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Air stagnation in China (1985–2014): climatological mean features and trends

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Abstract. Air stagnation is an important meteorological measure of unfavorable air pollution conditions, but little is known about it in China. We conducted a comprehensive investigation of air stagnation in China from January 1985 to December 2014 based on sounding and surface observations from 81 stations. The stagnation criteria were revised to account for the large topographical diversity in the country. It is found that the annual mean of air stagnation occurrences is closely related to general topography and climate features. Two basins in the northwest and southwest of China, the Tarim and Sichuan basins, exhibit the most frequent stagnation occurrence (50 % of days per year), whereas two plateaus (the Qinghai–Tibet Plateau and the Inner Mongolian plateau) and the eastern coastal areas experience the least (20 % of days per year). Over the whole country, air stagnation is at a maximum in summer and a minimum in winter, except for Urumchi, a major city in northwestern China where stagnation maintains a rather constant value year round with a minimum in spring. There is a nationwide positive trend in stagnation occurrence during 1985–2014, with the strongest increasing centers over Shandong Peninsula in eastern China and southern Shaanxi in central China. Changes in air stagnation occurrences are dependent on three components (upper- and lower-air winds and precipitation-free days). This shows that the behavior of upper-air wind speeds is the main driver of the spatial distribution and trends in air stagnation, followed by near-surface winds and dry days, which contribute the least.

1 Introduction

Air quality is strongly dependent on meteorological state, which controls the transport and dispersion of air pollutants within the lower atmosphere. A meteorological state with lingering anticyclones and persistent calm winds leading to poor ventilation and no precipitation to wash out pollutants is defined as an air stagnation event (Wang and Angell, 1999). It has been observed that stagnation events are usually related to air pollution episodes (Jacob et al., 1993; Wang and Angell, 1999; Mickley et al., 2004; Wu et al., 2008; Fiore et al., 2012). For example, ozone measurements from rural sites in the eastern and western United States in 1978 and 1979 indicated that the majority of ozone episodes occurred during stagnant atmospheric conditions (Logan, 1989). The stagnation of air masses led to an enhancement of surface ozone and CO mixing ratios over western and central Europe (Ordónˆez et al., 2010; Leibensperger et al., 2008) and a 2.6 $\mu g\, m^{-3}$ increase in fine particulate matter in the United States (Tai et al., 2010). The sensitivity of air quality to stagnation has been investigated by perturbing meteorological variables in regional chemical transport models (Liao et al., 2006). Jacob and Winner (2009) collected and compared results from different perturbation studies on the effects of weather conditions on ozone and particulate matter concentrations; they concluded that air stagnation demonstrates a robust positive correlation. However, the actual air pollution level is affected not only by meteorological conditions, but also other complex factors, such as emission sources and chemical reactions (Cao et al., 2007; Guo et al., 2009; He et al., 2001; Yang et al., 2016). With other factors unknown, the air stagnation index may show a poor correlation with the actual air pollution data in certain situations. The strength of the air stagnation index is that it provides an independent view of the meteorological background relevant to air pollution without interference from the complexity of other factors, such as the variation in source emissions (Horton et al., 2014).

Air stagnation is identified by thresholds of daily upper- and lower-air winds and precipitation (Wang and Angell, 1999). The "upper-air winds" refer to winds at about 5 km above the ground. From a meteorological perspective, this level is important because of its connection to near-surface synoptic systems. It is found that the movement of surface cyclones tends to travel in the direction of the upper flow at roughly one-quarter to one-half speed (Frederick et al., 2012). These kinds of near-surface synoptic systems are essential to air pollution (Jacob and Winner, 2009; Cai et al., 2017). On the other hand, near-surface winds and precipitation determine the dilution and washout of air pollutants, and both are also relevant to practical air quality. Therefore, air stagnation is a relatively simple but conceptually robust metric to air pollution.

In previous work by Korshover (1967) and Korshover and Angell (1982) for the United States, air stagnation events were defined using daily weather maps from the US National Weather Service. They are periods in which (i) the surface geostrophic wind is less than $8\,\mathrm{m\,s^{-1}}$, generally corresponding to a 10 m wind speed less than $3.2\,\mathrm{m\,s^{-1}}$ (Wang and Angell, 1999), and (ii) the wind speed at 500 hPa is less than $13\,\mathrm{m\,s^{-1}}$ with (iii) no precipitation. Wang and Angell (1999) followed this metric but replaced the dataset with a reanalysis archive ($2.5° \times 2.5°$) from the US National Centers for Environment Prediction (NCEP) National Center for Atmospheric Research (NCAR). With this dataset, they studied the climatology of air stagnation in the United States from 1948 to 1998 and found that air stagnation events happen most frequently in the southern states during an extended summer season from May to October. Based on the work of Wang and Angell (1999), the National Climatic Data Center (NCDC) monitors air stagnation days in the United States with finer-gridded reanalysis data ($0.25° \times 0.25°$) and provides maps on air stagnation distribution every month (http://www.ncdc.noaa.gov/societal-impacts/air-stagnation/). Following the NCDC metric, Leung and Gustafson (2005) examined the potential effects of climate change on US air quality by analyzing the simulated changes in stagnation events for 2045–2055. Horton et al. (2012, 2014) furthered this work and used a multi-model ensemble to project future air stagnation occurrence on a global scale. They found that global warming could be expected to result in increasing stagnation frequency over the eastern United States, Mediterranean Europe, and eastern China.

China has experienced rapid economic growth and industrialization in recent decades and become the second largest energy consumer in the world (Chan and Yao, 2008). Tremendous energy consumption results in heavy air pollution. Research on air quality is indispensable, and studies of the relevant meteorological states are essential. To the authors' knowledge, studies on air stagnation have thus far generally focused on the United States or on a global scale. Our primary purpose in the current study is to investigate the climatological mean features and trends in air stagnation in China based on 30-year (1985–2014) observations from stations across the country.

2 Data and methods

2.1 Data

Long-term (1985–2014) datasets of daily-mean surface wind speeds (observed at 10 m above the surface) and daily precipitation data were obtained from the China Meteorological Administration (CMA). These data are available from the CMA website (http://data.cma.cn/data/detail/dataCode/SURF_CLI_CHN_MUL_DAY_CES_V3.0.html). Upper-air wind speeds were obtained from the University of Wyoming soundings database (http://weather.uwyo.edu/upperair/sounding.html). This database provides twice daily (00:00 and 12:00 UTC) atmospheric soundings from stations that participate in global data exchange. Daily averages of upper-air wind speeds at mandatory levels of 500, 400, and 300 hPa were used here.

We obtained datasets for all the radiosonde stations across China (95 stations) and two stations (Blagoveshchensk and Vladivostok) outside the country but near the border. Among them, 66 stations have corresponding surface datasets from the CMA (see Appendix A). For each of the other 31 radiosonde stations, we considered the average for the surface stations within 150 km as a substitute. This gave us an additional 15 stations (see Appendix B). Air stagnation data from these 81 stations are analyzed in this study. Figure 1 displays the distribution of the stations. There are relatively fewer stations on the Qinghai–Tibet Plateau, particularly in western Tibet. Despite this, the 81 stations cover all of contiguous China well.

2.1.1 Quality control

Surface datasets have been quality controlled by the CMA (http://data.cma.cn/data/detail/dataCode/SURF_CLI_CHN_MUL_DAY_CES_V3.0.html). Upper-air wind data were eliminated from this analysis if

$$\left|U_i - \overline{U}\right| > 2\sigma, \tag{1}$$

where U_i denotes the ith upper-air wind speed at a given mandatory pressure level for a certain station, i ranges from 3 to $n-2$, and n is the total number of the data sample. $\overline{U}$ and σ are calculated as follows:

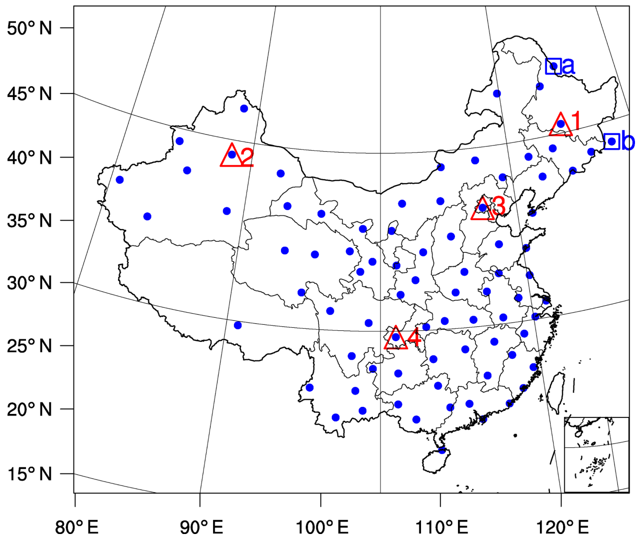

Figure 1. Distribution of the observation stations. The triangles indicate the four stations selected to discuss seasonal variations in air stagnation in Sect. 3: 1 is Harbin, 2 is Urumchi, 3 is Beijing, and 4 is Chongqing. The squares indicate the two stations outside of China at Blagoveshchensk **(a)** and Vladivostok **(b)**.

$$\overline{U} = \frac{1}{5}\sum_{i=i-2}^{i+2} U_i, \tag{2}$$

$$\sigma = \sqrt{\frac{\sum_{i=i-2}^{i+2}\left(U_i - \overline{U}\right)^2}{4}}. \tag{3}$$

A subjective quality control procedure was also applied. A time series plot of upper-air wind speeds at each station was drawn to screen temporally inhomogeneous data. Under these two quality control procedures, no upper-air wind data have been considered abnormal and therefore removed. We consider the data used in this study reliable.

2.1.2 Data completeness

A general survey shows that datasets from 73 stations are available from January 1985 to December 2014, while the other 8 stations (Wenjiang, Jinghe, Chongqing, Shanghai, Vladivostok, Yuzhong, Zhangqiu, Qingyuan) cover less than 30 years. The shortest duration is 7 years and 3 months (October 2007–December 2014) at Jinghe station. The percentage of valid data (data for upper- and lower-air winds and precipitation are all valid) for each station is summarized in Appendices A and B. It is shown that for all stations except Blagoveshchensk, more than 95 % of the data are valid. Overall, the datasets are sufficient to conduct climatological research on air stagnation over China.

2.2 Methods

We adjust the NCDC air stagnation index and a given day is considered stagnant when total daily precipitation is < 1 mm (i.e., a dry day), daily-mean surface wind speed is $< 3.2\,\mathrm{m\,s^{-1}}$, and upper-air wind speed is $< 13\,\mathrm{m\,s^{-1}}$. In previous studies, the upper-air wind is defined as the wind at 500 hPa. For China, however, this criterion is not appropriate because of the great physical diversity. The Qinghai–Tibet Plateau has an average height of over 4000 m, and wind speeds at 500 hPa are not representative of the upper-air winds above the ground. Therefore, we refined the criteria to be topographically dependent, and the mandatory level to provide upper-air wind is chosen according to the station's elevation (Table 1).

With the modified criteria, air stagnation days are identified by checking the meteorological conditions of every day at each station. Furthermore, if there are 4 or more consecutive days of air stagnation conditions at a given station, those days are considered as one air stagnation case (Wang and Angell, 1999). The results for stagnation days and cases were interpolated with cubic splines to a $2° \times 2°$ grid to show the spatial distribution over continental China.

3 Results

3.1 Annual occurrence

Annual mean air stagnation days are distributed with substantial regional heterogeneity (Fig. 2a). They are most prevalent over basins in the northwest and southwest of China (i.e., Xinjiang and Sichuan provinces) where stagnant atmospheric conditions account for 50 % of days per year on average. They are less prevalent (about 33 % days per year) over the northernmost and southernmost parts of the country. The remaining regions in China experience even fewer stagnant days, especially the Qinghai–Tibet Plateau, the Inner Mongolian plateau, and the eastern coastal areas where stagnant conditions occur the least (less than 20 % of days per year). The distribution of stagnation cases agrees well with that of stagnation days (Fig. 2b). The strongest stagnant centers in the Xinjiang and Sichuan basins exhibit more than 16 cases per year, while the weakest centers on the Qinghai–Tibet Plateau, the Inner Mongolian plateau, and the eastern coastal areas only experience fewer than 2 cases per year. Air stagnation cases usually persist for about 5 days in a majority of these areas (Fig. 2c). Those over the basins of Xinjiang and southern China last longer (6 days). The longest duration of air stagnation conditions occurs in the south of Guangxi, lasting more than 7 days.

3.2 Seasonal occurrence

Generally, most stagnant air stagnation conditions happen during the summer season, while only a few occur during

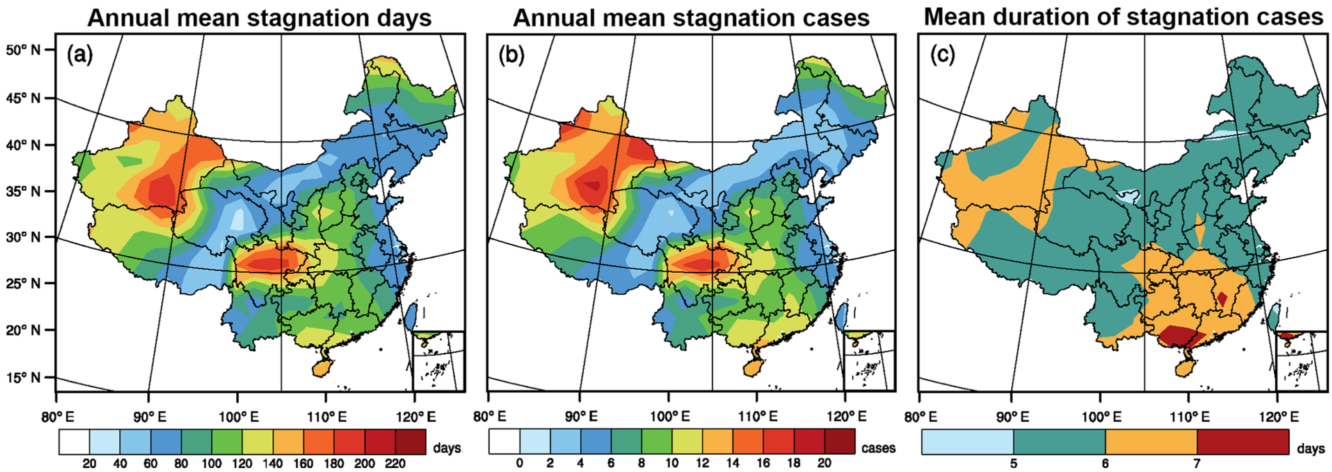

Figure 2. Annual mean air stagnation days **(a)** and cases **(b)** and the mean duration of stagnation cases in days **(c)** for China (1985–2014).

Table 1. Station elevations and the corresponding upper-air wind speed criteria.

Station elevation (m)	Topographically dependent upper-air wind speed criterion
0–1000	Wind speed at 500 hPa < 13 m s^{-1}
1000–3000	Wind speed at 400 hPa < 13 m s^{-1}
3000–4000	Wind speed at 300 hPa < 13 m s^{-1}

winter. Stagnation days in autumn are slightly more frequent than in spring (Fig. 3). A similar feature was also found in the earlier work of Wang and Angell (1999) for the United States. The seasonal variation in stagnation is attributed to a seasonal shift in pressure patterns and general circulation. A much weaker pressure gradient in summer is a well-known seasonal feature in the midlatitudes (Frederick et al., 2012). This feature is very evident in the upper layer of the atmosphere in China (Ding et al., 2013 and their Fig. 1.1). However, at sea surface level, the case in eastern Asia and China is complicated by the subtropical high in the east and the continental low and in the west. As a result, the Asian summer monsoon prevails in eastern China. Except for this, the sea level pressure gradient in summer is still much weaker than in winter (Ding et al., 2013 and their Fig. 1.1). A weaker wind in both the upper and surface layer accompanies the weaker pressure gradient and results in more air stagnation occurrences in China and North America (Wang and Angell, 1999).

We choose four stations (Harbin, Urumchi, Beijing, and Chongqing; shown in Fig. 1 as triangles) and the average for China (all stations in this study) to demonstrate the seasonal variation in air stagnation days and cases. Figure 4 shows that for all but Urumchi, stagnation days and cases begin to increase in March or May, grow dramatically and achieve maxima in July or August, and then fall sharply and reach minima in December or January. However, monthly stagnation days and cases for Urumchi show much less variation in a year with their minima in April. This may be attributed to the unique local climate there. Xinjiang basin is isolated at the center of the continent, far away from the coast and blocked by the huge Qinghai–Tibet Plateau in the south. Therefore, the eastern Asian monsoon, particularly the summer monsoon that prevails in eastern China, has little influence on Xinjiang. As a result, the seasonal feature of the stagnation in Urumchi is different from that in eastern China. By comparing these stations, we find that stagnation over Chongqing, Beijing, and Urumchi is higher than the average level of the entire country. Chongqing station has the largest variation in stagnation, followed by Beijing. Urumchi maintains a relatively high stagnation frequency throughout the year.

3.3 Trends in stagnation

The majority of China exhibits positive trends with about 10–20 stagnation days and 1–3 stagnation cases per decade (Fig. 5a, b). The strongest centers are located in Shandong Province and southern Shaanxi, with rising rates of more than 20 days and 3 cases per decade. Only four areas exhibit a weak decrease: the extreme north of China, regions located in southern Gansu and northern Sichuan, and the westernmost and southernmost parts of China. The negative trend in stagnation varies from 0 to 10 days and 0 to 1 case per decade over the first three regions and 30 days and 5 cases per decade over the last region. We have assessed the statistical significance of the above results, and 52 % of stations passed the 0.05 significance test. Not only stagnation frequencies show an increase over large areas, but the duration of stagnation cases also exhibits a nationwide extension of about 0.3 day $decade^{-1}$ (Fig. 5c). Only a few scattered regions show a gradually shortened stagnation duration, including the extreme north of China, the Yangtze River Delta, and the westernmost and southernmost regions.

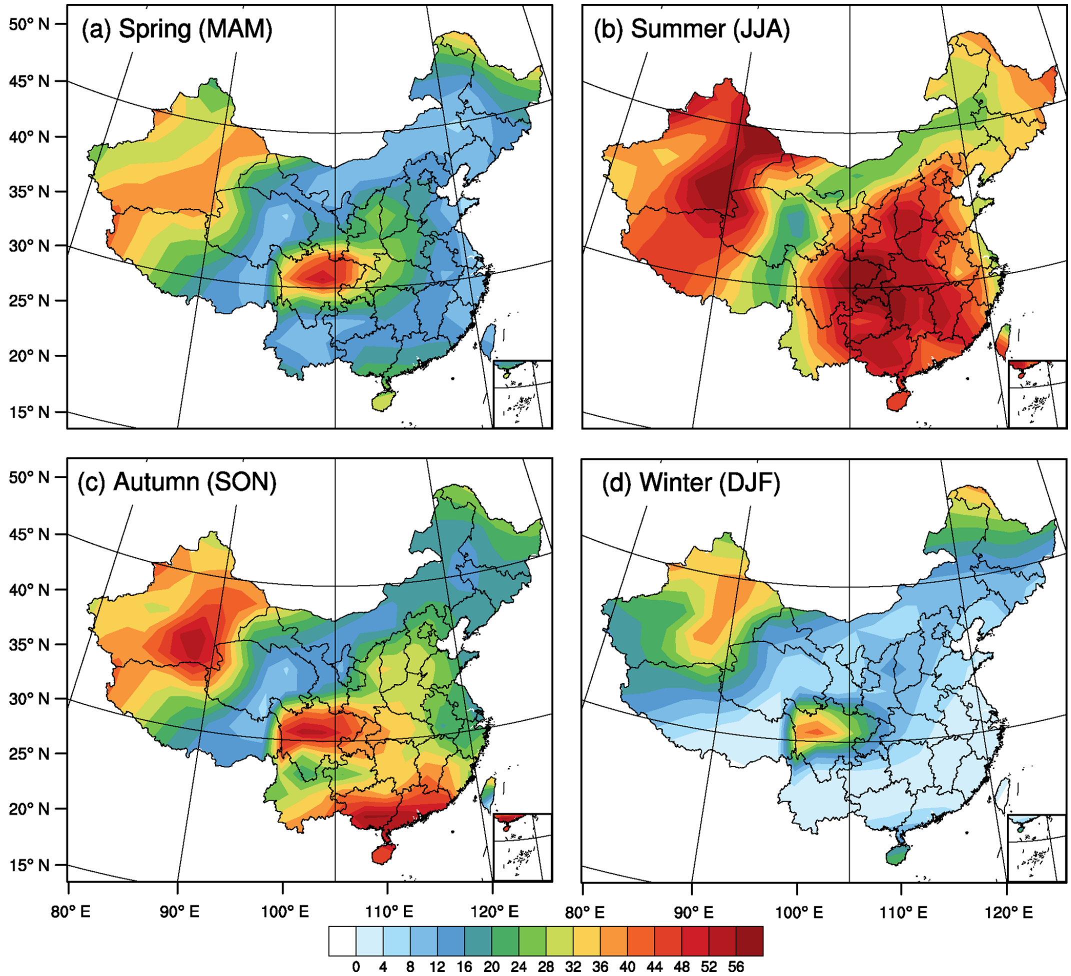

Figure 3. Average air stagnation days in spring **(a)**, summer **(b)**, autumn **(c)**, and winter **(d)** during 1985–2014.

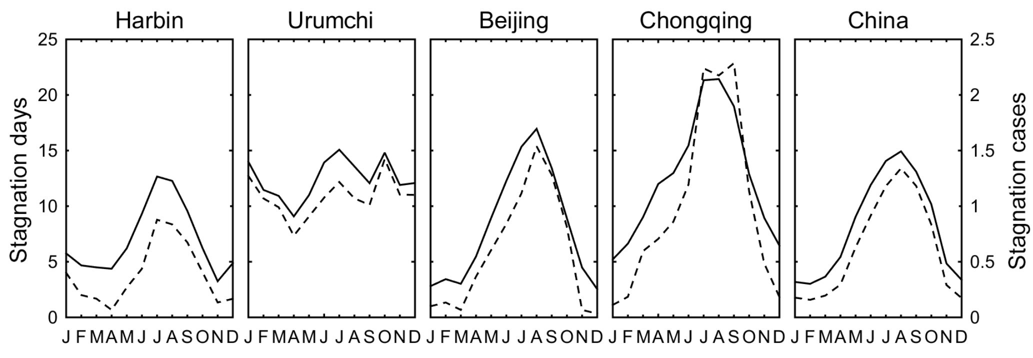

Figure 4. Seasonal cycles of monthly mean air stagnation days and cases for four stations (Harbin, Urumchi, Beijing, and Chongqing) and all of China. The solid line indicates stagnation days, and the dashed line indicates stagnation cases.

Stagnation trends for four stations (Harbin, Urumchi, Beijing, and Chongqing) are also specifically discussed along with the average results for the entire country. Figure 6 shows that all four stations exhibit positive trends in air stagnation days, ranging from 3 to 14 days decade^{-1}, and the nationally averaged increasing rate is about 6 days decade^{-1}. Moreover, the two stations experiencing more stagnant days (Urumchi and Chongqing) exhibit a slower rising rate of about 5 and 3 days decade^{-1}, respectively, whereas the other two stations having relatively less stagnation (Harbin and Beijing), showing a faster rate of about 14 and 8 days decade^{-1}, respectively.

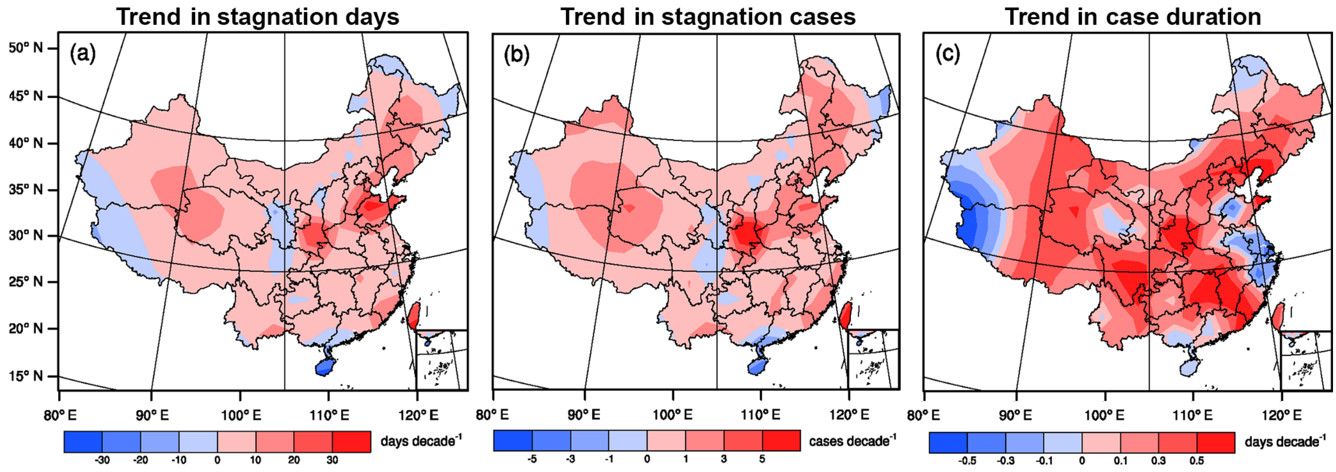

Figure 5. Trends in stagnation days **(a)** and cases **(b)** and the duration of stagnation cases **(c)** during 1985–2014.

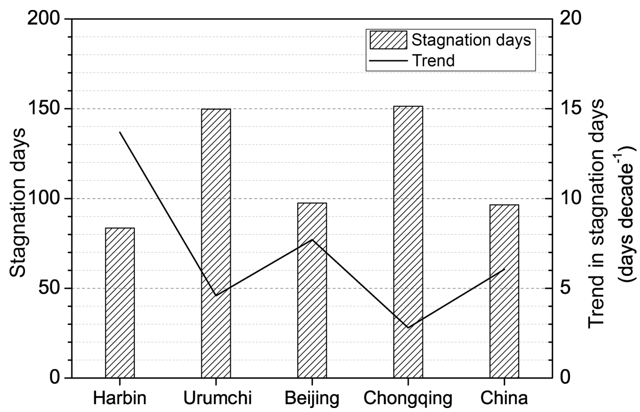

Figure 6. Annual mean stagnant days and the corresponding trends at four stations (Harbin, Urumchi, Beijing, and Chongqing) and for the whole country.

4 Discussion

Air stagnation is identified based on the thresholds of three components: the lower- and upper-air wind speeds and precipitation-free days. An analysis of each individual component is helpful in understanding the behavior of stagnation. Figure 7a shows that the distribution of the annual mean upper-air wind field is reversely correlated with that of stagnation occurrences. The upper-air wind is relatively weak in northeastern China, the Tarim basin, the Sichuan basin, and the southernmost part of the country; these are exactly the same four regions exhibiting frequent stagnation. In contrast to the pattern of the upper-air wind field, the surface wind field exhibits a strong wind center ($> 3\,m\,s^{-1}$) around northeastern China and a weak one (about $1.5\,m\,s^{-1}$) in the Sichuan basin (Fig. 7b). The surface wind speed over the remainder of China is around $2\,m\,s^{-1}$. The distribution of dry days (daily total precipitation < 1 mm) is largely related to the latitude. Figure 7c shows that dry days generally occur more often in the north than in the south. Specifically, southern Xinjiang Province experiences a maximum of more than 350 dry days per year, while southern Shaanxi Province shows a minimum of about 200 days per year.

We further analyze the degrees of stagnation dependence on each individual component (Fig. 8). The result implies that 76 % (R^2) of the spatial variation in stagnant days can be explained by the distribution of upper-air wind fields. The correlation even reaches as high as 82 % in autumn (Fig. S1 in the Supplement). The surface wind field only accounts for 20 % and the spatial distribution of dry days barely influences the stagnation variation. Figures 7 and 8 show that stagnation occurrences result from the cumulative responses of individual stagnation components, but the distribution of upper-air wind speeds exerts the dominant influence. The same feature was also suggested in the global research by Horton et al. (2012) in the area of China.

Similarly, we examine the relationship between stagnation trends and each component (Fig. 9) and find that the pattern of trends in the upper-air wind field is similar to that of stagnant conditions. Decreases in the upper-air wind field substantially outnumber increases throughout the country (Fig. 9a), and the regions showing rapidly decreasing winds coincide with those exhibiting robust growing stagnation in Fig. 7. Trends in surface wind field and dry days may show a slightly different pattern from trends in stagnation (Fig. 9b, c), but they still contribute more or less for some regions. For areas with increasing stagnation, like northeastern and southern Shaanxi Province, dry days show a substantial positive trend (about 3–7 days $decade^{-1}$) and upper- and lower-air wind speeds show a remarkable negative trend (about 0.3–$0.6\,m\,s^{-1}\,decade^{-1}$). For the Shandong region, both upper- and lower-air wind speeds exhibit a substantial decrease of more than $0.3\,m\,s^{-1}\,decade^{-1}$, although the dry days show a slightly decrease of about 1 day $decade^{-1}$. To summarize,

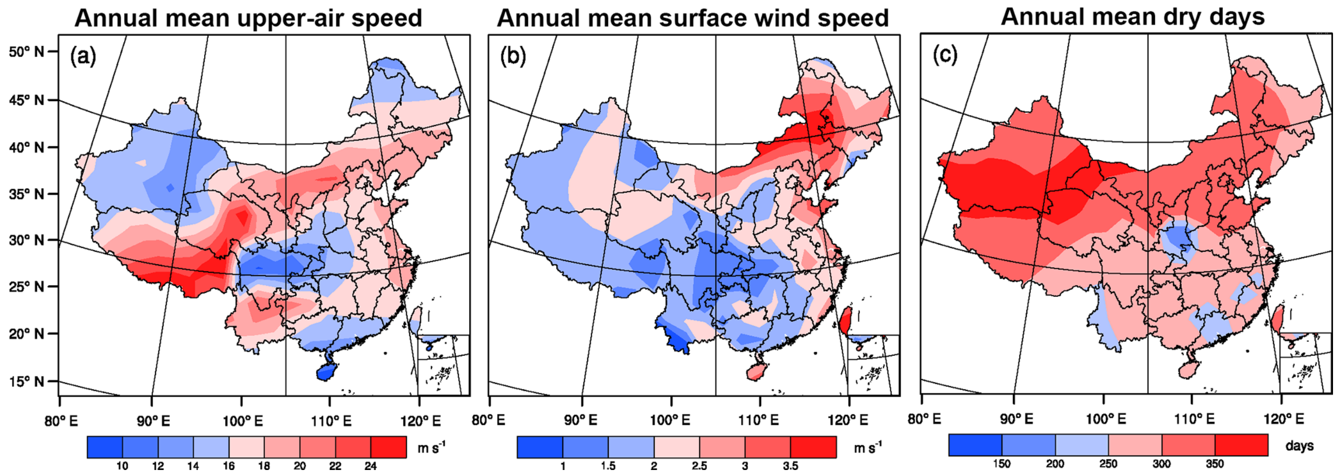

Figure 7. Annual mean upper-air wind speed **(a)**, surface wind speed **(b)**, and dry days **(c)** in China (1985–2014).

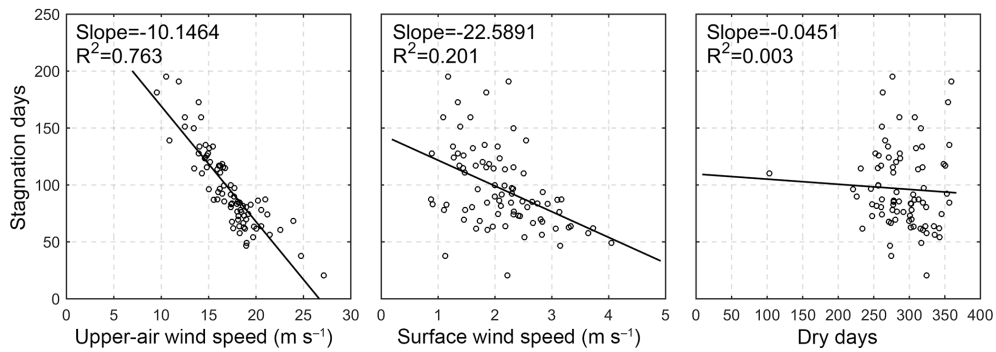

Figure 8. Dependence of the spatial distribution of stagnation days on three components (upper-air wind speed, surface wind speed, and dry days). Linear regression coefficients between annual mean stagnation days at 81 stations and each corresponding component are shown.

the stagnation trends are contemporaneous effects of two or three components.

The dependence of nationally averaged stagnation trends on each individual component is shown in Fig. 10. It can be seen that the negative trend in the upper-air wind speed accounts for 73 % of the increase in stagnant days. The ratio varies slightly with seasons, and the highest (79 %) occurs in spring (Fig. S2 in the Supplement). Interannual variations in surface wind speed and dry days explain 42 and 32 %, respectively. Still, trends in the upper-air wind are the dominant contributor.

The trends in these three components (upper-air winds, near-surface winds, and daily precipitation) are driven by climate change. The decrease in upper-air winds results from smaller contrasts of the sea level pressure and a weakened Hadley circulation, both as a consequence of global warming (Lau et al., 2006; Lu et al., 2007; Seidel et al., 2008). The near-surface wind decline is attributed to the slowdown in atmospheric general circulation (Guo et al., 2011; Xu et al., 2006; Vautard et al., 2010) and the stabilized atmosphere by light-absorbing aerosols (Li et al., 2016; Peng et al., 2016; Wang et al., 2013). The decreasing number of rainy days, due to suppressed light rainfall but intensified heavy rainfall, is mainly attributed to the accumulation of greenhouse gases and aerosols in China (Gong et al., 2004; Liu et al., 2015; Wang et al., 2011a, 2016). To sum up, climate changes alter atmospheric circulation and the hydrological cycle, which influence the occurrences of air stagnation as the meteorological background of air quality.

Stagnation is a meteorological metric for potential air pollution occurrence. Once there are anthropogenic or natural air pollutants, they are likely to accumulate and result in poor air quality over regions that experience frequent stagnant conditions. In contrast, over regions with infrequent stagnation, air pollutants will quickly be transported far away and diluted. The current results from the prevalent centers of stagnation days and cases are consistent with areas of heavy pollution in China (Mamtimin and Meixner, 2007; Wang et al., 2011b; Chen and Xie, 2012; Liu et al., 2013; Zhang et al., 2014; Li et al., 2015). The spatial distribution of annual mean visibility during 1985–2014 (Fig. S3 in the Supplement) shows that regions in the Sichuan basin, western Xinjiang, and the North China Plain exhibit low visibility. This feature corresponds well to the frequent air stagnation occur-

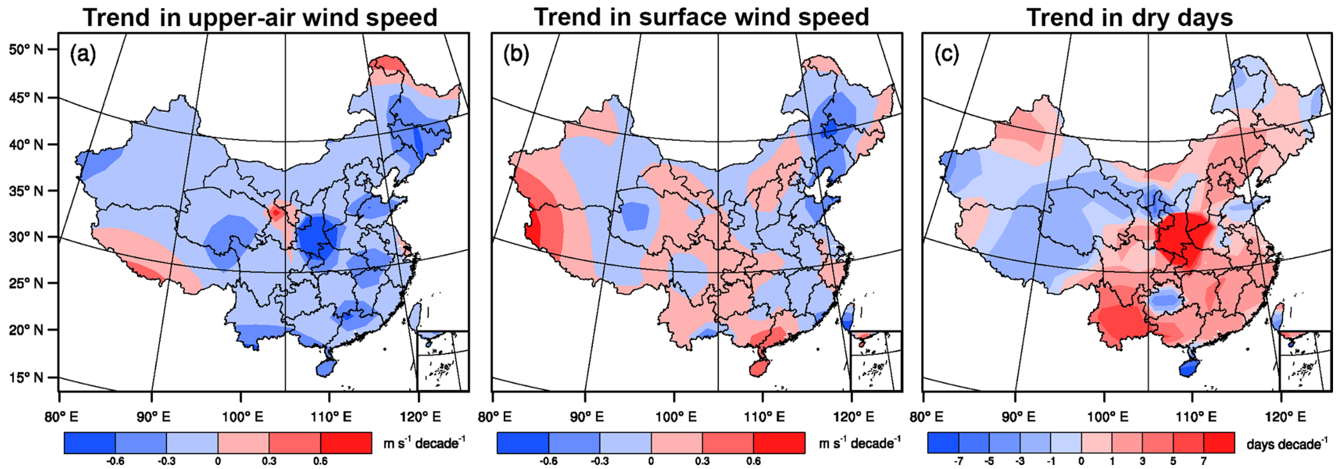

Figure 9. Trends in upper-air wind speed **(a)**, surface wind speed **(b)**, and dry days **(c)** during 1985–2014.

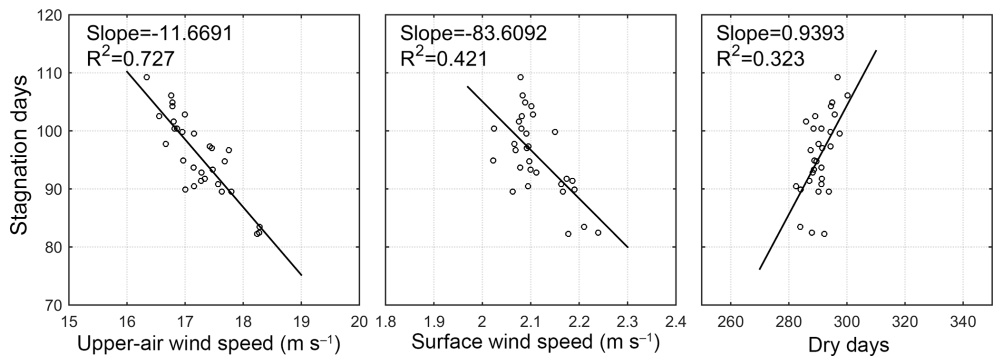

Figure 10. Same as Fig. 8, but for the trends in stagnant days. Linear regression coefficients between nationally averaged stagnant days in the 30-year period and each corresponding component are shown.

rences in Fig. 2. The correlation between the time series of air stagnation days and visibility over the whole country is −0.69 during 1985–2014 (Fig. S4 in the Supplement). This means that air stagnation correlates negatively with visibility in general. It confirms that stagnation is an effective metric to measure the potentially unfavorable meteorological states in terms of air quality.

It should be noted that the air stagnation metric does not take into account emissions or atmospheric chemical reactions, so there may be discrepancies between variations in the stagnation index and the actual air pollutant concentrations in certain situations. For example, the aerosol concentration in China is characterized by a high value in winter and a lower value in summer. This observational fact is clearly related to the seasonal variation in source emissions, since there is more coal consumption in winter for heating, particularly in northern China (Cao et al., 2007; He et al., 2001). To make this kind of meteorological metric applicable for practical air pollution forecasting, Yang et al. (2016) incorporate source emission information into their PLAM index and successively improve the forecasting skill. In this work, we aim to analyze the general features of the meteorological background relevant to air pollution by means of the air stagnation metric without concern for the complexity of source emissions or chemical reactions.

5 Conclusions

Based on upper and surface wind speeds and daily precipitation data from 81 stations across the country, this paper presented climatological mean values and trends in air stagnation in China from January 1985 to December 2014. The dependence of stagnation on three components (upper- and lower-air winds and dry days) was examined. A topographically dependent version of air stagnation criteria was applied to account for the terrain effect in China.

The annual mean air stagnation occurrence varies spatially, which is in agreement with topography and climate features. Two basins in northwestern and southwestern of China, the Tarim and Sichuan basins, exhibit the most frequent stagnation occurrence (50 % of days per year). Two plateaus (the Qinghai–Tibet and Inner Mongolian plateaus) and the eastern coastal areas experience the least (20 % of days per year). Seasonal variation in air stagnation is also presented. For a general view of the whole country, stagnation happens most frequently in summer and least frequently in winter. For specific stations in Harbin, Beijing, and Chongqing, stagnation varies dramatically by month and achieves maxima in July or August and minima in December or January; stagnation in Urumchi maintains a rather constant value with a minimum in April.

There is a nationwide positive trend in stagnation days, stagnation cases, and case duration during 1985–2014. The strongest increasing centers are located over Shandong Province in eastern China and southern Shaanxi in the middle of the country. Only two regions in the southernmost and westernmost parts of China exhibit a negative trend in both occurrence and duration.

Stagnation occurrence contemporaneously responds to three components: upper- and lower-air winds and precipitation-free days. Among these, the upper-air wind speed plays a dominant role, explaining 76 and 73 % of the spatial distribution and trends in air stagnation, respectively. The lower-air wind exerts a minor influence. These results are corroborated by the global research by Horton et al. (2012). The spatial variation in dry days barely influences stagnation, whereas interannual variability explains 32 % of the stagnation trend.

Air stagnation climatology presents a specific view of the natural background of the atmospheric features responsible for air pollution levels. The results presented in this paper may have significant implications for air pollution research and may be used in atmospheric environmental management or air pollution control.

Data availability. Dataset of daily-mean surface wind speeds and daily precipitation during 1985–2014 were obtained from CMA website (http://data.cma.cn/data/detail/dataCode/SURF_CLI_CHN_MUL_DAY_CES_V3.0.html). Upper-air wind speeds were obtained from the University of Wyoming (http://weather.uwyo.edu/upperair/sounding.html).

Appendix A

Table A1. The 66 radiosonde stations that have corresponding surface datasets from the CMA. The periods for which radiosonde and surface datasets were both available are summarized with the start and end dates in the column date range. Data periods of less than 30 years are highlighted in bold. The percentages of valid data are also presented here.

Station	ID*	Latitude (° N)	Longitude (° E)	Elevation (m)	Date range	Valid data
Hailar	50527	49.21	119.75	611	Jan 1985–Dec 2014	97.8 %
Nenjiang	50557	49.16	125.23	243	Jan 1985–Dec 2014	98.9 %
Harbin	50953	45.75	126.76	143	Jan 1985–Dec 2014	99.4 %
Altay	51076	47.72	88.08	737	Jan 1985–Dec 2014	99.2 %
Yining	51431	43.95	81.33	664	Jan 1985–Dec 2014	99.3 %
Urumchi	51463	43.77	87.62	919	Jan 1985–Dec 2014	99.2 %
Kuqa	51644	41.71	82.95	1100	Jan 1985–Dec 2014	99.4 %
Kashgar	51709	39.46	75.98	1291	Jan 1985–Dec 2014	99.2 %
Ruoqiang	51777	39.02	88.16	889	Jan 1985–Dec 2014	99.1 %
Hotan	51828	37.13	79.93	1375	Jan 1985–Dec 2014	99.4 %
Hami	52203	42.81	93.51	739	Jan 1985–Dec 2014	99.3 %
Dunhuang	52418	40.15	94.68	1140	Jan 1985–Dec 2014	99.1 %
Jiuquan	52533	39.75	98.48	1478	Jan 1985–Dec 2014	98.9 %
Minqin	52681	38.63	103.08	1367	Jan 1985–Dec 2014	98.5 %
Golmud	52818	36.4	94.9	2809	Jan 1985–Dec 2014	99.2 %
Dulan	52836	36.29	98.09	3192	Jan 1985–Dec 2014	96.9 %
Xining	52866	36.71	101.75	2296	Jan 1985–Dec 2014	99.1 %
Erenhot	53068	43.65	112	966	Jan 1985–Dec 2014	99.1 %
Hohhot	53463	40.81	111.68	1065	Jan 1985–Dec 2014	99.3 %
Yinchuan	53614	38.47	106.2	1112	Jan 1985–Dec 2014	98.2 %
Taiyuan	53772	37.77	112.55	779	Jan 1985–Dec 2014	99.1 %
Yan'an	53845	36.59	109.5	959	Jan 1985–Dec 2014	99.3 %
Pingliang	53915	35.54	106.66	1348	Jan 1985–Dec 2014	98.9 %
Xilinhot	54102	43.95	116.05	991	Jan 1985–Dec 2014	99.2 %
Tongliao	54135	43.6	122.26	180	Jan 1985–Dec 2014	99.3 %
Changchun	54161	43.9	125.21	238	Jan 1985–Dec 2014	99.0 %
Chifeng	54218	42.25	118.95	572	Jan 1985–Dec 2014	99.3 %
Yanji	54292	42.88	129.46	178	Jan 1985–Dec 2014	99.4 %
Shenyang	54342	41.75	123.43	43	Jan 1985–Dec 2014	99.2 %
Linjiang	54374	41.71	126.91	333	Jan 1985–Dec 2014	98.9 %
Beijing	54511	39.93	116.28	55	Jan 1985–Dec 2014	99.4 %
Dalian	54662	38.9	121.62	97	Jan 1985–Dec 2014	99.3 %
Lhasa	55591	29.65	91.12	3650	Jan 1985–Dec 2014	97.5 %
Yushu	56029	33	97.01	3682	Jan 1985–Dec 2014	97.1 %
Hezuo	56080	35	102.9	2910	Jan 1985–Dec 2014	98.4 %
Garzê	56146	31.61	100	522	Jan 1985–Dec 2014	98.7 %
Wenjiang	56187	30.7	103.83	541	**Jul 2004–Dec 2014**	98.1 %
Xichang	56571	27.9	102.26	1599	Jan 1985–Dec 2014	98.7 %
Tengchong	56739	25.11	98.48	1649	Jan 1985–Dec 2014	99.1 %
Kunming	56778	25.01	102.68	1892	Jan 1985–Dec 2014	99.0 %
Simao	56964	22.76	100.98	1303	Jan 1985–Dec 2014	99.3 %
Mengzi	56985	23.38	103.38	1302	Jan 1985–Dec 2014	99.2 %
Zhengzhou	57083	34.7	113.65	111	Jan 1985–Dec 2014	99.3 %
Hanzhong	57127	33.06	107.02	509	Jan 1985–Dec 2014	99.4 %
Jinghe	57131	34.26	108.58	411	**Oct 2007–Dec 2014**	100.0 %
Enshi	57447	30.28	109.46	458	Jan 1985–Dec 2014	99.4 %
Yichang	57461	30.7	111.3	134	Jan 1985–Dec 2014	99.3 %
Wuhan	57494	30.61	114.12	23	Jan 1985–Dec 2014	99.4 %
Chongqing	57516	29.51	106.48	260	**Aug 1987–Dec 2014**	98.2 %

Table A1. Continued.

Station	ID*	Latitude (° N)	Longitude (° E)	Elevation (m)	Date range	Valid data
Guiyang	57816	26.47	106.65	1222	Jan 1985–Dec 2014	98.0 %
Guilin	57957	25.33	110.3	166	Jan 1985–Dec 2014	99.4 %
Ganzhou	57993	25.85	114.94	125	Jan 1985–Dec 2014	99.1 %
Xuzhou	58027	34.27	117.15	42	Jan 1985–Dec 2014	99.3 %
Nanjing	58238	32	118.8	7	Jan 1985–Dec 2014	99.4 %
Shanghai	58362	31.4	121.46	4	**Jun 1991–Dec 2014**	98.3 %
Anqing	58424	30.53	117.05	20	Jan 1985–Dec 2014	99.4 %
Hangzhou	58457	30.22	120.16	43	Jan 1985–Dec 2014	99.3 %
Nanchang	58606	28.6	115.91	50	Jan 1985–Dec 2014	99.1 %
Quxian	58633	28.95	118.86	71	Jan 1985–Dec 2014	99.1 %
Fuzhou	58847	26.07	119.27	85	Jan 1985–Dec 2014	99.3 %
Xiamen	59134	24.47	118.08	139	Jan 1985–Dec 2014	99.3 %
Baise	59211	23.9	106.6	175	Jan 1985–Dec 2014	99.2 %
Wuzhou	59265	23.48	111.3	120	Jan 1985–Dec 2014	98.3 %
Shantou	59316	23.35	116.66	3	Jan 1985–Dec 2014	99.2 %
Nanning	59431	22.62	108.2	126	Jan 1985–Dec 2014	99.3 %
Haikou	59758	20.03	110.34	24	Jan 1985–Dec 2014	99.2 %

* World Meteorological Organization identification number.

Appendix B

Table B1. Same as Appendix A, but for the 15 radiosonde stations and corresponding surface stations within 150 km.

Station	ID	Latitude (° N)	Longitude (° E)	Elevation (m)	Surface stations (CMA)	Latitude (° N)	Longitude (° E)	Distance (km)	Date range	Valid data
Blagoveshchensk	31510	50.52	127.5	177	50353	51.43	126.4	127.58	Jan 1985–Dec 2014	65.9 %
					50564	49.26	127.2	141.64		
Vladivostok	31977	43.26	132.05	82	54096	44.23	131.1	132.61	**Aug 1994–Dec 2014**	96.1 %
King’s Park	45004	22.3	114.16	66	59287	23.1	113.2	132.7	Jan 1985–Dec 2014	99.1 %
					59293	23.44	114.4	129.34		
					59501	22.48	115.2	110.8		
Yuzhong	52983	35.87	104.15	1875	52884	36.21	103.6	65.18	**Jul 2001–Dec 2014**	94.5 %
Linhe	53513	40.75	107.4	1041	53336	41.34	108.3	100.66	Jan 1985–Dec 2014	99.0 %
Zhangqiu	54727	36.7	117.55	123	54725	37.3	117.3	70.05	**Aug 2003–Dec 2014**	98.3 %
					54823	36.36	117	59.92		
					54843	36.45	119.1	142.05		
Qingdao	54857	36.06	120.33	77	54843	36.45	119.1	117.68	Jan 1985–Dec 2014	99.3 %
Weining	56691	26.86	104.28	2236	57707	27.18	105.2	95.07	Jan 1985–Dec 2014	98.4 %
Nanyang	57178	33.03	112.58	131	57265	32.23	111.4	141.85	Jan 1985–Dec 2014	99.2 %
					57290	33	114	133.37		
Changsha	57679	28.2	113.08	46	57687	28.13	112.6	52.52	Jan 1985–Dec 2014	98.6 %
Huaihua	57749	27.56	110	261	57745	27.27	109.4	66.58	Jan 1985–Dec 2014	99.2 %
Sheyang	58150	33.75	120.25	7	58040	34.5	119.1	136.93	Jan 1985–Dec 2014	99.3 %
					58251	32.52	120.2	136.88		
Fuyang	58203	32.86	115.73	33	58102	33.52	115.5	77.52	Jan 1985–Dec 2014	99.3 %
					58221	32.57	117.2	143.98		
Shaowu	58725	27.32	117.45	219	58715	27.35	116.4	104.76	Jan 1985–Dec 2014	99.1 %
					58834	26.39	118.1	121.86		
Qingyuan	59280	23.66	113.05	19	59082	24.41	113.4	89.16	**Jan 1996–Dec 2014**	95.3 %
					59287	23.1	113.2	64.13		
					59293	23.44	114.4	140.78		

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Competing interests. The authors declare that they have no conflict of interest.

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