Variability in snow cover phenology in China from 1952 to 2010

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Abstract Daily snow observation data from 672 stations, particularly the 352 stations with over ten annual mean snow cover days (SCD), during 1952–2010 in China, are used in this study. We first examine spatiotemporal variations and trends of SCD, snow cover onset date (SCOD), and snow cover end date (SCED). We then investigate SCD relationships with number of days with temperature below 0°C (TBZD), mean air temperature (MAT), and Arctic Oscillation (AO) index, the latter two being constrained to the snow season of each snow year. The results indicate that years with positive SCD anomaly for the entire country include 1955, 1957, 1964, and 2010, and years with negative SCD anomaly include 1953, 1965, 1999, 2002, and 2009. The reduced TBZD and increased MAT are the main reasons for the overall late SCOD and early SCED since 1952, although it is not necessary for one station to experience both significantly late SCOD and early SCED. This explains why only 15% of the stations show significant shortening of SCD, while 75% of the stations show no significant change in the SCD trends. This differs with the overall shortening of the snow period in the Northern Hemisphere previously reported. Our analyses indicate that the SCD distribution pattern and trends in China are very complex and are not controlled by any single climate variable examined (i.e. TBZD, MAT, or AO), but a combination of multiple variables. It is found that the AO has the maximum impact on the SCD shortening trends in Shandong Peninsula, Changbai Mountains, and North Xinjiang, while the combined TBZD and MAT have the maximum impact on the SCD shortening trends in the Loess Plateau, Xiaoxingganling, and Sanjiang Plain.

Keywords: snow cover day; snow cover onset date; snow cover end date;

spatiotemporal variation; trend; days with temperature below 0°C; Arctic Oscillation

Abbreviations:

Snow Cover Day (SCD)

Snow Cover Onset Date (SCOD)

Snow Cover End Date (SCED)

Days with Temperature Below 0°C (TBZD)

Mean Air Temperature (MAT)

Arctic Oscillation (AO)

1 Introduction

Snow has a profound impact on the surficial and atmospheric thermal conditions, and is very sensitive to climatic and environmental changes, because of its high reflectivity, low thermal conductivity, and hydrological effects via snowmelt (Barnett et al., 1989; Groisman et al., 1994). The extent of snow cover in the Northern Hemisphere decreased significantly over the past decades because of global warming (Robinson and Dewey 1990; Brown and Robinson 2011). Snow cover showed the largest decrease in the spring, and the decrease rate increased for higher latitudes in response to larger albedo feedback (Déry and Brown, 2007). In North America, snow depth in central Canada showed the greatest decrease (Dyer and Mote, 2006), and snowpack in the

Rocky Mountains in the U.S. declined (Pederson et al., 2013). However, *in situ* data showed a significant increase in snow accumulation in winter but a shorter snowmelt season over Eurasia (Bulygina et al., 2009). Decreases in snow pack have also been found for the European Alps in the last 20 years of the 20th century (Scherrer et al., 2004), but a very long time series of snow pack suggests large decadal variability and overall weak long-term trends only (Scherrer et al., 2013). Meteorological data indicated that the snow cover over northwest China exhibited a weak upward trend in depth (Qin et al., 2006), but the spatiotemporal variations were large (Ke et al., 2009; Ma and Qin 2012). Simulation experiments using climate models indicated that, with continuing global warming, the snow variation in China would show more differences and uncertainties in space and time than ever before (Shi et al., 2011; Ji and Kang 2013). Spatiotemporal variations of snow cover are also manifested as snowstorms or blizzards, particularly, excessive snowfall over a short time duration (Bolsenga and Norton, 1992; Liang et al., 2008; Gao, 2009; Wang et al., 2013; Llasat et al., 2014).

Snow cover day (SCD) is an important index that represents the environmental features of climate (Ye and Ellison 2003; Scherrer et al., 2004), and is directly related to the radiation and heat balance of the Earth–atmosphere system. The SCD varies in space and time and contributes to climate change over short time scales (Zhang, 2005), especially in the Northern Hemisphere. Bulygina et al. (2009) investigated the linear trends of SCD observed at 820 stations from 1966 to 2007, and indicated that the duration of snow cover decreased in the northern regions of European Russia and in the mountainous regions of southern Siberia, while it increased in Yakutia and the Far East.

Peng et al. (2013) analysed trends in the snow cover onset date (SCOD) and snow cover end date (SCED) in relation to temperature over the past 27 years (1980–2006) from over 636 meteorological stations in the Northern Hemisphere. They found that the SCED remained stable over North America, whereas there was an early SCED over Eurasia. Satellite snow data indicated that the average snow season duration over the Northern Hemisphere decreased at a rate of 5.3 days per decade between 1972/73 and 2007/08 (Choi et al., 2010). Their results also showed that a major change in the trend of snow duration occurred in the late 1980s, especially in the Western Europe, central and East Asia, and mountainous regions in western United States.

There are large spatiotemporal differences in the SCD in China (Wang and Li, 2012). Analysis of 40 meteorological stations from 1971 to 2010 indicated that the SCD had a significant decreasing trend in the western and south-eastern Tibetan Plateau, with the largest decline observed in Nielamu, reaching 9.2 days per decade (Tang et al., 2012). Data analysis also indicated that the SCD had a linear decreasing trend at most stations in the Hetao region and its vicinity (Xi et al., 2009). However, analysis of meteorological station data in Xinjiang showed that the SCD had a slight increasing trend, occurring mainly in 1960–1980 (Wang et al., 2009b). Li et al. (2009) analysed meteorological data from 80 stations in Heilongjiang Province, Northeast China. Their results showed that the snow cover duration shortened, because of both the late SCOD (by 1.9 days per decade) and early SCED (by 1.6 days per decade), which took place mainly in the lower altitude plains.

The SCD is sensitive to local winter temperature and precipitation, latitude (Hantel et al., 2000; Wang et al., 2009a; Serquet et al., 2011; Morán-Tejeda et al., 2013), and altitudinal gradient and terrain roughness (Lehning et al., 2011; Ke and Liu, 2014). Essentially, the SCD variation is mainly attributed to large-scale atmospheric circulation or climatic forcing (Beniston, 1997; Scherrer and Appenzeller, 2006; Ma and Qin, 2012; Birsan and Dumitrescu, 2014), such as monsoons, El Niño/Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), and Arctic Oscillation (AO). Xu et al. (2010) investigated the relationship between the SCD and monsoon index in the Tibetan Plateau and indicated their great spatial differences. As an index of the dominant pattern of non-seasonal sea-level pressure variations, the AO shows a large impact on the winter weather patterns of the Northern Hemisphere (Thompson and Wallace, 1998; Thompson et al., 2000; Gong et al., 2001; Wu and Wang, 2002; Jeong and Ho, 2005). The inter-annual variation of winter extreme cold days in the northern part of eastern China is closely linked to the AO (Chen et al., 2013). Certainly, the AO plays an important role in the SCD variation. An increase in the SCD before 1990 and a decrease after 1990 have been reported in the Tibetan Plateau, and snow duration has positive correlations with the winter AO index (You et al., 2011), and a significant correlation between the AO and snowfall over the Tibetan Plateau on inter-decadal timescale was also reported by Lü et al. (2008).

The focus of this study is the variability in the snow cover phenology in China. A longer time series of daily observations of snow cover is used for these spatial and temporal analyses. We first characterize the spatial patterns of change in the SCD, SCOD, and SCED in different regions of China; we then examine the sensitivity of

SCD to the number of days with temperature below 0°C (TBZD), the mean air temperature (MAT), and the Arctic Oscillation (AO) index during the snow season (between SCOD and SCED).

2 Data and methods

2.1 Data

We use daily snow cover and temperature data in China from 1 September 1951 to 31 August 2010, provided by the National Meteorological Information Centre of China Meteorological Administration (CMA). According to the Specifications for Surface Meteorological Observations (China Meteorological Administration, 2003), an SCD is defined as a day when the snow cover in the area meets the following requirement: at least half of the observation field is covered by snow. For any day with at least half of the observation field covered by snow, snow depth is recorded as a rounded-up integer if it is more than or equal to 0.5 cm (measured with a ruler), i.e. a normal SCD, whereas the snow depth is denoted as 0 if it is less than 0.5 cm, i.e. a thin SCD. We define a snow year as the period from 1 September of the previous year to 31 August of the current year. For instance, September, October, and November 2009 are treated as the autumn season of snow year 2010, December 2009 and January and February 2010 as the winter season of snow year 2010, and March, April, and May 2010 as the spring season of snow year 2010.

Station density is high in eastern China, where the observational data for most stations are complete, with relatively long histories (as long as 59 years). Because of topography and climate conditions, the discontinuous nature of snowfall is obvious in western China, especially in the Tibetan Plateau, with patchy snow cover, and many thin SCDs in these station records (Ke and Li, 1998). At the same time, in western China, station density is low, and the observation history is relatively short, although two of the three major snow regions are located in western China. If all stations with short time series are eliminated, and thin SCDs are not taken into account, the spatial representativeness of the dataset would be a problem. Therefore, a time series of at least 30 years is included in this study, including those thin SCDs. Totally, there are 722 stations in the original dataset.

Since station relocation and changes in the ambient environment could cause inconsistencies in the recorded data, we implement strict quality controls (such as inspection for logic, consistency, and uniformity) on the observational datasets in order to reduce errors (Ren et al., 2005). The standard normal homogeneity test (Alexandersson and Moberg, 1997) at the 95% confidence level is applied to the daily SCD and temperature series data in order to identify possible breakpoints. Time series gap filling is performed after all inhomogeneities are eliminated, using nearest neighbour interpolation. After being processed as mentioned above, the 672 stations with annual mean SCDs greater than 1.0 (day) are finally selected for subsequent investigation (Fig. 1).

The observation period for each station is different, varying between 59 years (1951/1952–2009/2010) and 30 years (1980/1981–2009/2010). Overall, 588 stations have observation records between 50 and 59 years, 47 stations between 40 and 49 years, and 37 stations between 30 and 39 years (Fig. 2). Most of the stations with observation records of less than 50 years are located in remote or high elevation areas. All 672 stations are used to analyse the spatiotemporal distribution of SCD in China, while only 352 stations with more than ten annual mean SCDs are used to study the changes of SCOD, SCED, and SCD relationships with TBZD, MAT, and the AO index.

The daily AO index constructed by projecting the daily (00Z) 1,000 mb height anomalies poleward of 20°N from http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao.shtml, is used in this paper. A positive (negative) AO index corresponds to low (high) pressure anomalies throughout the polar region and high (low) pressure anomalies across the subtropical and mid-latitudes (Peings et al., 2013). We average the daily AO indexes during the snow season of each station as the AO index of the year. A time series of AO indexes from 1952 to 2010, for each of the 352 stations, is then constructed.

A digital elevation model (DEM) according to the Shuttle Radar Topographic Mission (SRTM, http://srtm.csi.cgiar.org) of the National Aeronautics and Space Administration (NASA) with a resolution of 90 m and the administration map of China are used as the base map.

2.2 Methods

We apply Mann–Kendall (MK) test to analyse the trends of SCD, SCOD, and SCED. The MK test is an effective tool to extract the trends of time series, and is widely applied to the analysis of climate series (Marty, 2008). The MK test is characterized as being more objective, since it is a non-parametric test. A positive standardized MK statistic value indicates an upward or increasing trend, while a negative value demonstrates a downward or decreasing trend. Confidence levels of 90% and 95% are taken as thresholds to classify the significance of positive and negative trends of SCD, SCOD, and SCED.

At the same time, if SCD, SCOD, or SCED at one climate station has significant MK trend (above 90%), their linear regression analyses are performed against time, respectively. The slopes of the regressions represent the changing trends and are expressed in days per decade. The statistical significance of the slope for each of the linear regressions is assessed by the Student's *t* test (two-tailed test of the Student *t* distribution), and only confidence levels above 90% are considered.

Correlation analysis is used to examine the SCD relationships with the TBZD, MAT, and the AO index, and the Pearson product-moment correlation coefficients (PPMCC) have been calculated. The PPMCC is a widely used estimator for describing the spatial dependence of rainfall processes, and it indicates the strength of the linear covariance between two variables (Habib et al., 2001; Ciach and Krajewski, 2006). The correlation coefficient can be defined as the covariance of the two variables (X, Y) divided by the product of their standard deviations, giving a value between +1 and −1 inclusive, where 1 is total positive correlation, 0 is no correlation, and −1 is total negative correlation. The statistical significance of the correlation coefficients is calculated using the Student's *t* test, and only confidence levels above 90% are considered in our analysis.

The spatial distribution of SCD, SCOD, and SCED, and their calculated results, are spatially interpolated by applying the universal kriging method (assuming the data is normally distributed). The universal kriging model is capable of simultaneously treating multiple variables and their cross-covariance, and has been successfully applied to spatial data interpolation (Kyriakidis and Goodchild, 2006). All mean errors are near zero, all average standard errors are close to the corresponding root mean squared errors, and all root mean squared standardized errors are close to 1 (Table 1). This fact indicates that prediction errors are unbiased and valid, except for slightly overestimated CV and slightly underestimated SCD in 2002. Overall, the interpolation results have fewer errors and are acceptable.

3 Results

3.1 Spatiotemporal variations of SCD

3.1.1 Spatial distribution of SCD

The analysis of observations from 672 stations indicates that there are three major stable snow regions with more than 60 annual mean SCDs: Northeast China, North Xinjiang, and the Tibetan Plateau, with Northeast China being the largest of the three (Fig. 3a). In the Daxingganling, Xiaoxingganling, and Changbai Mountains of Northeast China, there are more than 90 annual mean SCDs, corresponding to a relatively long snow season. The longest annual mean SCDs, 169 days, is at Arxan Station (in the Daxinganling Mountains) in Inner Mongolia. In North Xinjiang, the SCDs are relatively long in the Tianshan and Altun Mountains, followed by the Junggar Basin. The annual mean SCDs in the Himalayas, Nyainqentanglha, Tanggula Mountains, Bayan Har Mountains, Anemaqen Mountains, and Qilian Mountains of the Tibetan Plateau are relatively long, although most of these areas have less than 60 annual SCDs. The Tibetan Plateau has a high elevation, a cold climate, and many glaciers, but its mean SCD is not as large as that of the other two stable snow regions.

Areas with SCDs of 10–60 are called unstable snow areas with annual periodicity (there is definitely snow every winter), including the peripheral parts of the three major stable snow regions, and the Loess Plateau, Northeast Plain, North China Plain, Shandong Peninsula, and areas in north of the Qinling-Huaihe line (along the Qinling Mountains and Huaihe River to the east). Areas with SCDs of 1–10 are called unstable snow areas without annual periodicity (the mountainous areas are excluded, not every winter there is snow, especially in a warm winter), including the Tarim Basin, Qaidam Basin, Badain Jaran Desert, the peripheral parts of Sichuan Basin, the northeast part of the Yungui Plateau, and the middle and lower Yangtze River Plain. Areas with occasional snow and mean annual SCD of less than 1.0 (day) are distributed north of the Sichuan Basin and in the belt along Kunming, the Nanling Mountains, and Fuzhou (approximate latitude of 25°N). Because of the latitude or local climate and terrain, there is no snow in the Taklimakan Desert, Turpan Basin, the Yangtze River Valley in the Sichuan Basin, the southern parts of Yunnan, Guangxi, Guangdong and Fujian, and on the Hainan Island.

The spatial distribution pattern of SCD based on climate data with longer time series is similar to previous studies (Li and Mi, 1983; Li, 1990; Liu et al., 2012; Wang et al., 2009a; Wang and Li, 2012). The snow distribution is closely linked to latitude and elevation, and is generally consistent with the climate zones (Lehning et al., 2011; Ke and Liu, 2014). The higher the latitude, the lower the temperature and the more

SCDs there are. Therefore, there are relatively more SCDs in Northeast China and North Xinjiang, and fewer SCDs to the south (Fig. 3a). In the Tibetan Plateau, located in south-western China, the elevation is higher than eastern areas at the same latitude, and the SCDs are greater than in eastern China (Tang et al., 2012). The amount of precipitation also plays a critical role in determining the SCD (Hantel et al., 2000). In the north-eastern coastal areas of China, which are affected considerably by the ocean, there is much precipitation. In North Xinjiang, which has a typical continental (inland) climate, the precipitation is less than in Northeast China, and there are more SCDs in the north of Northeast China than in North Xinjiang (Dong et al., 2004; Wang et al., 2009b). Moreover, the local topography has a relatively large impact on the SCD (Lehning et al., 2011). The Tarim Basin is located inland, with relatively little precipitation, thus snowfall there is extremely rare except for the surrounding mountains (Li, 1993). The Sichuan Basin is surrounded by high mountains, therefore situated in the precipitation shadow in winter, resulting in fewer SCDs (Li and Mi, 1983; Li, 1990).

The three major stable snow regions, Northeast China, North Xinjiang, and the eastern Tibetan Plateau, have smaller coefficients of variation (CV) in the SCD (Fig. 3b). Nevertheless, the SCDs in arid or semi-arid areas, such as South Xinjiang, the northern and south-western Tibetan Plateau, and central and western Inner Mongolia, have large fluctuation because there is little precipitation during the cold seasons, and certainly little snowfall and large CVs of SCD. In particular, the Taklimakan Desert in the Tarim Basin is an extremely arid region, with only occasional snowfall. Therefore, it has a very large range of SCD fluctuations. Additionally, the middle and lower Yangtze River Plain also has large SCD fluctuations because of warm-temperate or sub-tropic climate with short winter and little snowfall. Generally, the smaller the SCD, the larger the CV (Wang et al., 2009a). This is consistent with other climate variables, such as precipitation (Yang et al., 2015).

3.1.2 Temporal variations of SCD

Seasonal variation of SCD is primarily controlled by temperature and precipitation (Hantel et al., 2000; Scherrer et al., 2004; Liu et al., 2012). In North Xinjiang and Northeast China, snow is primarily concentrated in the winter (Fig. 4). In these regions, the SCD exhibits a 'single-peak' distribution. In the Tibetan Plateau, however, the seasonal variation of SCD is slightly different, i.e. more snow in the spring and autumn combined than in the winter. The mean temperature and precipitation at Dangxiong station (30°29′ N, 91°06′E, 4200.0 m) in winter are -7.73^{o} C and 7.92 mm, respectively, and those at Qingshuihe station (33°48′ N, 97°08′E, 4415.4 m) are -15.8^{o} C and 16.3 mm, respectively. It is too cold and dry to produce enough snow in the Tibetan Plateau (Hu and Liang, 2014)

The temporal variation of SCD shows very large differences from one year to another. We define a year with a positive (negative) SCD anomaly in the following way: for a given year, if 70% of the stations have a positive (negative) anomaly and 30% of the stations have an SCD larger (smaller) than the mean +/− one standard deviation (1SD), it is regarded as a year with a positive (negative) SCD anomaly. The years with a positive SCD anomaly in China are 1955, 1957, 1964, and 2010 (Table 2). Moreover, the stations with SCDs larger than the mean + 2SD account for 29% of all stations in 1955 and 1957, and these two years are considered as years with an extremely positive SCD anomaly. In 1957, there was an almost nationwide positive SCD anomaly except for North Xinjiang (Fig. 5a). This 1957 event had a great impact on agriculture, natural ecology, and social-economic systems, and resulted in a tremendous disaster (Hao et al., 2002). The year 2010 was also a year with a positive SCD anomaly in China. At the same time, blizzards occurred in North America and Europe (including Spain) (Llasat et al., 2014). Globally, an unusual cold weather pattern caused by high pressure (the AO) brought cold, moist air from the north. Many parts of the Northern Hemisphere experienced heavy snowfall and record-low temperatures, leading to, among other things, a number of deaths, widespread transport disruption, and power failures (http://en.wikipedia.org/wiki/Winter_of_2009–10_in_Europe, http://en.wikipedia.org/wiki/February_9–10,_2010_North_American_blizzard). The blizzards across the Texas and Oklahoma panhandles in 1957 (Bolsenga and Norton, 1992; Changnon and Changnon, 2006) and across the east coast in 2010 were also recorded as the biggest snowstorms of the United States from 1888 to the present (http://www.crh.noaa.gov/mkx/?n=biggestsnowstorms-us).

Years with a negative SCD anomaly include 1953, 1965, 1999, 2002, and 2009 (Table 2). If there is too little snowfall in a specific year, a drought is possible. Drought resulting from little snowfall in the cold season is a slow process and can sometimes cause disasters. For example, East China displayed an apparent negative SCD anomaly in 2002 (Fig. 5b), and had very little snowfall, leading to an extreme winter drought in

Northeast China, where snowfall is the primary form of winter precipitation (Fang et al., 2014).

Because of different atmospheric circulation backgrounds, vapour sources, and topographic conditions in different regions of China, there are great differences in the SCD even in one year. For example, in 2008, there were more SCDs and longer snow duration in the Yangtze River Basin, North China, and the Tianshan Mountains in Xinjiang (Fig. 5c), especially in the Yangtze River Basin, where large snowfall is normally not observed. However, four episodes of severe and persistent snow, extreme low temperatures, and freezing weather occurred in early 2008, leading to a large-scale catastrophe in this region where there were no mitigation measures for this type of a disaster (Gao, 2009). As reported by the Ministry of Civil Affairs of China, the 2008 snow disaster killed 107 people and caused losses of US$ 15.45 billion. Both the SCDs and scale of economic damage broke records from the past five decades (Wang et al., 2008). On the contrary, in the same year (2008), there was no snow disaster in North Xinjiang, the Tibetan Plateau, and Pan-Bohai Bay region. Moreover, Northeast China had an apparent negative SCD anomaly (Fig. 5c).

There are great differences in the temporal variations of SCD even in the three major stable snow regions. If we redefine a year with a positive (negative) SCD anomaly, using the much higher standard that 80% of stations should have a positive (negative) anomaly and 40% of stations should have an SCD larger (smaller) than the mean +/- 1SD. It is found that 1957, 1973, and 2010 are years with a positive SCD anomaly in Northeast China, while 1959, 1963, 1967, 1998, 2002, and 2008 are years with a negative SCD anomaly there (Table 3, Fig. 5a–c). Years with a positive SCD anomaly in North Xinjiang include 1959, 1960, 1977, 1980, 1988, 1994, and 2010, and years with a negative SCD anomaly include 1974, 1995, and 2008 (Table 3, Fig. 5c). North Xinjiang is one of the regions prone to catastrophe, where frequent heavy snowfall greatly affects the development of animal husbandry (Hao et al., 2002).

Years with a positive SCD anomaly in the Tibetan Plateau include 1983 and 1990, whereas years with a negative SCD anomaly include 1965, 1969, and 2010 (Table 3). The climate in the Tibetan Plateau is affected by the Indian monsoon from the south, westerlies from the west, and the East Asian monsoon from the east (Yao et al., 2012). Therefore, there is a regional difference in the SCD within the Tibetan Plateau, and even a difference in the spatiotemporal distribution of snow disasters (Wang et al., 2013). Our results differ from the conclusions drawn by Dong et al. (2001), as they only used data from 26 stations, covering only a short period (1967–1996).

3.1.3 SCD trends

Changing trends of annual SCDs are examined, as shown in Figure 6, and summarized in Table 4. Among the 352 stations, there are 54 stations (15%) with a significant negative trend, and 35 stations (10%) with a significant positive trend (both at the 90% level), while 75% of stations show no significant trends. The SCD exhibits a significant downward trend in the Shandong Peninsula, and insignificant downward trends in the North China Plain, the Loess Plateau, the Xiaoxingganling, the Changbai Mountains, North Xinjiang, Northeast Qinghai, and the south-western Tibetan Plateau (Fig. 6a). Some station records indicate a decreasing rate of 1.3–7.2 days per decade.

For example, the SCD decreased by 40 days from 1955 to 2010 at the Kuandian station in Northeast China, 30 days from 1954 to 2010 at the Hongliuhe station in Xinjiang, and 15 days from 1958 to 2010 at the Gangcha station on the Tibetan Plateau (Fig. 7a–c).

The SCDs in the Bayan Har Mountains, the Anemaqen Mountains, the Inner Mongolia Plateau, and Daxingganling, exhibit a significant upward trend (Fig. 6a). For example, at the Shiqu station on the eastern border of the Tibetan Plateau, the SCD increased 26 days from 1960 to 2010 (Fig. 7d). The coexistence of negative and positive trends in the SCD change was also reported by Bulygina et al. (2009) and Wang and Li (2012).

3.2 Spatiotemporal variations of SCOD

3.2.1 SCOD variations

The SCOD is closely related to both latitude and elevation (Fig. 8a). For example, snowfall begins in September on the Tibetan Plateau, in early or middle October on the Daxingganling, and in middle or late October on the Altai Mountains of Xinjiang. The SCOD also varies from one year to another (Table 2). Using the definition of a year with a positive (negative) SCD anomaly, as introduced before (i.e. 70% stations with positive (negative) SCOD anomaly and 30% stations with SCOD larger (smaller) than the mean +/− 1SD), we consider a given year as a late (early) SCOD year. Only two years, 1996 and 2006, can be considered as late SCOD years on a large scale (Table 2), especially in 2006, in East China and the Tibetan Plateau (Fig.6d), while not any single year can be considered as an early SCOD year.

3.2.2 SCOD trends

There are 136 stations (39%) with a significant trend of late SCOD, and 23 stations (7%) with a significant trend of early SCOD (both at the 90% level), while 54% of the stations show no significant trends (Table 4). The SCOD in Northeast China, the central and eastern Tibetan Plateau, the upper reach of the Yellow River, North Gansu, and North Xinjiang exhibits a significant trend towards late SCOD (Fig. 6b). These significantly late trends dominate the major snow areas of China. In particular, the late SCOD in Northeast China is consistent with a previous study (Li et al., 2009). The SCOD in the Pan-Bohai Bay region and the Tianshan Mountains exhibits a trend towards early SCOD. However, this trend is only significant in the Liaoxi corridor and the Tianshan Mountains. For example, the SCOD at the Pingliang station in Gansu Province shows a late rate of 5.2 days per decade from 1952 to 2010, but the SCOD at the Weichang station in Hebei Province shows an early rate of 5.2 days per decade from 1952 to 2010 (Fig. 7e–f).

3.3 Spatiotemporal variations of SCED

3.3.1 SCED variations

The pattern of SCED is similar to that of SCOD (Fig. 8b), i.e. places with early snowfall normally show late snowmelt, while places with late snowfall normally show early snowmelt. Like the SCOD, temporal variations of SCED are large (Table 2). Using the same standard for defining the SCOD anomaly, we judge a given year as a late (early) SCED year. It is evident that 1957 was a typical year whose SCED was late, which was also the reason for the great SCDs (Table 2, Fig. 5e). The SCEDs in 1997 and 2004 were very early. For example, in 1997, the SCED was early for almost all of China except for the Tibetan Plateau, western Tianshan, and western Liaoning (Fig. 5f). In general, the early SCED is dominant and more evident than the late SCED (Table 2).

3.3.2 SCED trends

For the SCED, there are 138 stations (39%) with a significantly early trend (at the 90% level), while 60% of stations show no significant trends (Table 4). Major snow areas in China all show early SCED, significant for Northeast China and the Tibetan Plateau (Fig. 6c). The tendency of late SCED is limited, with only two stations showing a significant trend. For example, the SCED at the Jixi station in Northeast China shows an early rate of 4.4 days per decade from 1952 to 2010, while the SCED at the Maerkang station in Sichuan Province shows a late rate of 4.2 days per decade from 1954 to 2010 (Fig. 7g–h).

4 Discussion

In the context of global warming, 136 stations (39%) show significantly late SCOD, and 138 stations (39%) show significantly early SCED, all at the 90% confidence level. It is not necessary for one station to show both significantly late SCOD and early SCED. This explains why only 15% of stations show a significantly negative SCD trend, while 75% of stations show no significant change in the SCD trends. The latter is inconsistent with the overall shortening of the snow period in the Northern Hemisphere reported by Choi et al. (2010). One reason could be the different time periods used in the two studies, 1972–2007 in Choi et al. (2010) as compared with 1952–2010 in this study. Below, we discuss the possible connections between the spatiotemporal variations of snow cover and the warming climate and changing AO.

4.1 Relationship with TBZD

The number of days with temperature below 0°C (TBZD) plays an important role in the SCD. There are 330 stations (94% of all stations) showing positive correlations between TBZD and SCD, with 193 of them (55%) having significantly positive correlations (Table 4, Fig. 6d). For example, there is a significantly positive correlation between SCD and TBZD at the Chengshantou station (Fig. 9a). Therefore, generally speaking, the smaller the TBZD, the shorter the SCD.

For the SCOD, there are 287 stations with negative correlations with TBZD, accounting for 82% of 352 stations, whereas only 63 stations (18%) show positive correlations (Table 4). This means that for smaller TBZD, the SCOD is later. For the SCED, there are 318 stations with positive correlations, accounting for 90% of 352 stations, whereas only 34 stations (10%) have negative correlations. This means that for smaller TBZD, the SCED is earlier.

Very similar results are found for MAT (Table 4, Fig. 6e), and Fig. 9b shows an example (the Baicheng station).

4.2 Relationship with AO

Although the AO index showed a strong positive trend in the past decades (Thompson et al., 2000), its impact on the SCD in China is spatially distinctive. Positive correlations (47% of 352 stations) are found in central China, i.e. the eastern Tibetan Plateau, the upper reach of the Yangtze River, and the upper and middle reaches of the Yellow River (Table 4, Fig. 6f), and Fig. 9c shows an example (the

Huajialing station). Negative correlations (53% of 352 stations) exist in North Xinjiang, the Changbaishan Mountain and the coasts of the Liaoning and Shandong Peninsula, and Fig. 9d shows an example (the Tonghua station).

5 Conclusion

This study examines the snow cover change based on 672 stations in 1952–2010 in China. Specifically, the 352 stations with more than ten annual mean SCDs are used to study the changing trends of SCD, SCOD, and SCED, and SCD relationships with TBZD, MAT, and AO index during snow seasons. Some important results are summarized below.

Northeast China, North Xinjiang, and the Tibetan Plateau are the three major snow regions, with Northeast China being the largest. In North Xinjiang and in central and north-eastern China, the SCDs are concentrated in the winter season. On the Tibetan Plateau, however, snowfall is more frequent in the spring and fall. The overall inter-annual variability of SCD is large in China. The years with a positive SCD anomaly in China include 1955, 1957, 1964, and 2010, while the years with a negative SCD anomaly are 1953, 1965, 1999, 2002, and 2009. Only 15% of stations show a significantly negative SCD trend, while 75% of stations show no significant SCD trends. This differs from the overall shortening of the snow period in the Northern Hemisphere previously reported. One reason could be the different time periods used in the two studies, 1972–2007 in the work of Choi et al. (2010) compared with 1952–2010 in this study. Our analyses indicate that the SCD distribution pattern and trends in China are very complex and are not controlled by any single climate variable examined (i.e. TBZD, MAT, or AO), but a combination of multiple variables. However, it seems that the AO index has the most impact on the SCD shortening trends in the Shandong Peninsula, Changbai Mountains, and North Xinjiang; the combination of smaller TBZD and increasing MAT has the largest impact on the SCD shortening trends on the Loess Plateau, Xiaoxingganling, and the Sanjiang Plain.

It is found that significantly late SCOD occurs in Northeast China, the central and eastern Tibetan Plateau, the upper reach of the Yellow River, North Gansu, and North Xinjiang; significantly early SCED occurs in Northeast China and the Tibetan Plateau. Both the SCOD and SCED are closely related to the TBZD and MAT, and are mostly controlled by local latitude and elevation. Owing to global warming since 1950s, the reduced TBZD and increased MAT are the main reasons for overall late SCOD and early SCED, although it is not necessary for one station to experience both significantly late SCOD and early SCED. This explains why only 15% of stations show significantly negative SCD trends, while 75% of stations show no significant SCD trends.

Long-duration, consistent records of snow are rare in China because of many challenges associated with taking accurate and representative measurements, especially in western China. The station density and metric choice also vary with time and locality, therefore, more accurate and reliable observation data are needed to further analyse the spatiotemporal distribution and features of snow cover phenology. Atmospheric circulation causes variability in the snow cover phenology, and this effect also requires deeper investigation.

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Table Captions

Table 1. Prediction errors of cross validation for the spatial interpolation with the universal kriging method.

Item (Figure)	Mean error	Average standard error	Root mean squared error	Root mean squared standardized error
SCD (Fig.3a)	-0.0078	9.3710	10.3351	1.1729
CV (Fig.3b)	0.0027	70.9203	56.7797	0.8236
SCD in 1957 (Fig.5a)	-0.0001	10.1066	11.6712	1.1430
SCD in 2002 (Fig.5b)	0.0170	5.7430	7.9122	1.2862
SCD in 2008 (Fig.5c)	0.0008	6.8352	7.3988	1.0627
SCED in 1957 (Fig.5d)	0.0050	14.7432	14.8384	1.0112
SCED in 1997 (Fig.5e)	0.0026	16.9098	19.5960	1.1420
SCOD in 2006 (Fig.5f)	-0.0035	15.4075	16.2315	1.0396
SCOD (Fig.8a)	0.0037	13.8313	15.3312	1.1001
SCED (Fig.8b)	-0.0038	17.1397	19.9136	1.1376

Table 2. Percentage (%) of stations with anomalies (P for positive and N for negative) of snow cover day (SCD), snow cover onset date (SCOD), and snow cover end date (SCED). Percentage (%) of stations with anomalies of SCD, SCOD, and SCED larger (smaller) than the mean +/- one or two standard deviations (1SD or 2SD), with the bold number denoting years with a positive (negative) SCD anomaly, and late (early) years for SCOD or SCED in China. All the percentages are calculated based on 672 stations.

	SCD						SCOD						SCED					
Year	P	1SD	2SD	-2SD	-1SD	N	P	1SD	2SD	-2SD	-1SD	N	P	1SD	2SD	-2SD	-1SD	N
1952	33	5	0	12	31	67	67	39	21	2	12	33	57	17	2	11	16	43
1953	30	6	0	**3**	**34**	**70**	40	8	2	2	18	60	39	9	1	9	17	61
1954	59	29	11	0	8	41	36	8	4	1	17	64	57	12	0	0	9	43
1955	**80**	**48**	**29**	1	5	20	35	8	3	1	24	65	78	21	2	1	5	22
1956	48	11	0	0	4	52	70	20	2	0	8	30	62	23	1	2	12	38
1957	**85**	**64**	**29**	0	3	15	25	5	1	0	14	75	**85**	**35**	**5**	1	4	15
1958	45	15	4	0	14	55	46	17	0	0	19	54	51	16	3	3	17	49
1959	27	6	1	4	23	73	55	27	9	1	17	45	57	22	3	1	5	43
1960	37	12	2	0	15	63	47	10	2	2	13	53	60	25	5	4	17	40
1961	34	7	1	1	19	66	24	9	2	1	28	76	29	6	1	9	28	71
1962	40	10	3	0	10	60	43	13	4	2	10	57	60	18	3	0	11	40
1963	24	5	1	1	25	76	33	13	5	1	26	67	52	14	0	8	16	48
1964	**77**	**39**	**11**	0	1	23	30	3	1	4	23	70	66	17	1	0	5	34
1965	25	8	0	**1**	**33**	**75**	56	18	5	1	9	44	56	14	2	3	16	44
1966	27	7	1	0	12	73	46	20	5	0	12	54	69	12	1	1	4	31
1967	32	7	1	3	23	68	39	10	3	1	14	61	44	4	0	3	11	56
1968	59	28	11	3	8	41	37	9	1	0	13	63	33	13	0	4	27	67
1969	45	21	8	4	21	55	45	13	1	3	19	55	68	21	1	1	7	32
1970	44	14	1	2	10	56	37	10	3	2	26	63	64	18	3	0	6	36
1971	52	12	1	1	11	48	38	14	4	1	17	63	54	8	1	1	9	46
1972	56	24	11	0	7	44	38	10	3	1	20	62	45	16	4	1	9	55
1973	49	19	2	1	7	51	37	10	1	1	22	63	44	9	1	1	8	56
1974	34	9	0	3	23	66	55	30	6	1	10	45	54	12	1	1	9	46
1975	40	9	3	1	14	60	26	7	2	1	21	74	42	14	3	3	17	58
1976	35	11	3	1	22	65	58	24	11	0	5	42	76	29	5	1	3	24
1977	45	20	3	0	9	55	29	5	1	0	24	71	55	14	3	2	12	45
1978	58	21	8	0	2	42	45	13	2	2	12	55	53	10	1	0	8	47

1979	41	9	1	0	7	59	43	10	1	0	18	57	78	25	2	0	4	22
1980	39	11	1	0	5	61	43	9	1	1	16	57	82	28	2	0	3	18
1981	42	12	2	0	12	58	48	21	4	2	17	52	44	13	1	2	14	56
1982	39	11	1	1	15	61	25	9	2	0	29	75	58	24	6	6	16	42
1983	48	19	6	0	15	52	45	14	1	1	11	55	65	25	2	1	10	35
1984	27	10	2	1	28	73	69	33	16	0	5	31	46	8	1	2	13	54
1985	68	25	3	0	3	32	31	8	1	1	23	69	48	9	2	1	8	52
1986	49	14	2	0	13	51	33	5	1	1	19	67	61	17	3	4	12	39
1987	66	22	4	0	4	34	39	6	1	2	15	61	62	26	3	1	8	38
1988	56	16	1	0	2	44	23	6	1	3	29	77	71	25	0	1	7	29
1989	48	19	4	0	11	52	70	28	7	1	6	30	43	5	1	3	17	57
1990	56	19	2	0	6	44	50	9	1	0	8	50	49	11	1	2	10	51
1991	33	4	0	2	10	67	60	24	5	0	3	40	73	26	3	1	4	27
1992	52	14	3	1	7	48	55	17	5	0	4	45	52	14	1	5	18	48
1993	59	18	2	1	4	41	45	9	1	0	16	55	48	17	2	2	21	52
1994	59	18	2	0	4	41	27	6	2	1	25	73	41	11	0	3	17	59
1995	34	10	3	3	19	66	58	23	3	1	15	42	48	8	1	8	20	52
1996	26	7	2	2	22	74	**72**	**30**	**4**	0	4	28	56	10	1	2	14	44
1997	35	3	0	1	18	65	46	16	3	2	12	54	18	4	2	**9**	**50**	**82**
1998	33	7	2	3	17	67	39	12	3	1	19	61	32	11	1	7	25	68
1999	24	4	1	**1**	**35**	**76**	59	23	12	1	7	41	51	13	2	7	16	49
2000	63	16	4	0	5	37	60	18	2	0	9	40	37	6	0	4	22	63
2001	67	28	7	0	5	33	38	15	1	1	22	62	42	17	1	3	15	58
2002	17	2	0	**5**	**31**	**83**	57	21	4	1	5	43	32	6	0	12	30	68
2003	58	28	4	1	8	42	35	5	1	0	20	65	52	9	1	6	18	48
2004	33	3	1	0	17	67	43	12	2	1	25	57	30	7	1	**12**	**35**	**70**
2005	61	20	1	0	4	39	47	15	2	0	12	53	35	4	0	2	19	65
2006	49	11	2	0	8	51	**72**	**32**	**7**	0	5	28	59	15	0	1	10	41
2007	28	5	1	0	23	72	68	24	5	1	5	32	28	3	1	9	28	72
2008	46	21	5	3	19	54	69	27	6	0	8	31	42	9	1	4	23	58
2009	23	5	0	**1**	**32**	**77**	73	23	9	0	4	27	29	4	0	3	25	71
2010	**75**	**40**	**11**	0	9	25	41	10	1	1	21	59	73	19	1	1	7	27

Table 3. The same as Table 2, but only for the years with a positive (negative) SCD anomaly and only for the three major stable snow regions: Northeast China (78 stations), North Xinjiang (21 stations) and the Tibetan Plateau (63 stations).

	Northeast China						North Xinjiang						Tibetan Plateau					
Year	P	1SD	2SD	-2SD	-1SD	N	P	1SD	2SD	-2SD	-1SD	N	P	1SD	2SD	-2SD	-1SD	N
1957	**98**	**20**	**54**	0	0	2	20	0	0	30	0	80	77	12	42	4	0	23
1959	1	0	0	**58**	**14**	**99**	**89**	**0**	**44**	0	0	11	45	3	15	5	0	55
1960	42	1	15	24	0	58	**100**	**26**	**58**	0	0	0	22	0	0	29	2	78
1963	13	0	0	**35**	**5**	**87**	24	0	0	19	5	76	22	0	0	27	0	78
1965	68	1	23	13	1	32	24	0	0	38	0	76	13	0	4	**42**	**4**	**87**
1967	20	0	0	**43**	**13**	**80**	75	0	20	10	0	25	26	0	7	14	0	74
1969	23	0	3	26	14	77	75	0	30	5	0	25	3	0	0	**47**	**5**	**97**
1973	**90**	**4**	**55**	0	0	10	38	0	0	5	10	62	34	2	10	20	0	66
1974	53	0	17	18	3	47	5	0	0	**33**	**19**	**95**	40	0	3	11	2	60
1977	74	5	26	5	0	26	**95**	**0**	**71**	5	0	5	40	6	17	6	0	60
1980	62	1	16	8	0	38	**95**	**5**	**57**	0	0	5	43	2	10	3	0	57
1983	63	3	19	3	0	37	24	0	0	24	0	76	**95**	**24**	**38**	0	0	5
1988	71	0	23	3	0	29	**100**	**10**	**62**	0	0	0	51	5	16	2	0	49
1990	39	0	0	13	1	61	33	0	5	19	0	67	**81**	**3**	**38**	0	0	19
1994	95	1	26	0	0	5	**95**	**0**	**48**	0	0	5	44	2	11	10	0	56
1995	32	0	1	13	4	68	10	0	0	**29**	**19**	**90**	76	10	31	0	0	24
1998	5	0	0	**49**	**13**	**95**	62	0	5	5	10	38	77	11	24	2	0	23
2002	4	0	0	**43**	**21**	**96**	24	0	0	19	5	76	20	0	2	13	0	80
2008	6	0	0	**38**	**12**	**94**	5	0	0	**48**	**5**	**95**	61	2	7	11	2	39
2010	**92**	**17**	**50**	3	0	8	**100**	**10**	**55**	0	0	0	14	0	5	**49**	**2**	**86**

Table 4. Number of stations with SCD, SCOD, and SCED trends, number of stations with relationships of SCD, SCOD, and SCED, respectively, with TBZD, number of stations with relationship between SCD and MAT, and number of stations with relationship between SCD and AO (352 stations in total). All of them have two significance levels, the 90% and 95%.

		SCD			SCOD			SCED		
		95%	90%	I*	95%	90%	I*	95%	90%	I*
Trend	Positive	18	35	136	93	136	124	1	2	43
	Negative	38	54	127	13	23	69	92	138	169
TBZD	Positive	156	193	137	0	2	63	85	115	203
	Negative	0	0	22	64	93	194	0	2	32
MAT	Positive	0	2	30						
	Negative	129	171	149						
AO	Positive	35	87	77						
	Negative	33	82	106						

(Note: I* for insignificant trends or relations)

Figure Captions

Figure 1. Locations of weather stations and major basins, mountains and plains mentioned in the paper, overlying the digital elevation model for China.

Figure 2. Percentage of weather stations with different measurement lengths.

Figure 3. Annual mean snow cover days (SCDs) from 1980/81 to 2009/10 (a), and their coefficients of variation (CV) (b).

Figure 4. Seasonal variation of SCDs; the number in the centre denotes annual mean SCDs, the blue colour in the circle the SCDs for winter season, the yellow colour for spring, and the red colour for autumn.

Figure 5. SCD anomalies in 1957 (a), 2002 (b) and 2008 (c), anomaly of snow cover onset date (SCOD) in 2006 (d), and anomalies of snow cover end date (SCED) in 1957 (e) and 1997 (f).

Figure 6. Trends of annual mean SCDs (a), SCOD (b), and SCED (c) from the 352 stations of more than ten annual mean SCDs with Mann–Kendall test, and relationships among the SCD and day with temperature below 0°C (TBZD) (d), mean air temperature (MAT) (e), and Arctic Oscillation (AO) index (f).

Figure 7. SCD variations at Kuandian (40°43′ N, 124°47′E, 260.1 m) (a), Hongliuhe (41°32′ N, 94°40′E, 1573.8 m) (b), Gangcha (37°20′ N, 100°08′E, 3301.5 m) (c) and Shiqu (32°59′ N, 98°06′E, 4533.0 m) (d), SCOD at Pingliang (35°33′ N, 106°40′E, 1412.0 m) (e) and Weichang (41°56′ N, 117°45′E, 842.8 m) (f), and SCED at Jixi

(45°18′ N, 130°56′E, 280.8 m) (g) and Maerkang (31°54′ N, 102°54′E, 2664.4 m) (h). (The unit on the Y-axis in the figures e, f, g, h denotes the Julian day using 1st September as reference).

Figure 8. Spatial distribution of SCOD (a) and SCED (b) based on the stations with an average of more than ten SCDs.

Figure 9. SCD relationships with TBZD at Chengshantou (37°24′ N, 122°41′E, 47.7 m) (a), MAT at Baicheng (41°47′ N, 81°54′E, 1229.2 m) (b), and AO index at Huajialing (35°23′ N, 105°00′E, 2450.6 m) (c) and Tonghua (41°41′ N, 125°54′E, 402.9 m) (d).

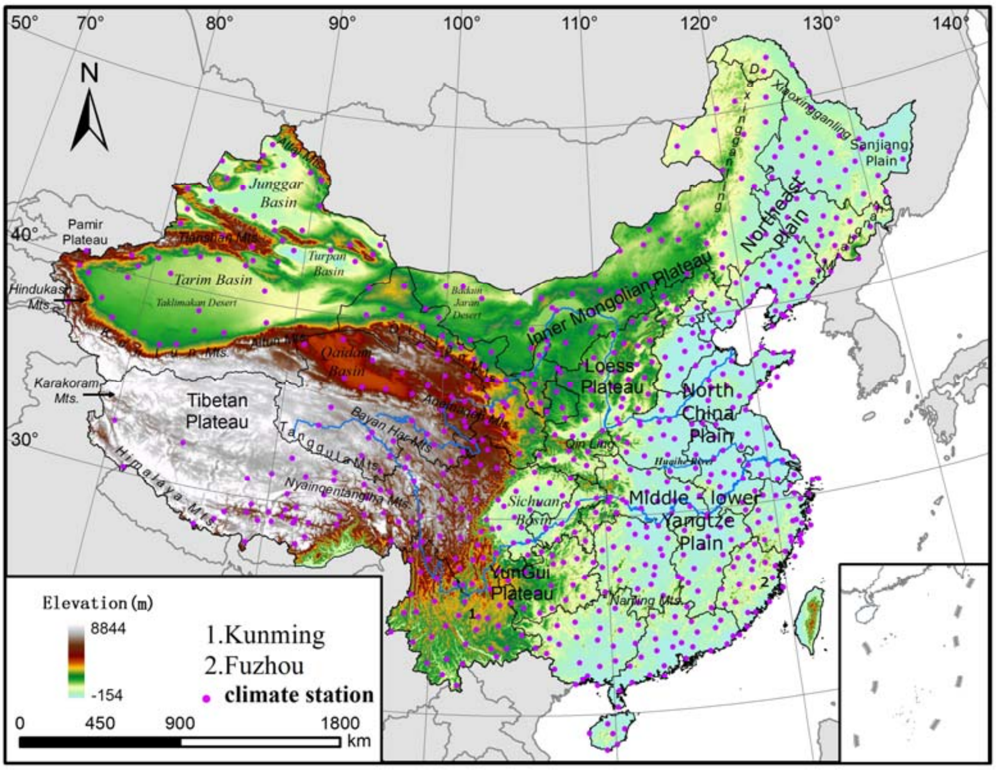

Figure 1

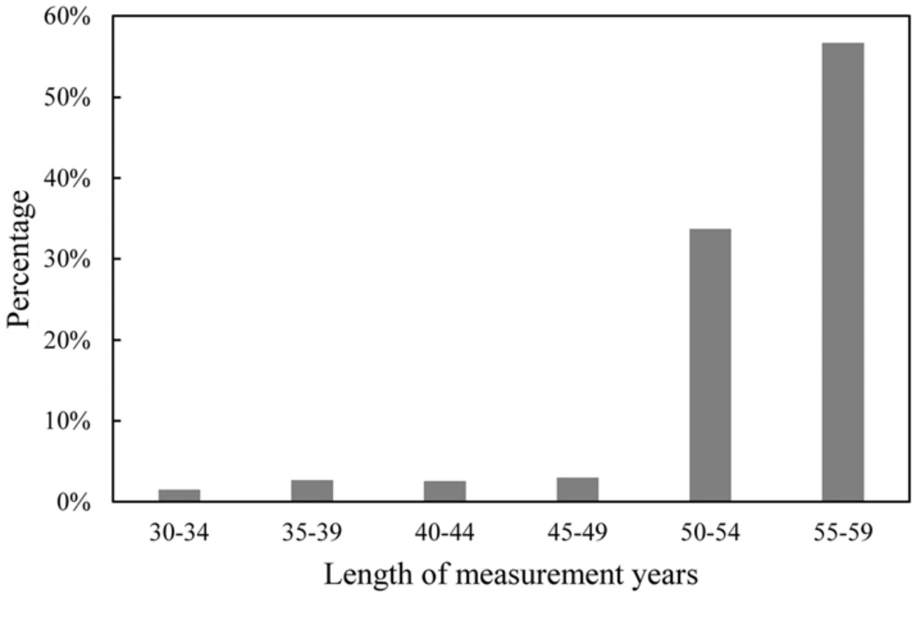

Figure 2

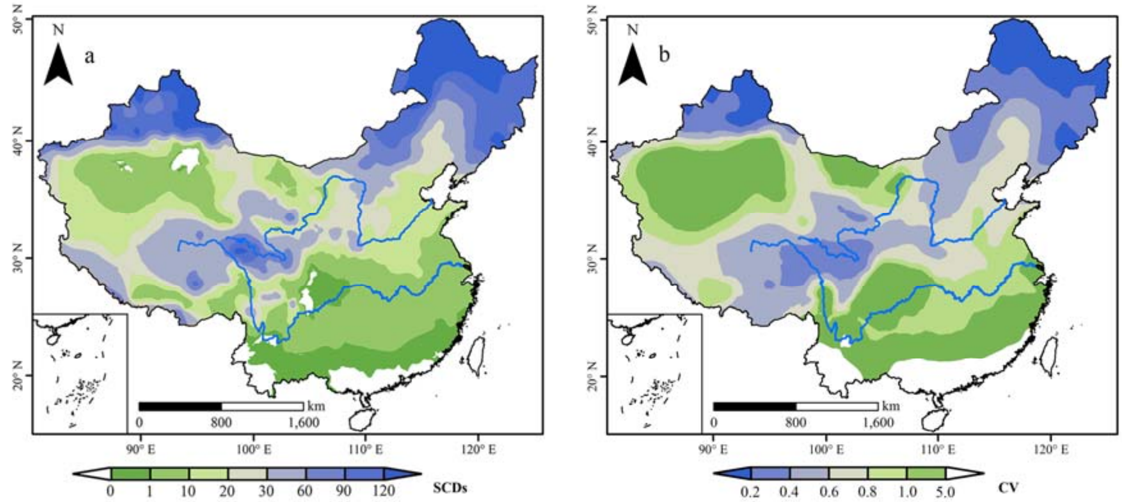

Figure 3

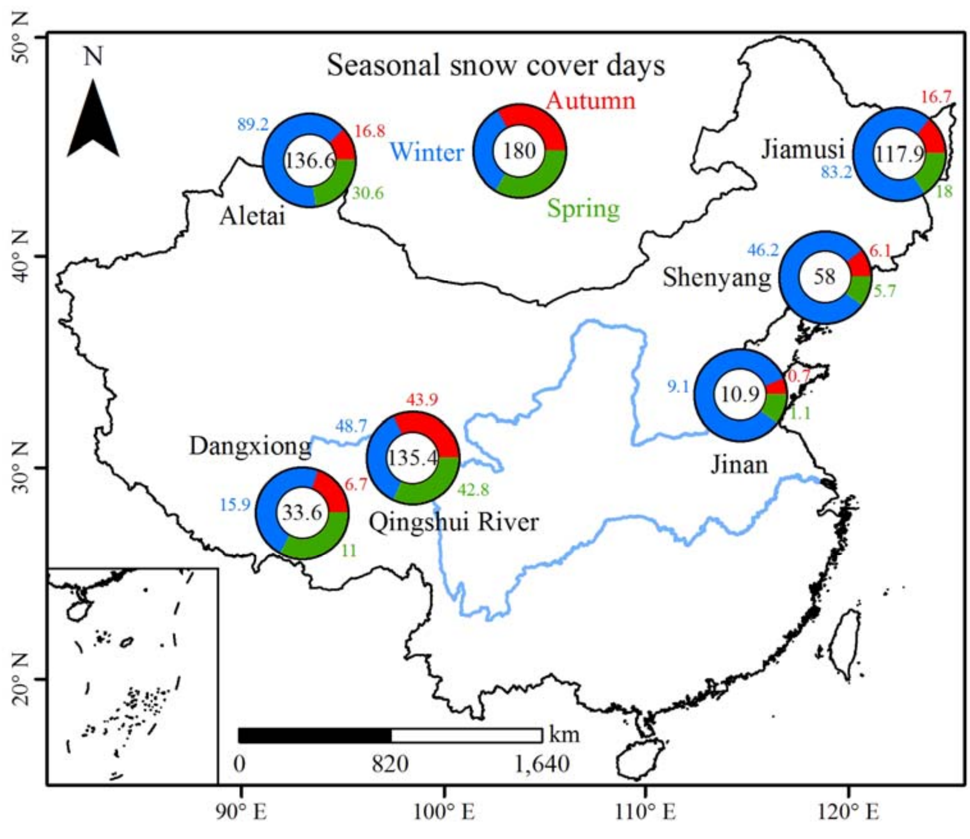

Figure 4

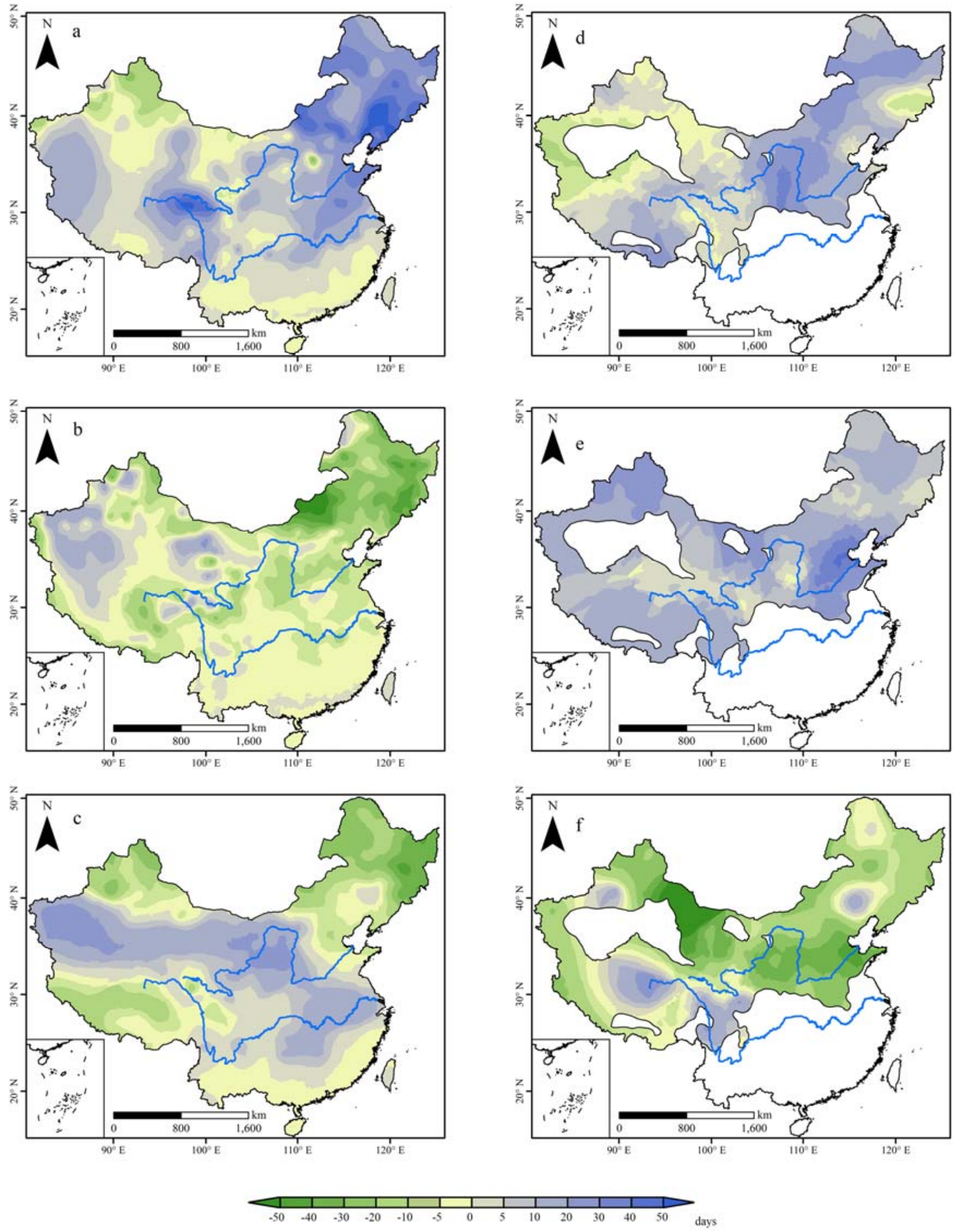
a
b
c
d
e
f
N
km
0
800
1,600
90° E
100° E
110° E
120° E
20° N
30° N
40° N
50° N
-50
-40
-30
-20
-10
-5
0
5
10
20
30
40
50
days

Figure 5

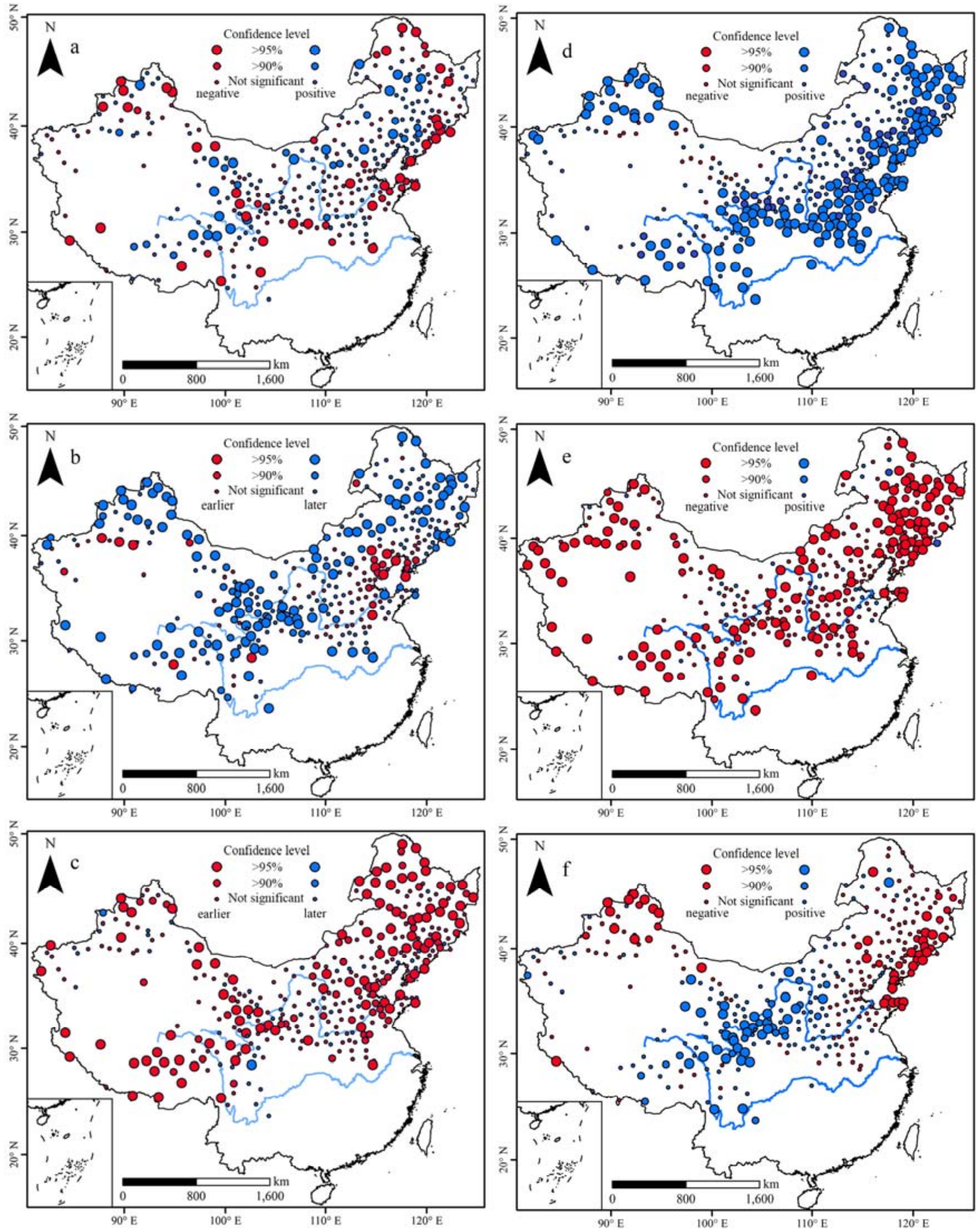
a
N
Confidence level
>95%
>90%
Not significant
negative
positive
km
0
800
1,600
b
earlier
later
c
d
e
f
50° N
40° N
30° N
20° N
90° E
100° E
110° E
120° E

Figure 6

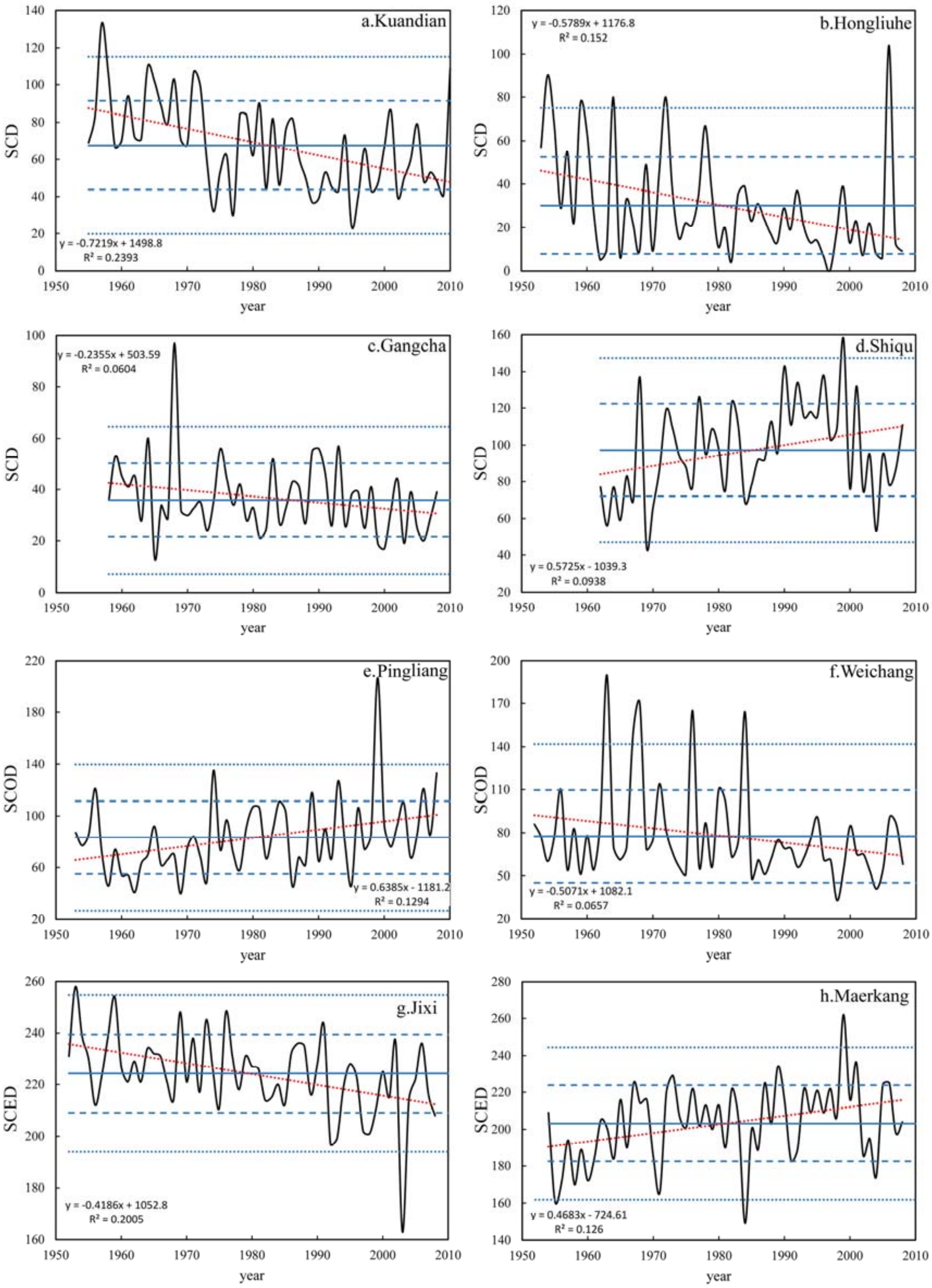
a.Kuandian
y = -0.7219x + 1498.8
R² = 0.2393
b.Hongliuhe
y = -0.5789x + 1176.8
R² = 0.152
c.Gangcha
y = -0.2355x + 503.59
R² = 0.0604
d.Shiqu
y = 0.5725x - 1039.3
R² = 0.0938
e.Pingliang
y = 0.6385x - 1181.2
R² = 0.1294
f.Weichang
y = -0.5071x + 1082.1
R² = 0.0657
g.Jixi
y = -0.4186x + 1052.8
R² = 0.2005
h.Maerkang
y = 0.4683x - 724.61
R² = 0.126
SCD
SCOD
SCED
year

Figure 7

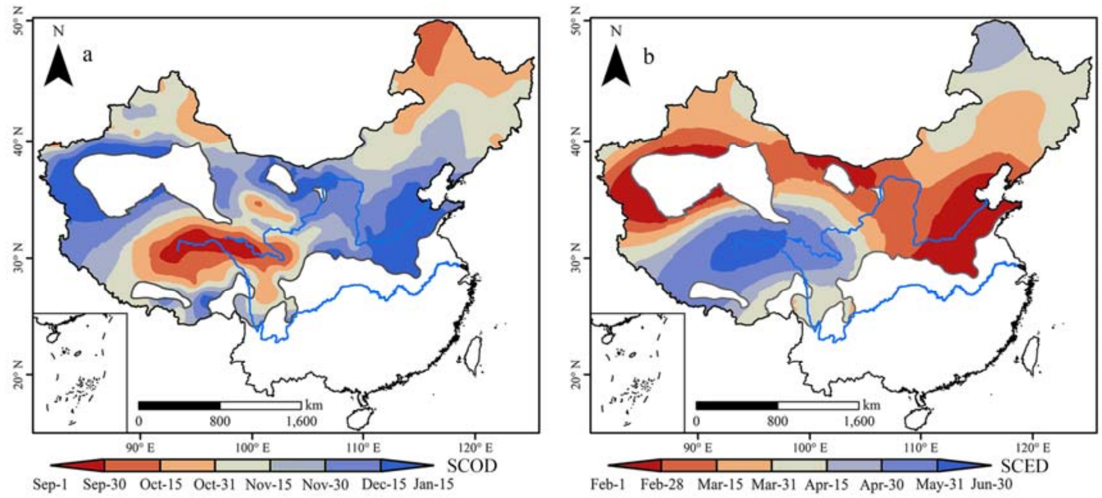

Figure 8

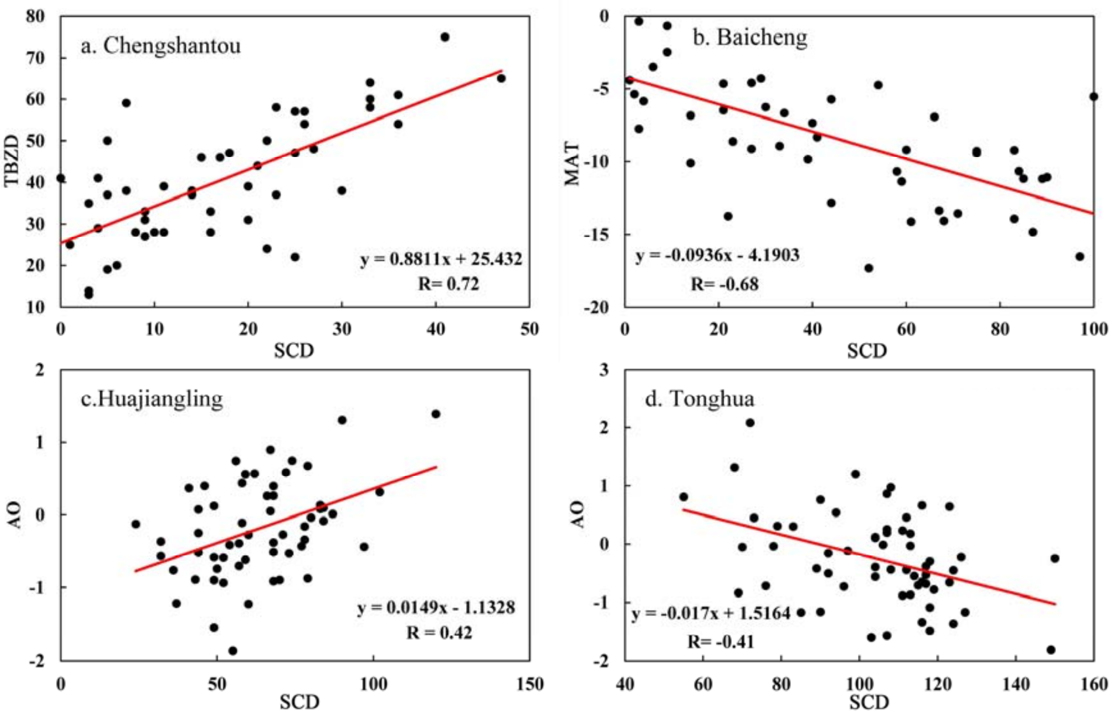

Figure 9