 1989, the decline of annual and seasonal SD account for the decline of DTR in China. From 1990 to 2011, annual average DTR and SD showed no significant changes (Tables 1 and 5); the decline of autumn SD accounts for the significant decline of autumn DTR in China (Tables 2 and 6).

For the Tibetan Plateau, however, there was no significant correlation between DTR and SD from 1962 to 1989 (Table 3). The seasonal correlation analysis also showed no significant relationship between DTR and SD for all seasons during this period (Table 4) in the Tibetan Plateau. This partly explains the lowest correlation coefficients between DTR and SD in the Tibetan Plateau during the entire study period (Figure 4i). From 1962 to 1989, DTR showed a significant decline in the Tibetan Plateau, but the SD showed slight increase (Tables 1 and 5). Thus, SD change cannot account for the decrease of DTR in the Tibetan Plateau, and the exact reason for the decrease of DTR in this region remains to be further investigated.

3.3.2. Effect of Precipitation on DTR

Results from the time series analysis of the precipitation and DTR showed inverse trends, indicating that precipitation may have a negative effect on DTR (Figures 2, 3, 5, and 7). The results of correlation analysis also showed negative relationship between DTR and precipitation during two time periods (Table 3). However, the changes of annual precipitation were not significant during two time periods (Table 5), suggesting that precipitation may not be the main reason for DTR changes in China.

Table 6. Seasonal Trends of Sunshine Duration (SD) and Precipitation in China and the Eight Climatic Regions

		Winter		Spring		Summer		Autumn	
		SD (h)	Precipitation (mm)	SD (h)	Precipitation (mm)	SD (h)	Precipitation (mm)	SD (h)	Precipitation (mm)
Nationwide	1962–1989	−0.020**	0.245	−0.017**	0.379	−0.027**	−0.872	−0.014*	0.091
	1990–2011	0.002	−0.774	0.015	−0.648	−0.012	−1.664	−0.014*	0.147
	1962–2011	−0.013**	0.214	−0.008**	−0.116	−0.022**	0.119	−0.011**	−0.380*
Northeast China	1962–2011	−0.008**	0.179**	−0.009*	0.368*	−0.007	−0.516	−0.003	−0.419
North China Plain		−0.015**	0.018	−0.015**	0.202	−0.025**	−1.188*	−0.016**	−0.091
East China		−0.020**	0.677*	−0.001	−1.004	−0.044**	1.841**	−0.016**	−0.698
Southeast China		−0.015*	0.206	−0.018*	0.033	−0.020**	2.130	−0.015*	−0.356
North central China		−0.012**	0.048	0.003	−0.074	−0.011*	−0.064	−0.007	−0.087
Southwest China		−0.008*	0.130	−0.011**	−0.389	−0.019**	−0.256	−0.005	−1.107**
Northwest China		−0.017**	0.216**	−0.001	0.184*	−0.010**	0.290*	−0.008**	0.174*
Tibetan Plateau		−0.003	0.049	−0.001	0.588**	−0.006	−0.222	−0.004**	0.219

*Significant at $P < 0.05$.
**Significant at $P < 0.01$.

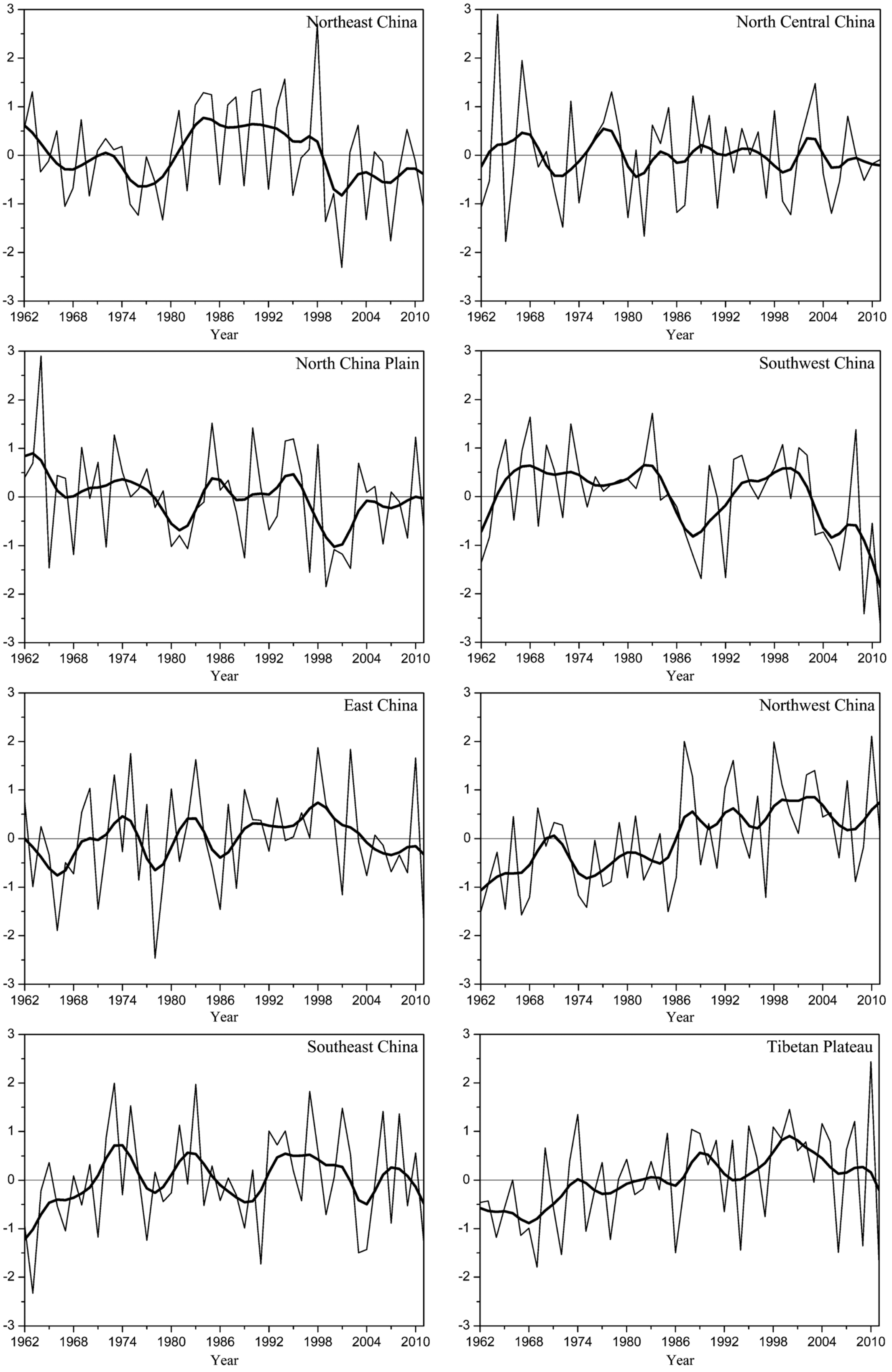

Figure 7. Time series of regional normalized (by standard deviation) precipitation from 1962 to 2011. The heavy line is the result of smoothing with a 9 year binomial filter with reflected ends.

During the whole study period, annual precipitation was decreasing in Southwest China, whereas no significant change of precipitation was found in Northeast China, North China Plain, East China, Southeast China, and north central China (Table 5). The trend of decreasing precipitation would have a negative effect on DTR change. It is concluded that the change of precipitation cannot account for the decrease of DTR in these regions. Increasing of precipitation occurred in Tibetan Plateau and Northwest China (Table 5), but the correlation between DTR and precipitation was statistically significant only in Northwest China (Figure 4).

Previous studies showed that precipitation could affect DTR by increasing the soil moisture content [*Dai et al.*, 1999; *Zhou et al.*, 2009]. Soil moisture can damp $T_{\max}$ and thus DTR by increasing daytime evaporative cooling through evapotranspiration, which is more effective when the potential evapotranspiration is high [*Dai et al.*, 1999; *Zhou et al.*, 2009]. Therefore, the evaporative cooling effect on $T_{\max}$ could be larger in dry region than humid region [*Dai et al.*, 1999]. *Zhou et al.* [2009] found that the strongest effect of precipitation on DTR occurred in the driest regions. Our results also confirmed that precipitation had strongest effect of on DTR in Northwest China, which is the driest region in China.

Precipitation increased significantly in all seasons in Northwest China (Table 6). The seasonal trends of DTR in Northwest China were smaller than most of other climate regions (Table 2), indicating that both the changes of SD and precipitation contribute to the decline of DTR in this region. In other regions, the seasonal changes of precipitation and SD can also account for the special spatial pattern of seasonal $T_{\max}$ and DTR changes (see section 3.2). In winter, although the SD decreased more slowly in Northeast China than that of North China Plain, the significant increase of precipitation in Northeast China could reduce $T_{\max}$ by enhancing the surface albedo (in Northeast China, precipitation falls in the form of snow since low temperature in winter), explaining why the increase of $T_{\max}$ was slower than North China Plain (Table 2). In spring, precipitation increased significantly in Northeast China, and SD declined significantly in Northeast China and North China Plain. Both the increase of precipitation and decline of SD tend to reduce the $T_{\max}$, explaining why $T_{\max}$ increased from Northeast China to East China (Tables 2 and 6). In summer, the most significant increase of precipitation occurred in East China (Table 6). Considering $T_{\max}$ showed no significant change and DTR declined rapidly in East China (Table 2), we concluded that the increased summer precipitation may be a cause for the decrease of DTR in East China through its influence on $T_{\max}$.

3.3.3. Other Factors That Affect DTR

Many studies reported that CC has a negative effect on DTR [e.g., *Campbell and Vonder Haar*, 1997; *Dai et al.*, 1997, 1999]. Clouds can cool the Earth's surface from reflecting sunlight in the daytime and warm the surface from emitting longwave radiation, thereby exerting a damping effect on DTR [*Xia*, 2013]. In our study, CC had positive effect on DTR in the Tibetan Plateau and Northeast China and negative effect on DTR in other regions (Figure 4), but all of them were not statistically significant. During two different periods, we also found no significant correlation between CC and DTR in eight climatic regions (Table 3). In addition, we found that contrary to the trend in the rest of the world, China's CC had decreased during this study period (Table 5), which confirms some earlier findings [*Baker et al.*, 1995; *Kaiser*, 2000]. Given the trend of declining cloud cover in China as well as cloud cover's negative effect on DTR, we would expect DTR to increase if cloud cover was the main cause of the change in DTR. Thus, we concluded that total CC cannot explain the decrease of DTR in China. Although decreased CC may increase the SD, SD decreased in China during the study period. Previous studies suggested that increased atmospheric aerosols could reduce SD in China [*Liu et al.*, 2004; *Liang and Xia*, 2005; *Wang et al.*, 2014]. Increased atmospheric aerosols resulting from industrial pollution may reduce SD by cutting down on the amount of sunlight reaching the ground [*Power*, 2003]. Thus, it becomes reasonable that DTR is correlated with SD but not with CC in our study.

We recognize that the local anthropogenic influence especially the urbanization effect on DTR trends should not be ignored though it is not the focus of the current study. Some previous studies suggested that the urbanization effect might have played an important role in the temperature trend, which should be given more consideration [e.g., *Karl et al.*, 1988; *Portman*, 1993; *Hughes and Balling*, 1996; *Ren*, 2003; *Zhou et al.*, 2004; *Fujibe*, 2009]. However, there are also many studies that found no significant impact of urbanization on global or regional temperature change [e.g., *Jones et al.*, 1990; *Easterling et al.*, 1997; *Peterson*, 2003; *Hansen et al.*, 2010; *Wickham et al.*, 2013]. *Jones et al.* [1990] compared the mean surface air temperature (SAT) changes between urban and rural stations in the former Soviet Union, east Australia, east China, and America, finding that urbanization has had little effect on temperature change over those regions, and annual mean temperature increase observed at the rural stations was even larger than that recorded at the urban stations in east China. By comparing SAT trends between rural and urban stations in China, *Li et al*. [2004] also found a much weaker urban warming in some regions of China and the country as a whole. On the other hand, some scholars found significant urbanization effects on SAT trends in China [e.g., *Zhou et al*., 2004; *Ren et al*., 2008; *Zhou and Ren*, 2011; *Yang et al*., 2011; *Ren and Zhou*, 2014]. The causes for these differences may be related to the criteria for defining rural and urban stations, station network density, analytical methods, and so on [*Ren et al*., 2008].

For evaluating the urbanization effect on trends of SAT, it is crucial to have a set of representatively reference stations [*Hansen et al*., 2001; *Ren et al*., 2008]. By applying a comprehensive procedure and all the available weather stations in Mainland China, *Ren et al*. [2010] developed a relatively high quality data set of 143 rural/reference temperature stations (reference stations hereafter). The novel procedure considered a number of indicators, such as spatial distribution and density of stations, distance and times of relocations, length and complicity of records, the ratio of built-up area around the station, population near a station, and the distance of the observational grounds from the center of the cities [*Ren et al*., 2010]. Using this data set of reference stations and more sophisticated methodologies, some recent studies found that urbanization had significant effect on the increasing T_{min} and declining DTR in China, especially in north China [*Zhou and Ren*, 2011; *Ren and Zhou*, 2014], which was consistent with some previous studies [*Chen et al*., 2005; *Zhou and Ren*, 2009]. In our study, DTR in China decreased significantly before 1980s, which was similar to most other regions of the world [*Vose et al*., 2005]. The urbanization in China has developed rapidly since 1978 and became much faster after 1990 [*Chen et al*., 2013]. Based on the results of previous studies about the obvious effect of urbanization on DTR [*Zhou and Ren*, 2011; *Ren and Zhou*, 2014], DTR would continue to decrease due to the more rapid urbanization after 1990. However, we found that DTR showed no significant change during 1990 to 2011. Therefore, it seems that there are some other factors affecting DTR changes, which may offset the effect of rapid urbanization after 1990. In order to better investigate the contribution of urbanization effect on DTR changes in China, it is necessary to separate the effects of urbanization from other factors such as aerosol and precipitation. The interpretation of urbanization effect on climate in China is complicated because often studies have used distinct versions of station series [*Intergovernmental Panel on Climate Change Fifth Assessment Report* (*IPCC AR5*), 2013]. A "unified" standard is still needed to identify urban and rural stations. On the other hand, urbanization is a dynamic process and there is an important distinction to be made between urbanization trend effects in regions that have been developed for a long time and those under rapid development [*IPCC AR5*, 2013]. Thus, further research is needed to investigate how much effect the urbanization has had on the changes of DTR in China.

4. Conclusions

Maximum temperature and minimum temperature increased by 0.221°C/decade and 0.378°C/decade, respectively, across China in the past 50 years, whereas the DTR decreased by 0.157°C/decade which was mainly due to the higher rate of increase for T_{min} relative to T_{max}. From 1962 to 1989, DTR decreased rapidly (0.291°C/decade) when T_{min} increased while T_{max} decreased slightly. Since 1990, the decrease of DTR has stopped since T_{max} and T_{min} kept pace with each other. But unlike the slight increase of DTR in the 1990s due to comparable rapid increase in T_{max} and T_{min}, DTR showed slight decrease from 2000 to 2011 when both T_{max} and T_{min} showed no obvious change.

At regional scale, DTR decreased significantly before 1989 but showed no significant change from 1990 to 2011 for all the climate regions. Over the whole study period, DTR decreased significantly in all eight climate regions as T_{min} increased faster than T_{max}. Decreases in DTR were greatest in Northeast China (-0.273°C/decade) and lowest in Southwest China (-0.067°C/decade) with a clear transect running from northeast to southwest showing the decreasing trends change from high to low during the study period. Seasonally, decreases of DTR were greatest in winter and lowest in summer both on the nationwide and regional scales. Similar to the spatial pattern of annual trends, the seasonal decreasing trends of DTR reduced from the north to south of China.

It is suggested that the decline of SD is one of the most important reasons for the DTR decrease in all parts of China except the Tibetan Plateau. From 1962 to 1989, the decline of SD accounts for the decline of DTR in China. From 1990 to 2011, both DTR and SD remained trendless, with slight increases in the 1990s and slight decreases during 2000–2011. In addition to the contribution of SD decrease, the increasing of precipitation played an important role in DTR decrease in Northwest China, the most arid region of China. Different from most other parts of the world, China's CC has decreased during the study period. It appeared that changes of CC were not the reasons for the changes of DTR in the past 50 years.

Acknowledgments
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