Response to Referees

Manuscript: Air Stagnations for China (1985–2014): Climatological

Mean Features and Trends (acp-2016-1072)

According to the comment from Co-editor, we re-revised the manuscript based on the recommendations from referees. The changes in the first-time revision are marked in blue color and those in the second-time revision are marked in purple.

We are very grateful to the referees for their insightful comments. We carefully consider all the comments and suggestions, and carry out additional analysis on relevant problems. We hope that we have taken most of the referees' concerns into the revised manuscript. All the referees' comments are copied below in italics, and followed by our responses. Additional material containing four figures (Figs. R2–5 in this Response) is supplied in the Supplement as Figs. S1–4.

Referee #1:

General comments:
This manuscript presents very intriguing results with regard to the current status and positive trend of air stagnation in China during the previous 30 years. The analysis method is sounding and structure is well organized. This work certainly fit the scope of ACP. Overall, the results obtained here gain additional insight into how meteorology modulates the air pollution that is blanket across China. However, traditional, the atmospheric stability is characterized by thermodynamic metrics, such as PLAM developed by Yang et al. ACP 2016, which has been demonstrated to sufficiently reflect the real air pollution condition at most regions of China. The stagnation index (SI) was improved in this study by taking the terrain into account, which is composed of three components, but by nature it is quite different metric for characterize the atmospheric stability highly associated with air pollution. As such, more discussions are required, as detailed in the following comments. Therefore, I recommend this work be published in ACP after the following concerns have been adequately addressed.
<u>Response:</u>
We thank the referee for the positive evaluation to this article. As the referee mentioned, there are different metrics related to air pollution. Among them, the PLAM is of solid theoretic bases and is also successfully applied in China to analyze and forecast air pollution (Yang et al., 2016). The air stagnation index (SI) is a different metric and, to our knowledge, has not yet been systematically applied in China. So, in the revised manuscript, we try to add more discussions on relevant questions. The difference between SI and PLAM is also remarked.

References:

Yang, Y. Q., Wang, J. Z., Gong, S. L., Zhang, X. Y., Wang, H., Wang, Y. Q., Wang, J., Li, D., and Guo, J. P.: PLAM - a meteorological pollution index for air quality and its applications in fog-haze forecasts in North China, Atmos. Chem. Phys., 16, 1353-1364, doi:10.5194/acp-16-1353-2016, 2016.

Specific comments:

1. The seasonality of stagnation index (SI) with maximum in summer but minima in winter reported here seems contrary to the actual air pollution. For example, a large amount of previous studies (e.g., Cao et al., JGR 2007; Guo et al., AE 2009; He et al., AE 2011) have shown that seasonal variation of aerosol concentrations is significant in China, characterized by highest concentration in the winter and lowest in the summer. More interestingly, Guo et al. (2009) revealed more complicated seasonality of aerosol concentrations based on 11 PM observations sites. Therefore, the appropriate discussion concerning how the SI connects with aerosol pollution on the monthly scale is needed, given the easy availability nowadays. In other words, I would like to see the scatter plots of Stagnation days versus PM2.5 or PM10, similar to the plot convention in Fig. 8.

Response:

Air stagnation index (SI) has long been studied in North America continent (as introduced in the manuscript). This is a simple and meaningful metric to air pollution. However, this metric indicates adverse meteorological condition to air pollution, rather than the air pollution itself. Because air pollution level is determined by not only 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., 2011; Yang et al, 2016), etc. So, this kind of metric is only an indicator for air pollution potential—the potential for air pollution events. This is the reason that the metric may show bad correlation or even contrary to actual air pollution, when comparing them ***directly***.

For the fact that aerosol concentration in China is characterized by high value in winter and lower one in summer, it is obviously related to the seasonal variation of source emission, since there is more coal consumption in winter for heating, particularly in north China (Cao et al., 2007; He et al., 2011). Therefore, to make this kind of metric applicable for practical air pollution forecasting, Yang et al. (2016) incorporate source emission information into their PLAM index, and improve the forecasting skill successively. On the other hand, one can also investigate the sensitivity of air quality to stagnations 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* about the influence of meteorological variables on ozone and particulate matter concentrations, and summarized that air stagnation is the only metric that consistently shows a robust positive correlation.

The purpose of this paper is to provide a general distribution of air pollution potential over China, as well as its long-term trend, by the metric of air stagnation.

This is also an effort to "isolate the meteorological factors that produce poor air quality" (Horton et al., 2012). The strength of this work is that, it provide an independent view to the meteorological background relevant to air pollution, without being interfered by the complexity of other factors, e.g. the variation of source emissions.

Since our purpose is not to apply directly to air pollution diagnosis or forecasting, like the work of Yang et al. (2016), and previous works have demonstrated good correlation between air stagnation and air pollution (Jacob and Winner, 2009), therefore at least at this stage, we do not try to compare the metric with concentrations of air pollutants.

This discussion has been added in the revised manuscript.

References:

Cao, J. J., Lee, S. C., Chow, J. C., Watson, J. G., Ho, K. F., Zhang, R. J., Jin, Z. D., Shen, Z. X., Chen, G. C., Kang, Y. M., Zou, S. C., Zhang, L. Z., Qi, S. H., Dai, M. H., Cheng, Y., and Hu, K.: Spatial and seasonal distributions of carbonaceous aerosols over China, J. Geophys. Res.-Atmos., 112, doi:10.1029/2006JD008205, 2007.

Guo, J. P., Zhang, X. Y., Che, H. Z., Gong, S. L., An, X. Q., Cao, C. X., Guang, J., Zhang, H., Wang, Y. Q., Zhang, X. C., Xue, M., and Li, X. W.: Correlation between PM concentrations and aerosol optical depth in eastern China, Atmos. Environ., 43, 5876–5886, doi:10.1016/j.atmosenv.2009.08.026, 2009.

He, K. B., Yang, F. M., Ma, Y. L., Zhang, Q., Yao, X. H., Chan, C. K., Cadle, S., Chan, T., and Mulawa, P.: The characteristics of PM2.5 in Beijing, China, Atmos. Environ., 35, 4959–4970, doi:10.1016/S1352-2310(01)00301-6, 2001.

Horton, D. E. and Diffenbaugh, N. S.: Response of air stagnation frequency to anthropogenically enhanced radiative forcing, Environ. Res. Lett., 7, 044034, doi:10.1088/1748-9326/7/4/044034, 2012.

Jacob, D. J., and Winner, D. A.: Effect of climate change on air quality, Atmos. Environ., 43, 51–63, doi:10.1016/j.atmosenv.2008.09.051, 2009.

Liao, H., Chen, W. T., and Seinfeld, J. H.: Role of climate change in global predictions of future tropospheric ozone and aerosols, J. Geophys. Res.-Atmos., 111(D12), doi:10.1029/2005JD006852, 2006.

Yang, Y. Q., Wang, J. Z., Gong, S. L., Zhang, X. Y., Wang, H., Wang, Y. Q., Wang, J., Li, D., and Guo, J. P.: PLAM - a meteorological pollution index for air quality and its applications in fog-haze forecasts in North China, Atmos. Chem. Phys., 16, 1353-1364, doi:10.5194/acp-16-1353-2016, 2016.

2. Page 3, line 13-17: For each of the other radiosonde stations: it is better to clarify how many station, for example 8 other radiosonde stations? According to Guo et al., ACP 2016, there are 120 radiosonde stations across China, and actually only part of the whole radiosonde netword was used in this study.
Response:
We obtained datasets of all the radiosonde stations across China (95 stations) and two stations (Blagovescensk and Vladivostok) outside but near the border of the

country. Among them, 66 stations have corresponding surface datasets from CMA (See Appendix A). For each of the other 31 radiosonde stations without corresponding surface data, we considered the average of surface stations within 150 km as a substitute. In this way, we got additional 15 stations (See Appendix B). Air stagnations of these 81 stations are analyzed in this study. We have rewritten this part of sentences in the revised the manuscript to clarify.

There are 120 upper-air sounding stations in China, except for Hong Kong and Taiwan district (Li, 2006; Guo et al., 2016). The stations used in our study are those participate in global data exchange, which are available from the free-access Wyoming University soundings database (http://weather.uwyo.edu/upperair/sounding.html).

Reference:
Guo, J. P., Miao, Y. C., Zhang, Y., Liu, H., Li, Z. Q., Zhang, W. C., He, J., Lou, M. Y., Yan, Y., Bian, L. G., and Zhai, P.: The climatology of planetary boundary layer height in China derived from radiosonde and reanalysis data, Atmos. Chem. Phys., 16, 13309-13319, doi:10.5194/acp-16-13309-2016, 2016.
Li F. New Development with Upper Air Sounding in China. WMO TECO, 2, 2006.

3. Figure 1: The site outside of China like Blagovescensk, Vladivostok, and KingsPark should be plotted and marked.
Response:

Blagovescensk and Vladivostok have been marked on Fig. 1 in the revised manuscript. Kings Park is a site in Hong Kong, and has been treated as a normal site in China.

4. Page 4, line 25: What kind of spatial interpolation methods have the authors applied? More details should be given, like the size of grid point for the maps.
Response:

Results of stagnation days and cases were interpolated with cubic splines to $2°×2°$ grid. This detail has been added in the revised manuscript.

5. Section 3.2:" During summer a weaker pressure gradient lingers over China, which results in weaker atmospheric circulations and more frequent stagnations." I think at least one figure is needed to corroborate this argument, e.g., the pressure gradient difference between summer and annual mean.
Response:

Pressure patterns vary in strength and location seasonally. This is a fact known in climate studies in China (e.g. Ding et al., 2013). Figure R1 shows that in upper layer, the gradient of geopotential height is much weaker in summer than that in winter, so the pressure gradient varies in the same way. At surface (sea level), in winter, a very strong high-pressure center (i.e. the Siberian high) is generated over the frozen landscape of northern Asia. In summer, high surface temperatures over the land generate lows that replace wintertime highs. In general, pressure gradient at surface is

also weaker in summer than in winter over most of China.

We are sorry that we had not properly cited reference about this fact. Now, we add the citation and the fact description in the revised manuscript.
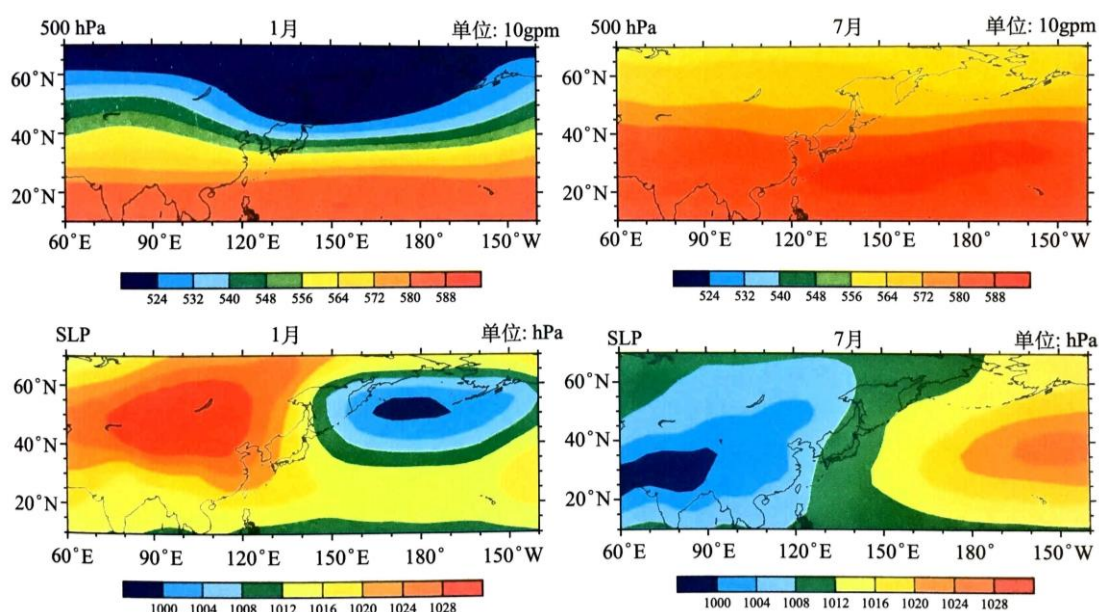

Figure R1. Atmospheric circulation in East Asia. Upper: geopotential height (unit: 10gpm) of 500 hPa in January (left) and July (right). Bottom: sea level pressure (unit: hPa) in January (left) and July (right). This figure is copied from Ding et al. (2013), their Fig. 1.1.

Reference:
Ding, Y. H., Wang, S. W., Zheng, J. Y., Wang, H. J., and Yang, X. Q.: Climate of China, Science Press, Beijing, 557pp, 2013 (in Chinese).

Referee #2

General comments:
This study explores the long-term surface meteorology and sounding measurements in China to study the climatology and inter-decadal trends of air stagnation in China since the 1980s. Considering the current severe haze pollution in China, this topic is interesting to the community and the compiled data sets are valuable for other pollution-related researches. Therefore, the materials in the manuscript are definitely publishable. However, my major concern is that, in contrast to the abundance of data involved in this study, the analyses of the data and the exploration of physics behind the observed relationships are quite inadequate. The authors should carefully address this issue before I can recommend its publication on ACP. Some detailed comments are provided below.

Response:
We thank the referee very much for the positive evaluation to this paper. We have added more introduction and discussion to improve the knowledge behind the

phenomena in the revised manuscript. We hope that we have explored more physics behind air stagnation index and its trend in this revision.

Specific comments:
1) Section 3.2, the seasonality of air stagnation is interesting, but the authors' explanation and analysis are insufficient. For example, authors simply attributed the peak of stagnation in the summer to the "weak pressure gradient", but failed to explain what cause the weak pressure gradient in the summertime Eastern China. How is it linked to the sub-tropical high or the monsoon circulation? Answers can be found by looking at reanalysis of meteorological fields.

Response:

This question is similar to Question 5 of Referee #1. Our explanation is based on a fact in climate studies of China (Ding et al. 2013), but we are sorry that we had not cited proper reference about it in the original manuscript.

A much weaker pressure gradient in summer is the seasonal feature in mid-latitudes (Frederick et al., 2012). This feature is very evident in upper layer atmosphere in China (Fig. R1, Ding et al. 2013). However at the sea-level surface, the case in eastern Asia and China are complicated by the sub-tropical high in the east and the continental low and in the west respectively. As a result, Asia summer monsoon prevails in eastern China. Though for this, the sea level pressure gradient in summer is still much weaker than that in winter (Fig. R1, Ding et al. 2013).

This explanation has been added in the revised manuscript.

Reference:

Ding, Y. H., Wang, S. W., Zheng, J. Y., Wang, H. J., and Yang, X. Q.: Climate of China, Science Press, Beijing, 557pp, 2013 (in Chinese).

Frederick, K. L., Edward, J. T., and Dennis, G. T.: The atmosphere: an introduction to meteorology, Prentice Hall, 528pp, 2012.

2) Similarly, it is interesting to see the larger influence of upper-level wind on air stagnation than that of the surface wind (this point should be highlighted in the abstract), but the physical relationship between upper-level wind and air stagnation is vaguely described in the manuscript. It should be thoroughly discussed in the introduction part. Is the upper-level wind here associated with moving speed of high pressure systems?

Response:

The "upper-air winds" in air stagnation index refer to winds at about 5 kilometers 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 a quarter to half of the 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). This simply means, the weather system has large impacts on air stagnation.

This part of discussion has been added in the revised manuscript.

Reference:

Cai, W., Li, K., Liao, H., Wang, H., and Wu, L.: Weather conditions conducive to Beijing severe haze more frequent under climate change, Nat. Clim. Change, 7, 257–262, doi: 10.1038/nclimate3249, 2017.

Frederick, K. L., Edward, J. T., and Dennis, G. T.: The atmosphere: an introduction to meteorology, Prentice Hall, 528pp, 2012.

Jacob, D. J., and Winner, D. A.: Effect of climate change on air quality, Atmos. Environ., 43, 51–63, doi:10.1016/j.atmosenv.2008.09.051, 2009.

3) Inter-decadal trends of air stagnation in China are derived in this study, but what drive these trends are not discussed in the paper. Greenhouse gas, anthropogenic aerosol, or some other forcing agents? I understand that this complex question may be beyond the main scope of the paper, but some discussions along this line could largely sharpen the climatic implication of this study. I suggest a more thorough literature review about recent climate changes in China, in terms of hydrological cycle and precipitation extremes (Wang Y. et al., 2016, JGR), monsoon circulations (Li Z., et al., 2016, Rev. Geos.), etc, and the authors can link the trends to the possible factors at play.

Response:

We thank the referee for this suggestion. As mentioned by the referee, the climate system is complex, so is the climate change. Although the greenhouse gas and anthropogenic aerosol may provide a general background to global climate change, there are still large uncertainties in regional climate responses or trends. Our work shows the fact of trends only based on the air stagnation metric.

Three components of the air stagnation metric are: upper-air winds, near-surface winds and daily precipitation. Our results have shown that the increasing trend of air stagnation is mainly caused by the decreasing trend of upper-air winds. The decreasing trend of near-surface winds exerts a minor influence, while the increasing number of dry days has the least influence.

Studies have shown that wind speeds of mid- and upper-troposphere decrease in the past 30 years (Zhang et al., 2009). The trend can be attributed to global warming, which results in smaller contrasts of the sea level pressure, and near-surface temperature between the Asian continent and the Pacific Ocean. A consistent weakening and poleward expansion of the Hadley circulation in the climate change background also plays a role (Frierson et al., 2007; Hu et al., 2011; Jiang et al., 2010; Lau et al., 2006; Lu et al., 2007; Seidel et al., 2008).

Over China, near-surface wind decline is attributed to (1) slowdown in atmospheric general circulation and weakening in synoptic weather activity, and thus reduced downward transport of the horizontal momentum by the faster wind aloft (Guo et al., 2011; Jiang et al., 2010; Vautard et al., 2010; Xu et al., 2006). (2) increasing surface roughness in the near field of each station and/or in boundary layer structure (Vautard et al., 2010); (3) light absorbing aerosols, which stabilize the

atmosphere by cooling the surface and warming the upper. As a result, the vertical flux of horizontal momentum is reduced (Erlick et al., 2003; Li et al., 2016; Pandithurai et al., 2008; Peng et al., 2016; Wang et al., 2013; Yang et al., 2013).

The decreasing number of rainy days (Li et al., 2016; Gong et al., 2004; Liu et al., 2002) also play a positive role in the increasing of air stagnation over China. According to Gong et al. (2004), such trend is mainly caused by the significant reduction of days with light rain. And accumulation of greenhouse gases and dramatic increases of anthropogenic aerosols may be responsible for that (Liu et al., 2015; Wang et al., 2016).

We have added this literature review in the revised manuscript.

References:

Erlick, C., and Ramaswamy, V.: Sensitivity of the atmospheric lapse rate to solar cloud absorption in a radiative-convective model, J. Geophys. Res.-Atmos., 108, doi:10.1029/2002JD002966, 2003.

Frierson, D. M. W., Lu, J., and Chen, G.: Width of the Hadley cell in simple and comprehensive general circulation models, Geophys. Res. Lett., 34, doi:10.1029/2007GL031115, 2007.

Gong, D. Y., Shi, P. J., and Wang, J. A.: Daily precipitation changes in the semi-arid region over northern China, J. Arid Environ., 59, 771-784, doi:10.1016/j.jaridenv.2004.02.006, 2004.

Guo, H., Xu, M., Hu, Q.: Changes in near-surface wind speed in China: 1969-2005, Int. J. Climatol., 31, 349-358, doi:10.1002/joc.2091, 2011.

Hu, Y., Zhou, C., and Liu, J.: Observational evidence for poleward expansion of the Hadley circulation, Adv. Atmos. Sci., 28, 33-44, doi:10.1007/s00376-010-0032-1, 2011.

Jiang, Y., Luo, Y., Zhao, Z., Tao, S.: Changes in wind speed over China during 1956–2004, Theor. Appl. Climatol., 99, 421-430, doi:10.1007/s00704-009-0152-7, 2010.

Lau, N. C., Leetmaa, A., and Nath, M. J.: Attribution of atmospheric variations in the 1997–2003 period to SST anomalies in the Pacific and Indian Ocean basins, J. Clim., 19, 3607-3628, doi:10.1175/JCLI3813.1, 2006.

Li, Z. Q., Lau, W. K. M., Ramanathan, V., Wu, G., Ding, Y., Manoj, M. G., Liu, J., Qian, Y., Li, J., Zhou, T., Fan, J., Rosenfeld, D., Ming, Y., Wang, Y., Huang, J., Wang, B., Xu, X., Lee, S. S., Cribb, M., Zhang, F., Yang, X., Zhao, C., Takemura, T., Wang, K., Xia, X., Yin, Y., Zhang, H., Guo, J., Zhai, P. M., Sugimoto, N., Babu, S. S., and Brasseur, G. P.: Aerosol and monsoon climate interactions over Asia, Rev. Geophys., 54, 866-929, doi:10.1002/2015rg000500, 2016.

Liu, R., Liu, S. C., Cicerone, R. J., Shiu, C. J., Li, J., Wang, J. L., and Zhang, Y. H.: Trends of Extreme Precipitation in Eastern China and Their Possible Causes, Adv. Atmos. Sci., 32, 1027-1037, doi:10.1007/s00376-015-5002-1, 2015.

Liu, S. C., Wang, C. H., Shiu, C. J., Chang, H. W., Hsiao, C. K., and Liaw, S. H.: Reduction in sunshine duration over Taiwan: Causes and implications, Terr. Atmos. Ocean. Sci., 13, 523-545, 2002.

Lu, J., Vecchi, G. A., and Reichler, T.: Expansion of the Hadley cell under global warming, Geophys. Res. Lett., 34, 5, doi:10.1029/2006gl028443, 2007.

Pandithurai, G., Seethala, C., Murthy, B. S., and Devara, P. C. S.: Investigation of atmospheric boundary layer characteristics for different aerosol absorptions: Case studies using CAPS model, Atmos. Environ., 42, 4755-4768, doi:10.1016/j.atmosenv.2008.01.038, 2008.

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Vautard, R., Cattiaux, J., Yiou, P., Thepaut, J.-N., and Ciais, P.: Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness, Nat. Geosci., 3, 756-761, doi:10.1038/ngeo979, 2010.

Wang, Y., Khalizov, A., Levy, M., and Zhang, R. Y.: New Directions: Light absorbing aerosols and their atmospheric impacts, Atmos. Environ., 81, 713-715, doi:10.1016/j.atmosenv.2013.09.034, 2013.

Wang, Y., Ma, P.-L., Jiang, J. H., Su, H., and Rasch, P. J.: Toward reconciling the influence of atmospheric aerosols and greenhouse gases on light precipitation changes in Eastern China, J. Geophys. Res.-Atmos., 121, 5878-5887, doi:10.1002/2016jd024845, 2016.

Xu, M., Chang, C. P., Fu, C. B., Qi, Y., Robock, A., Robinson, D., and Zhang, H. M.: Steady decline of east Asian monsoon winds, 1969-2000: Evidence from direct ground measurements of wind speed, J. Geophys. Res.-Atmos., 111, doi:10.1029/2006jd007337, 2006.

Yang, X., Yao, Z., Li, Z., and Fan, T.: Heavy air pollution suppresses summer thunderstorms in central Chin J. Atmos. Sol.-Terr. Phy., 95-96, 28-40, doi:10.1016/j.jastp.2012.12.023, 2013.

Zhang, A. Y., Ren, G. Y., Guo, J., and Wang, Y.: Change trend analyses on upper-air wind speed over China in past 30 years, Plateau Meteor, 28, 680-687, 2009 (in Chinese).

4) Would the increasing trend of air stagnation be partly caused by the accumulation of the absorbing aerosols in boundary layer and a consequent stabilization effect (Wang Y., et al., 2013, AE; Peng J. et al., 2016, PNAS)?
<u>Response:</u>
     Our response for 3) has covered this question.

5) The correlation analyses in Fig. 8 and 10 use annual mean values. Why not monthly mean? That would give you more dots and larger statistical significance.
<u>Response:</u>
     As suggested, we also use seasonal mean values to conduct correlation analyses (Figs. R2 and R3). According to Fig. 8, the spatial distribution of dry days barely correlates with that of air stagnations. So we did not further investigate the seasonal difference of correlation between them. Figures R2 and R3 are presented in the supplement as Fig. S1 and Fig. S2.
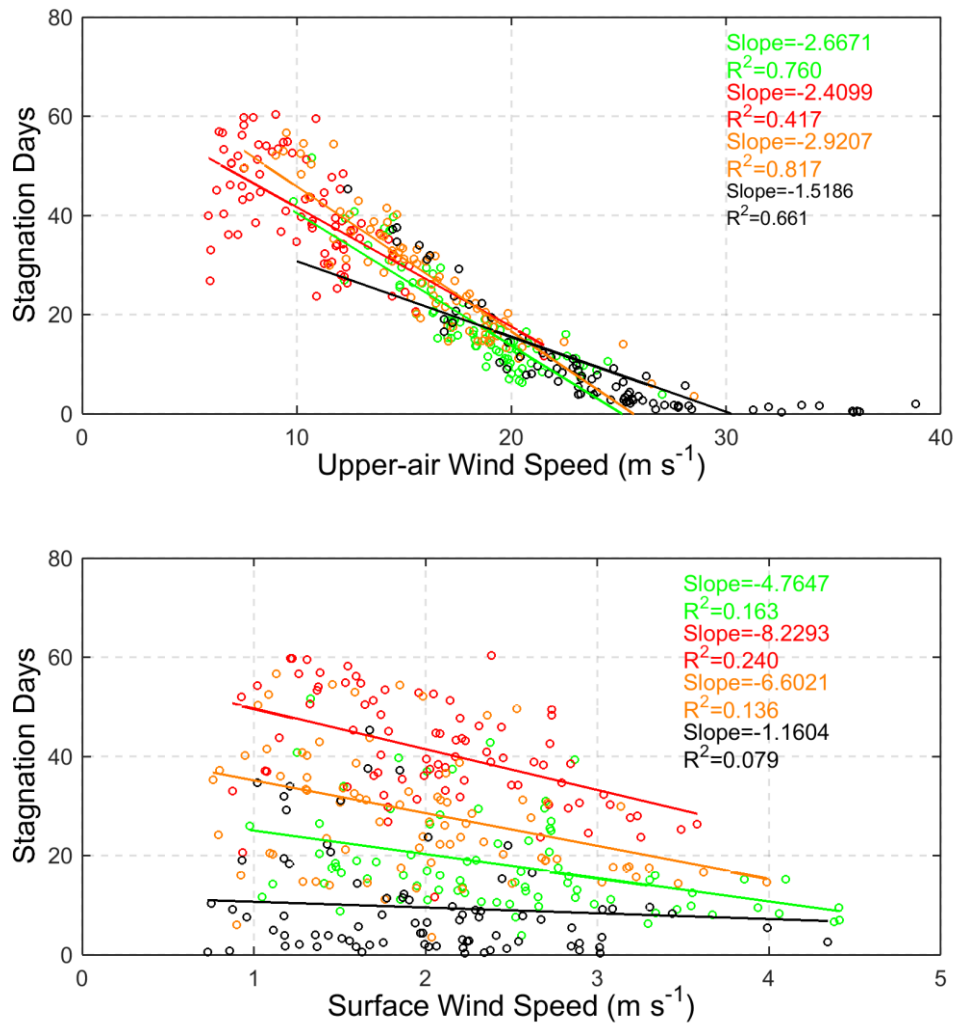
Figure R2. Seasonal dependence of spatial distribution of stagnation days on upper-air wind speed and surface wind speed. Linear regression coefficients between seasonal-mean stagnation days at 81 stations and each corresponding component are shown. Green: spring (MAM); red: summer (JJA); orange: autumn (SON); black: winter (DJF).
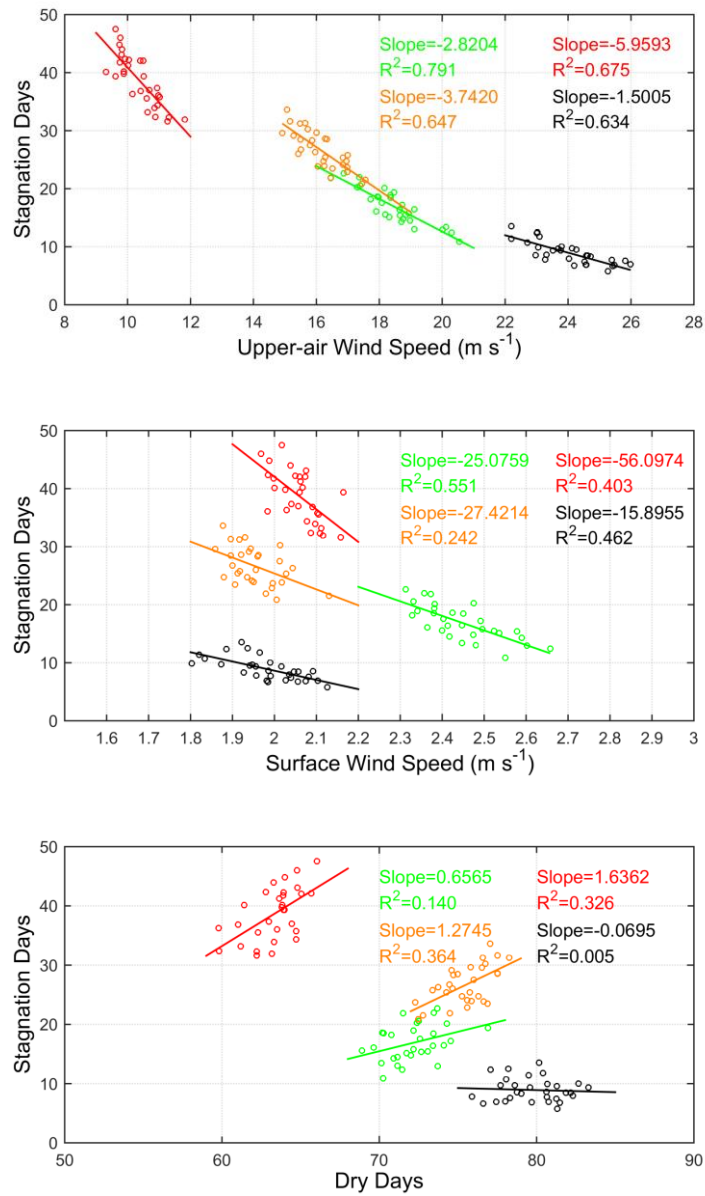
Figure R3. Same as Fig. R2, but for the seasonal trends of stagnant days. Linear regression coefficients between national-averaged stagnant days in different seasons over 30-year period and corresponding components (upper-air wind speed, surface wind speed and dry days) are shown. Green: spring (MAM); red: summer (JJA); orange: autumn (SON); black: winter (DJF).

6) What is the correlation between the air stagnation and visibility measurements in China since the 1980s? I assume they are highly correlated, but it is still interesting to see their relationships in time series and spatial distribution in China.

Response:

This question is similar to Question 1 of Referee #1. We carry out additional analysis on this topic.

30-year (1985–2014) visibility data of 360 stations across China were obtained from NCDC (U.S. National Climatic Data Center). Figure R4 displays the spatial distribution of the stations and annual mean visibility. It shows that generally the east and south regions of China exhibit poor visibility, while the west and north regions exhibit a good one. Regions of Sichuan basin, the west of Xinjiang and North China Plain are the centers exhibit low visibility. This feature corresponds well to the frequent air stagnation occurrences in Fig. 2. Yangtze River Delta also exhibits poor visibility, but shows relatively less stagnant days (Fig. 2). The correlation between a time series of air stagnation days and visibility over the whole country is −0.69 during 1985–2014 (Fig. R5). It means that the air stagnation does correlate negatively to visibility, in general.

Air stagnation is a simple and meaningful metric to air pollution. Jacob and Winner (2009) have summarized results from different studies about the influence of meteorological factors on ozone and particulate matter concentrations, and concluded that air stagnation consistently demonstrates a strong positive correlation. In this paper, we are trying to present the climatological features of air pollution potential over China by analyzing stagnation index, rather than directly applying to air pollution diagnosis or forecasting. Therefore, at this stage, we do not emphasize the correlation between the metric and visibility. This part is included in the discussion of revised manuscript and Figs. R4 and R5 are displayed as Figs. S3 and S4 in the Supplement.
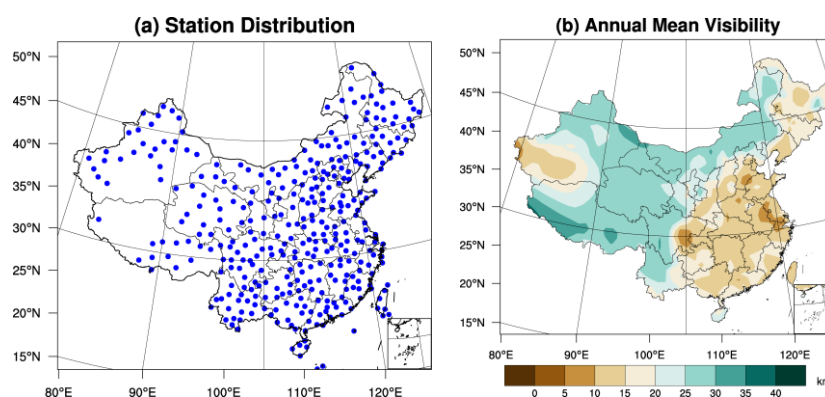

Figure R4. (a) Spatial distribution of 360 visibility observation stations across China. 30-year (1985–2014) visibility data were obtained from NCDC (U.S. National Climatic Data Center). (b) Annual mean visibility throughout China (1985–2014).
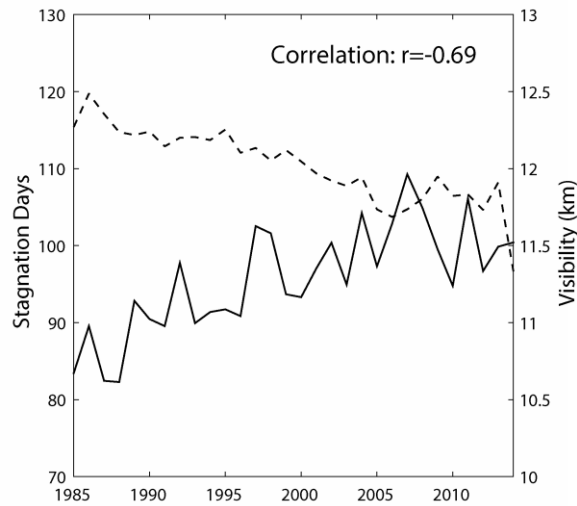
Figure R5. Time series of national averaged stagnant days and visibility during 1985–2014. Solid line: stagnation days; dashed line: visibility. Linear regression correlation between them are shown.

Reference:

Jacob, D. J., and Winner, D. A.: Effect of climate change on air quality, Atmos. Environ., 43, 51–63, doi:10.1016/j.atmosenv.2008.09.051, 2009.

Air Stagnations for China (1985–2014): Climatological Mean Features and Trends

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Abstract. Air stagnation is an important meteorological measurement for unfavourable air pollution conditions, but little is known about it in China. We conducted a comprehensive investigation of air stagnation in China, based on sounding and surface observations of 81 stations, from January 1985 to December 2014. The stagnation criteria were revised to be topographically dependent for the great physical diversity in this country. It is found that the annual mean air stagnation occurrences are closely related to general topography and climate features. Two basins in the northwest and southwest of China—Tarim and Sichuan Basins—exhibit the most frequent stagnation occurrence (50% days per year), whereas two plateaus (Tibet-Qinghai and Inner Mongolia Plateau) and the east coastal areas experience the least (20% days per year). Over the whole country, air stagnations achieve maxima in summer and minima in winter, except for Urumqi, a major city in the northwest of China, where stagnations keep a rather constant value yearly around with a minimum in spring. There is a nationwide positive trend in stagnation occurrence during 1985–2014, with the strongest increasing centres over Shandong Peninsula in eastern China and the south of Shaanxi in central China. Dependence degrees of air stagnations on three components (upper- and lower-air winds, precipitation-free days) are examined. ~~It shows that the spatial distribution and trend of air stagnations are mainly driven by the behaviours of upper-air wind speeds.~~ It shows that the behaviours of upper-air wind speeds are main drivers of the spatial distribution and trend of air stagnations, near-surface winds the next, and dry days 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. The 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 air stagnant conditions (Logan, 1989). The stagnation of air masses led to an enhancement of surface ozone and CO mixing ratios over Western/Central Europe (Ordónez et al., 2010; Leibensperger et al., 2008), and a 2.6 μg m^{-3} increase of fine particulate matter in the United States (Tai et al., 2010). The sensitivity of air quality to stagnations 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 about the effects of weather conditions on ozone and particulate matter concentrations, and summarized that air stagnation demonstrates a robust positive correlation. However, actual air pollution level is affected by not only 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., 2011; Yang et al, 2016). With other factors unknown, the air stagnation index may show poor correlation to actual air pollution data, in certain situations. The strength of air stagnation index is that, it provide an independent view to the meteorological background relevant to air pollution, without being interfered by the complexity of other factors such as the variation of 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" here 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 tend to travel in the direction of the upper flow at roughly a quarter to half of the 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 dilution and washout of air pollutants, both of them are also relevant to practical air quality. Therefore, the air stagnation is a relatively simple, but conceptually robust metric to air pollution.

~~Air stagnation is identified by thresholds of daily lower- and upper- air winds and precipitation.~~ In previous works 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 with (i) the surface geostrophic wind is less than 8 m s^{-1}, generally corresponding to a 10m wind speed less than 3.2 m s^{-1} (Wang and Angell, 1999); (ii) the wind speed at 500 hPa is less than 13 m s^{-1}; (iii) no precipitation. Wang and Angell (1999)

followed this metric but replaced the dataset with US National Centres for Environment Prediction (NCEP)/National Centre for Atmospheric Research (NCAR) reanalysis archive ($2.5° \times 2.5°$). With this dataset, they studied the climatology of air stagnation for 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 a finer gridded reanalysis data ($0.25° \times 0.25°$) and provides maps about air stagnation distribution every month (http://www.ncdc.noaa.gov/societal-impacts/air-stagnation/). Following the NCDC's metric, Leung and Gustafson (2005) examined the potential effects of climate change on U.S. air quality by analyzing the simulated changes in stagnation events during 2045–2055. Horton et al. (2012, 2014)

furthered this work and used a multi-model ensemble to project the 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 the 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 its air quality is indispensable and studies of the relevant meteorological states are essential. Up to now, to the authors' knowledge, studies about air stagnation generally focused on the United States or on a global scale. Our focus in the current study is investigating the climatological mean features and trends of air stagnations for China, based on 30-year (1985–2014) observations on stations across the country.

2 Data and Method

2.1 Data

Long-term (1985–2014) dataset of daily-mean surface wind speeds (observed at 10 m above the surface) and daily precipitation data were obtained from China Meteorological Administration (CMA). These data are available at website (http://data.cma.cn/data/detail/dataCode/SURF_CLI_CHN_MUL_DAY_CES_V3.0.html). Upper-air wind speeds were obtained from Wyoming University soundings database (http://weather.uwyo.edu/upperair/sounding.html). This database provides twice daily (0000 and 1200 UTC) atmospheric soundings from stations that participate in global data exchange. Daily averages of upper-air wind speed at mandatory levels of 500, 400, and 300 hPa were used here.

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We obtained datasets of all the radiosonde stations across China (95 stations) and two stations (Blagovescensk and Vladivostok) outside but near the border of the country. Among them, 66 stations have corresponding surface datasets from CMA (See Appendix A). For each of the other 31 radiosonde stations, we considered the average of surface stations within 150 km as a substitute. In this way, we got additional 15 stations (See Appendix B). Air stagnations of these 81 stations are analyzed in this study. Figure 1 displays the distribution of the stations. It shows that there are relatively less stations in Tibet-Qinghai Plateau, particularly in the western Tibet. Besides of this, the 81 stations cover all the contiguous China well.

2.1.1 Quality Control

Surface datasets have been quality controlled by CMA (http://data.cma.cn/data/detail/dataCode/SURF_CLI_ CHN_MUL_DAY_CES_V3.0.html). Upper-air winds data were eliminated from this analysis if

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

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

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

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

Subjective quality control procedure was also applied. 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 removed. Therefore, we consider the data used in this study are reliable.

2.1.2 Data Completeness

A general survey shows that datasets of 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 (200710–201412) at Jinghe station. The percentage of valid data (data of upper- and lower-air wind and precipitation all valid) of each station is

summarized in Appendices A and B. It is shown that for all stations except Blagovescensk, more than 95% of the data are valid. Overall, the datasets are sufficient to conduct a climatological research about air stagnations over China.

2.2 Method

5 We adjust the NCDC air stagnation index and a given day is considered stagnant when daily total precipitation is < 1 mm (i.e. a dry day), daily-mean surface wind speed is < 3.2 m s^{-1} and upper-air wind speed is < 13 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 for its great physical diversity. Particularly, the Tibet-Qinghai Plateau has the average height of over 4000 m. The wind speeds at 500 hPa are not a good representative to the upper-air winds above ground.

10 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 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,

15 those days are considered as one air stagnation case (Wang and Angell, 1999). ~~Spatial interpolation is applied to show the distribution over continental China.~~ Results of stagnation days and cases were interpolated with cubic splines to 2 °×2 °grid to show the spatial distribution over continental China.

3 Results

3.1 Annual Occurrence

20 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 air stagnant conditions account for 50% of days per year on average, and less prevalent (about 33% days per year) over the northernmost and southernmost of the country. The remainder domains of China experience even less stagnant days, especially Tibet-Qinghai Plateau, Inner Mongolia Plateau and the east coastal areas, where

25 stagnant conditions are the least (less than 20% days per year). The distribution of stagnation cases agrees well with that of stagnation days (Fig. 2b). The strongest stagnant centers—Xinjiang and Sichuan basins—exhibit more than 16 cases per year, while the weakest centers—Tibet-Qinghai and Inner Mongolia Plateau and east

coastal areas—only experience less than 2 cases per year. Air stagnation cases usually persist about 5 days in a majority of these areas (Fig. 2c). The ones over basins of Xinjiang and the 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

5   Generally, most air stagnant conditions happen during summer season while only a few of those occur during winter. Stagnation days in autumn are slightly more than those in spring (Fig. 3). Similar feature was also found in the earlier work of Wang and Angell (1999) for the United States. ~~During summer a weaker pressure gradient lingers over China, which results in weaker atmospheric circulations and more frequent stagnations.~~ The seasonal variation of stagnation is attributed to seasonal shift of pressure patterns and general circulation. A much weaker

10   pressure gradient in summer is a well-known seasonal feature in mid-latitudes (Frederick et al., 2012). This feature is very evident in upper layer atmosphere in China (Ding et al., 2013, their Fig. 1.1). However at sea-level surface, the case in eastern Asia and China are complicated by the sub-tropical high in the east and the continental low and in the west respectively. As a result, Asia summer monsoon prevails in eastern China. Though for this, the sea level pressure gradient in summer is still much weaker than that in winter (Ding et al.,

15   2013, their Fig. 1.1). A weaker wind in both upper and surface layer accompanies the weaker pressure gradient, and results in more air stagnant occurrence in China and North America (Wang and Angell 1999).

We choose four stations (Harbin, Urumqi, Beijing and Chongqing shown in Fig. 1 as triangles) as well as the average of entire China (all stations in this study) to demonstrate the seasonal variation of air stagnation days and

20   cases. Figure 4 shows that for all but Urumqi, stagnation days and cases begin to increase in March or May, then grow dramatically and achieve maxima in July or August, then fall sharply and reach minima in December or January. However, monthly stagnation days and cases of Urumqi show much small variation in a year with their minima in April. This may attributes 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 Tibet-Qinghai Plateau in the south. Therefore, the

25   East Asia monsoon, particularly the East Asia summer monsoon, which is prevailing in east of China, influences little to Xinjiang. As a result, the seasonal feature of the stagnation in Urumqi is different from that in east of China. By comparing between these stations, we find that stagnations over Chongqing, Beijing and Urumqi are more than the average level of the entire country. Among them, Chongqing station has the largest variation of stagnations, and Beijing the next. Urumqi keeps a relatively high stagnation frequencies throughout the year.

3.3 Trend of Stagnations

The majority of China exhibits positive trends about 10–20 days and 1–3 cases per decade in stagnation days and cases, respectively (Fig. 5a, b). The strongest center located in Shandong Province and the south of Shaanxi, with rising rates of more than 20 days and 3 cases per decade. Only four fragments exhibit weak decrease: the extreme north of China, regions located in the south of Gansu and north of Sichuan, the westernmost and the southernmost part of China. The negative trend of 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 above results and 52% of stations have passed the 0.05 significance test. Not only stagnation frequencies show an increase over large areas, the duration of stagnation cases also exhibits a nationwide extension 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, Yangtze River Delta, and the westernmost and southernmost region.

Stagnation trends of four stations (Harbin, Urumqi, Beijing and Chongqing) are also discussed specifically, as well as the average results of 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 national-averaged increasing rate is about 6 days decade^{-1}. Moreover, the two stations experiencing more stagnant days (Urumqi and Chongqing) exhibit a slower rising rate about 5 and 3 days decade^{-1}, respectively, whereas the other two stations having relatively less stagnations (Harbin and Beijing) show a faster rate about 14 and 8 days decade^{-1}, respectively.

4 Discussions

Air stagnation is identified based on the thresholds of three components: the lower- and upper-air wind speeds and precipitation-free days. Analysis of each individual component is helpful in understanding the behaviour of stagnations. Figure 7a shows that the distribution of annual mean upper-air wind field is reversely correlated to that of stagnation occurrences. The upper-air wind is relatively weak in the northeast of China, Tarim Basin, Sichuan Basin and the southernmost of the country, which are exactly the same four regions exhibiting frequent stagnations. Different from the pattern of upper-air wind field, surface wind field exhibits a strong wind center (> 3 m s^{-1}) around the northeast of China, and a weak one (about 1.5 m s^{-1}) in Sichuan Basin (Fig.7b). 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 generally dry days in the north is more than that in the south. But, specifically, the south of Xinjiang Province experiences maximum dry days of more than 350 days per year, while the south of Shaanxi Province shows the minimum about 200 days per year.

We further analyse the degrees of stagnation's dependence on every individual component (Fig. 8). It 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. Figure 7 and 8 show that stagnation occurrences result from the cumulative responses of individual stagnation components, but the distribution of upper-air wind speed 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 of stagnation trends with each component (Fig. 9) and find that the pattern of trends in upper-air wind field is similar to that of stagnant conditions. Decreases in 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 stagnations 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 stagnations like the northeast and the south of 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 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 about 1 day decade^{-1}. To summarize, the stagnation trends are contemporaneous effects of two or three components.

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

The trends of these three components (upper-air winds, near-surface winds and daily precipitation) are driven by climate change. The decrease in upper-air winds is resulted 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). 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 stabilized atmosphere by light absorbing aerosols (Li et al., 2016; Peng et al., 2016; Wang et al., 2013). The decreasing number of rainy days is also closely related to the accumulation of greenhouse gases and anthropogenic aerosols (Gong et al., 2004; Liu et al., 2015; Wang et al., 2016). To sum up, climate changes alter atmospheric circulation and the hydrological cycle, which influence the occurrences of air stagnations—the meteorological background of air quality.

~~Stagnation is a metric for potential air pollution risk.~~ Stagnation is a meteorological metric for potential air pollution occurrence. Once there exist anthropogenic or natural air pollutants, they are liable to accumulate and result in poor air quality over regions that experience frequent air stagnant conditions. In contrast, over regions with infrequent stagnations, air pollutants will quickly be transported far away and diluted. Current results of the prevalent centers of stagnation days and cases are consistent with areas of heavy pollutions in China (Mamtimin and Meixner, 2007; Wang et al., 2011; 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 of Sichuan basin, the west of Xinjiang and North China Plain are the centres exhibit low visibility. This feature corresponds well to the frequent air stagnation occurrences in Fig. 2. The correlation between a time series of air stagnation days and visibility over the whole country is −0.69 during 1985–2014 (Fig. S4 in the Supplement). It means that the air stagnation does correlate negatively to visibility, in general. It confirms that stagnation is an effective metric to measure the potential unfavourable meteorological states on air quality.

It should be noted that air stagnation metric does not take into account emissions or atmospheric chemical reactions. So there may be discrepancies between variations of stagnation index and actual air pollutant concentrations in certain situations. For example, aerosol concentration in China is characterized by high value in winter and lower one in summer. This observational fact is obviously related to the seasonal variation of source emission, since there is more coal consumption in winter for heating, particularly in north China (Cao et al., 2007; He et al., 2011). 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 improve the forecasting

skill successively. In this work, we aim to analyse the general features of meteorological background relevant to air pollution by means of the air stagnation metric, without concerning more about 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 of air stagnations for China, in the period from January 1985 to December 2014. The dependence of stagnations 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.

Annual mean of air stagnation occurrence varies spatially, in agreement with topography and climate features. Two basins in the northwest and southwest of China—Tarim and Sichuan Basins—exhibit the most frequent stagnation occurrence (50% days per year), while two plateaus (Tibet-Qinghai and Inner Mongolia Plateaus) and the east coastal areas experience the least (20% days per year). Seasonal variation of air stagnations is also presented. For a general view of the whole country, stagnations happen the most frequently in summer and the least in winter. For specific stations of Harbin, Beijing and Chongqing, stagnations vary with months dramatically and achieve maxima in July or August and minima in December or January, whereas stagnations in Urumqi keep a rather constant value with minimum in April.

There is a nationwide positive trend in stagnation days and cases, as well as case duration, in 1985–2014. The strongest increasing centres are located over Shandong Province in the eastern China and the south of Shaanxi in the central of the country. Only two exceptional regions—the southernmost and westernmost part of China—exhibit a negative trend in both occurrence and duration.

Stagnation occurrence contemporaneously response to three components, i.e., upper- and lower-air winds and precipitation-free days. Among them, upper-air wind speed plays a dominant role, explaining 76% and 73% of the spatial distribution and trend of air stagnations respectively. The lower-air wind exerts a minor influence.

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These results are corroborated by the global research from Horton et al. (2012). The spatial variation of dry days barely influences that of stagnations, whereas their inter-annual variability explains 32% of stagnation trend.

Air stagnation climatology presents a specific view to the natural background of atmosphere features being responsible to air pollution levels. The results presented in this paper may have significant implication to air pollution research, and may be used in atmospheric environment management or air pollution control.

Competing interests:

The authors declare that they have no conflict of interest.

Appendix A

The 66 radiosonde stations that have corresponding surface datasets from 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 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	198501–201412	97.8%
Nenjiang	50557	49.16	125.23	243	198501–201412	98.9%
Harbin	50953	45.75	126.76	143	198501–201412	99.4%
Altay	51076	47.72	88.08	737	198501–201412	99.2%
Yining	51431	43.95	81.33	664	198501–201412	99.3%
Urumqi	51463	43.77	87.62	919	198501–201412	99.2%
Kuqa	51644	41.71	82.95	1100	198501–201412	99.4%
Kashi	51709	39.46	75.98	1291	198501–201412	99.2%
Ruoqiang	51777	39.02	88.16	889	198501–201412	99.1%
Hotan	51828	37.13	79.93	1375	198501–201412	99.4%
Hami	52203	42.81	93.51	739	198501–201412	99.3%
Dunhuang	52418	40.15	94.68	1140	198501–201412	99.1%
Jiuquan	52533	39.75	98.48	1478	198501–201412	98.9%
Minqin	52681	38.63	103.08	1367	198501–201412	98.5%
Golmud	52818	36.4	94.9	2809	198501–201412	99.2%
Dulan	52836	36.29	98.09	3192	198501–201412	96.9%
Xining	52866	36.71	101.75	2296	198501–201412	99.1%
Erenhot	53068	43.65	112	966	198501–201412	99.1%
Hohhot	53463	40.81	111.68	1065	198501–201412	99.3%
Yinchuan	53614	38.47	106.2	1112	198501–201412	98.2%
Taiyuan	53772	37.77	112.55	779	198501–201412	99.1%
YanAn	53845	36.59	109.5	959	198501–201412	99.3%
Pingliang	53915	35.54	106.66	1348	198501–201412	98.9%
XilinHot	54102	43.95	116.05	991	198501–201412	99.2%
Tongliao	54135	43.6	122.26	180	198501–201412	99.3%
Changchun	54161	43.9	125.21	238	198501–201412	99.0%

(Appendix A Continued)

Station	ID*	Latitude (°N)	Longitude (°E)	Elevation (m)	Date Range	Valid Data
Chifeng	54218	42.25	118.95	572	198501–201412	99.3%
Yanji	54292	42.88	129.46	178	198501–201412	99.4%
Shenyang	54342	41.75	123.43	43	198501–201412	99.2%
Linjiang	54374	41.71	126.91	333	198501–201412	98.9%
Beijing	54511	39.93	116.28	55	198501–201412	99.4%
Dalian	54662	38.9	121.62	97	198501–201412	99.3%
Lhasa	55591	29.65	91.12	3650	198501–201412	97.5%
Yushu	56029	33	97.01	3682	198501–201412	97.1%
Hezuo	56080	35	102.9	2910	198501–201412	98.4%
Garze	56146	31.61	100	522	198501–201412	98.7%
Wenjiang	56187	30.7	103.83	541	**200407–201412**	98.1%
Xichang	56571	27.9	102.26	1599	198501–201412	98.7%
Tengchong	56739	25.11	98.48	1649	198501–201412	99.1%
Kunming	56778	25.01	102.68	1892	198501–201412	99.0%
Simao	56964	22.76	100.98	1303	198501–201412	99.3%
Mengzi	56985	23.38	103.38	1302	198501–201412	99.2%
Zhengzhou	57083	34.7	113.65	111	198501–201412	99.3%
Hanzhong	57127	33.06	107.02	509	198501–201412	99.4%
Jinghe	57131	34.26	108.58	411	**200710–201412**	100.0%
Enshi	57447	30.28	109.46	458	198501–201412	99.4%
Yichang	57461	30.7	111.3	134	198501–201412	99.3%
Wuhan	57494	30.61	114.12	23	198501–201412	99.4%
Chongqing	57516	29.51	106.48	260	**198708–201412**	98.2%
Guiyang	57816	26.47	106.65	1222	198501–201412	98.0%
Guilin	57957	25.33	110.3	166	198501–201412	99.4%
Ganzhou	57993	25.85	114.94	125	198501–201412	99.1%
Xuzhou	58027	34.27	117.15	42	198501–201412	99.3%
Nanjing	58238	32	118.8	7	198501–201412	99.4%
Shanghai	58362	31.4	121.46	4	**199106–201412**	98.3%

(Appendix A Continued)

Station	ID*	Latitude (°N)	Longitude (°E)	Elevation (m)	Date Range	Valid Data
Anqing	58424	30.53	117.05	20	198501–201412	99.4%
Hangzhou	58457	30.22	120.16	43	198501–201412	99.3%
Nanchang	58606	28.6	115.91	50	198501–201412	99.1%
QuXian	58633	28.95	118.86	71	198501–201412	99.1%
Fuzhou	58847	26.07	119.27	85	198501–201412	99.3%
Xiamen	59134	24.47	118.08	139	198501–201412	99.3%
Baise	59211	23.9	106.6	175	198501–201412	99.2%
Wuzhou	59265	23.48	111.3	120	198501–201412	98.3%
Shantou	59316	23.35	116.66	3	198501–201412	99.2%
Nanning	59431	22.62	108.2	126	198501–201412	99.3%
Haikou	59758	20.03	110.34	24	198501–201412	99.2%

* World Meteorological Organization Identification Number.

5

Appendix B

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
Blagovescensk	31510	50.52	127.5	177	50353	51.43	126.4	127.58	198501–201412	65.9%
					50564	49.26	127.2	141.64		
Vladivostok	31977	43.26	132.05	82	54096	44.23	131.1	132.61	**199408–201412**	96.1%
					59287	23.1	113.2	132.7		
KingsPark	45004	22.3	114.16	66	59293	23.44	114.4	129.34	198501–201412	99.1%
					59501	22.48	115.2	110.8		
YuZhong	52983	35.87	104.15	1875	52884	36.21	103.6	65.18	**200107–201412**	94.5%
Linhe	53513	40.75	107.4	1041	53336	41.34	108.3	100.66	198501–201412	99.0%
					54725	37.3	117.3	70.05		
Zhangqiu	54727	36.7	117.55	123	54823	36.36	117	59.92	**200308–201412**	98.3%
					54843	36.45	119.1	142.05		
Qingdao	54857	36.06	120.33	77	54843	36.45	119.1	117.68	198501–201412	99.3%
Weining	56691	26.86	104.28	2236	57707	27.18	105.2	95.07	198501–201412	98.4%
Nanyang	57178	33.03	112.58	131	57265	32.23	111.4	141.85	198501–201412	99.2%
					57290	33	114	133.37		

(Appendix B continued)

Station	ID	Latitude (°N)	Longitude (°E)	Elevation (m)	Surface Stations (CMA)	Latitude (°N)	Longitude (°E)	Distance (km)	Date Range	Valid Data
Changsha	57679	28.2	113.08	46	57687	28.13	112.6	52.52	198501–201412	98.6%
Huaihua	57749	27.56	110	261	57745	27.27	109.4	66.58	198501–201412	99.2%
Sheyang	58150	33.75	120.25	7	58040	34.5	119.1	136.93	198501–201412	99.3%
					58251	32.52	120.2	136.88		
Fuyang	58203	32.86	115.73	33	58102	33.52	115.5	77.52	198501–201412	99.3%
					58221	32.57	117.2	143.98		
Shaowu	58725	27.32	117.45	219	58715	27.35	116.4	104.76	198501–201412	99.1%
					58834	26.39	118.1	121.86		
QingYuan	59280	23.66	113.05	19	59082	24.41	113.4	89.16	**199601–201412**	95.3%
					59287	23.1	113.2	64.13		
					59293	23.44	114.4	140.78		

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15   a month of serious pollution in beijing, 2013. Atmos. Chem. Phys., 14, 1431–1432, doi:10.5194/acp-14-2887-2014, 2014.

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

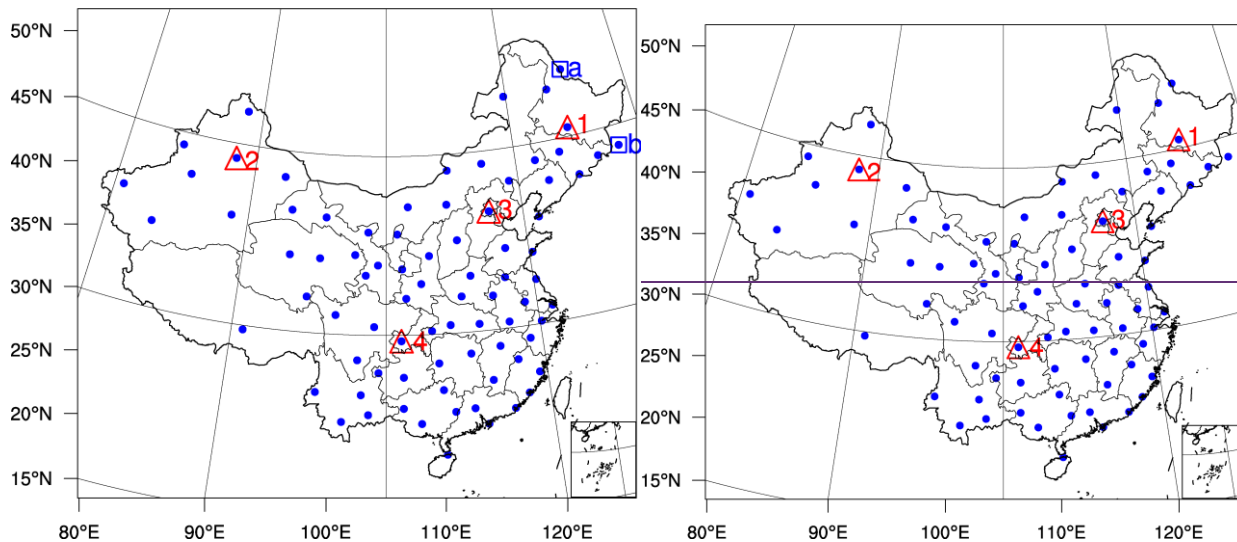| Station Elevation (m)	Topographically dependent upper-air wind speed criterion
0–1000	wind speed at 500 hPa < 13 m s^{-1}
1000–3000	wind speed at 400 hPa < 13 m s^{-1}
3000–4000	wind speed at 300 hPa < 13 m s^{-1}

Figure 1. Distribution of observation stations. Triangles indicate four stations selected to discuss seasonal variations of air stagnations in Section 3: 1 for Harbin, 2 for Urumqi, 3 for Beijing, 4 for Chongqing. Squares indicate two stations outside of China: Blagovescensk (a) and Vladivostok (b).
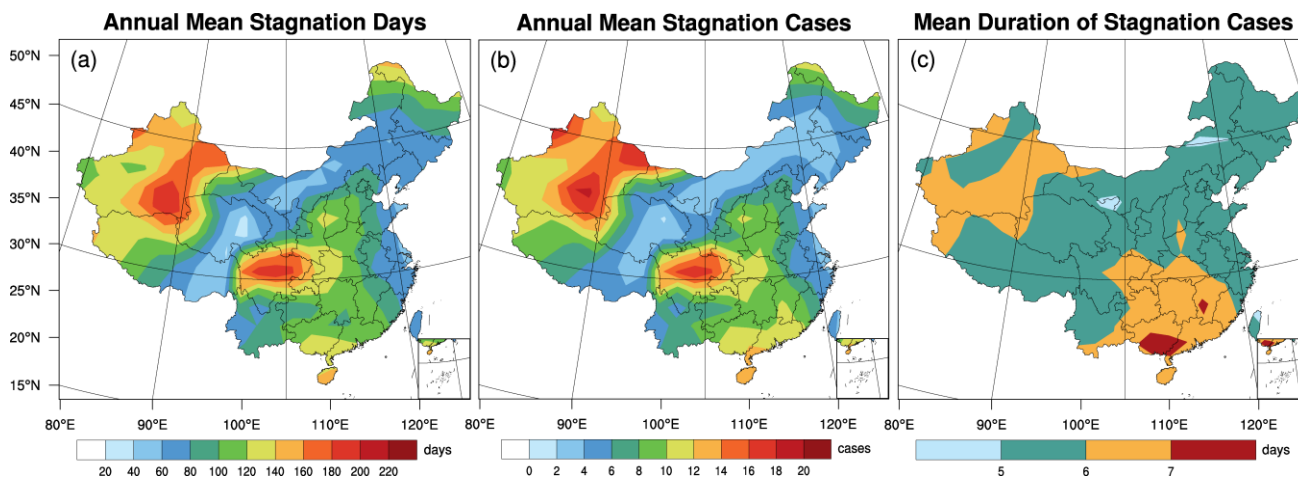
Figure 2. Annual mean air stagnation days (a) and cases (b) and mean duration of stagnation cases in days (c) for China (1985–2014).
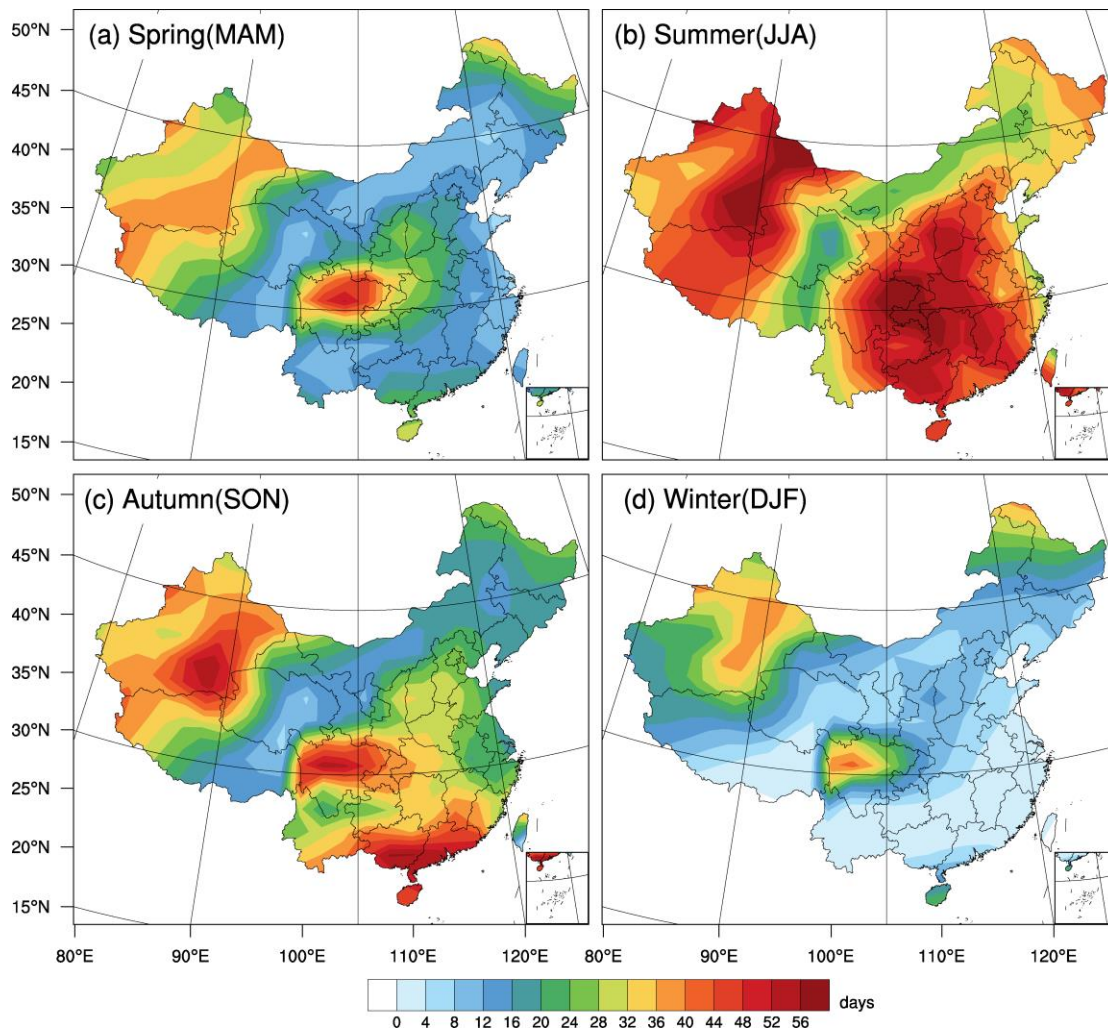
Figure 3. Average air stagnation days in spring (a), summer (b), autumn (c) and winter (d), 1985–2014.
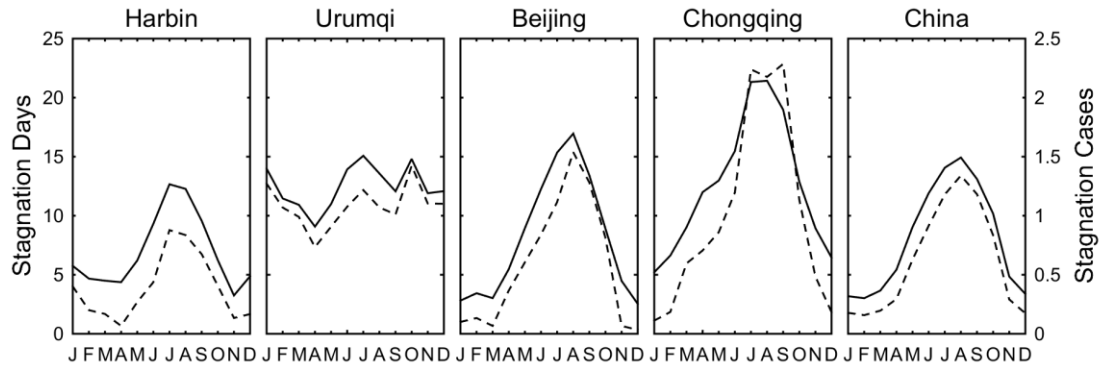
Figure 4. Seasonal cycles of monthly mean air stagnation days and cases for four stations (Harbin, Urumqi, Beijing and Chongqing) and the entire China. Solid line: stagnation days; dashed line: stagnation cases.
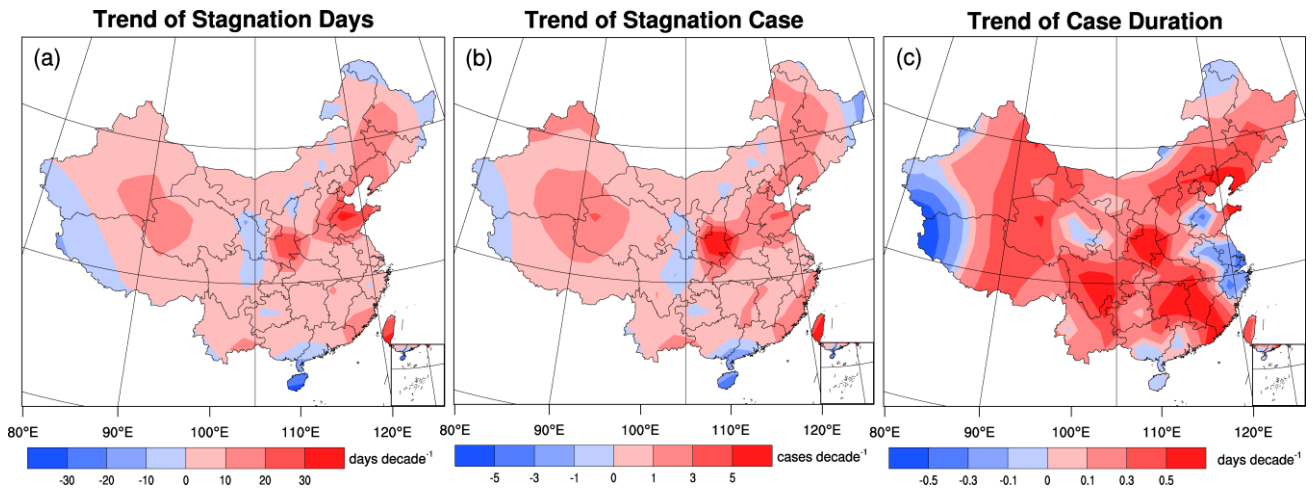
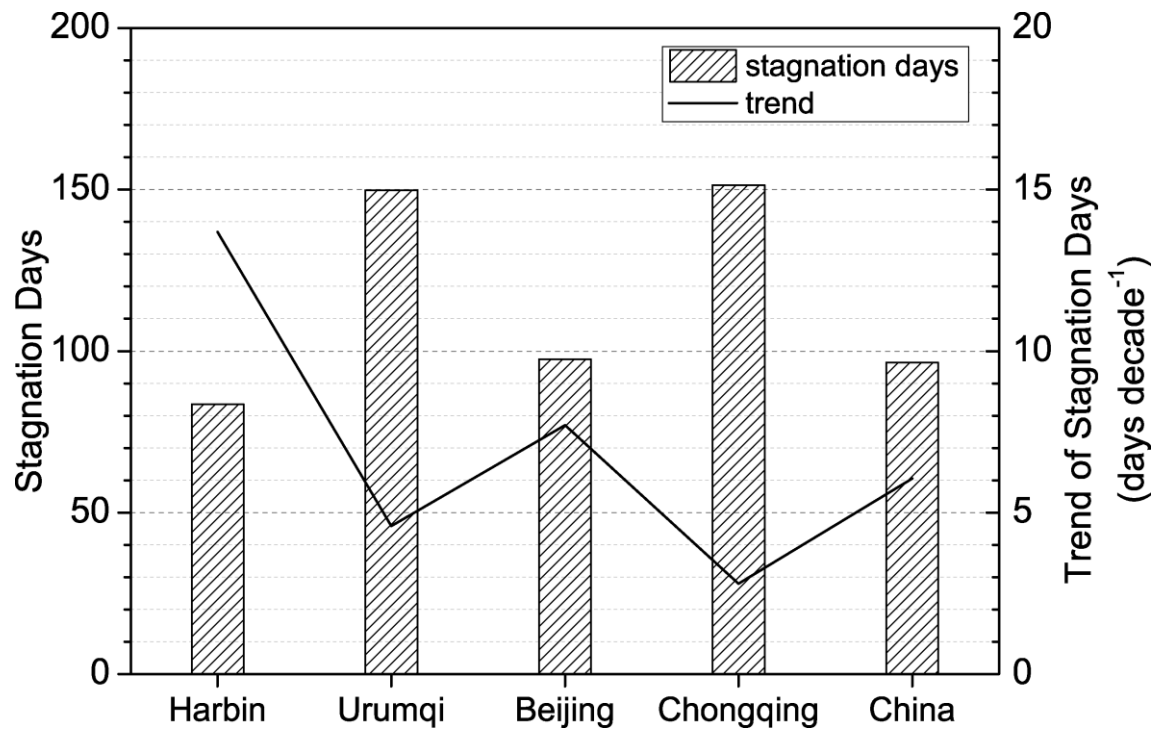**Figure 5. Trends of stagnation days (a), cases (b) and the duration of stagnation cases (c), 1985–2014.**

Figure 6. Annual mean stagnant days and the corresponding trend at four stations (Harbin, Urumqi, Beijing and Chongqing) and for the whole country.
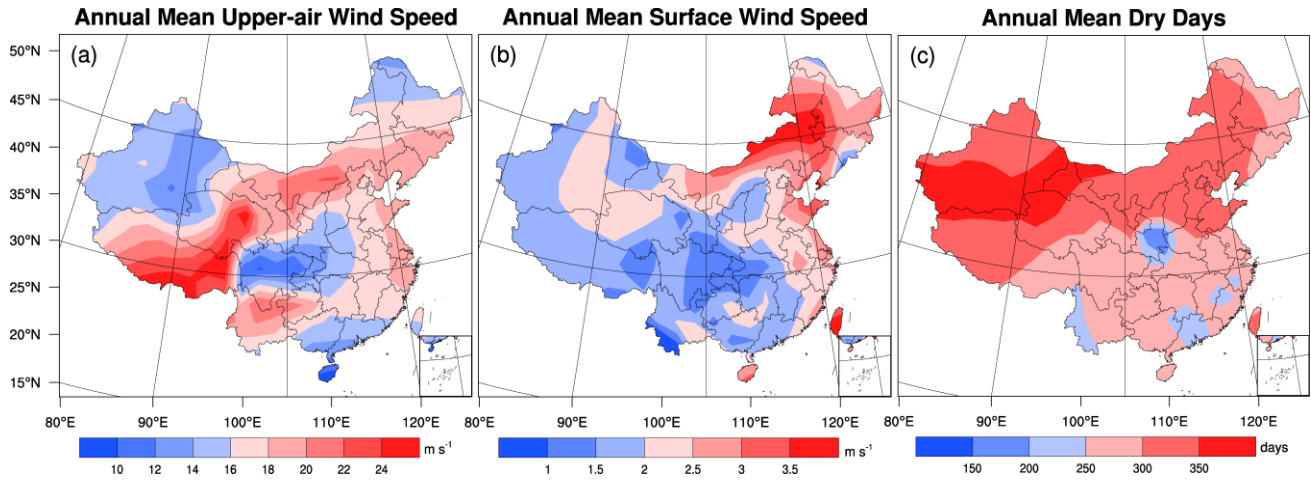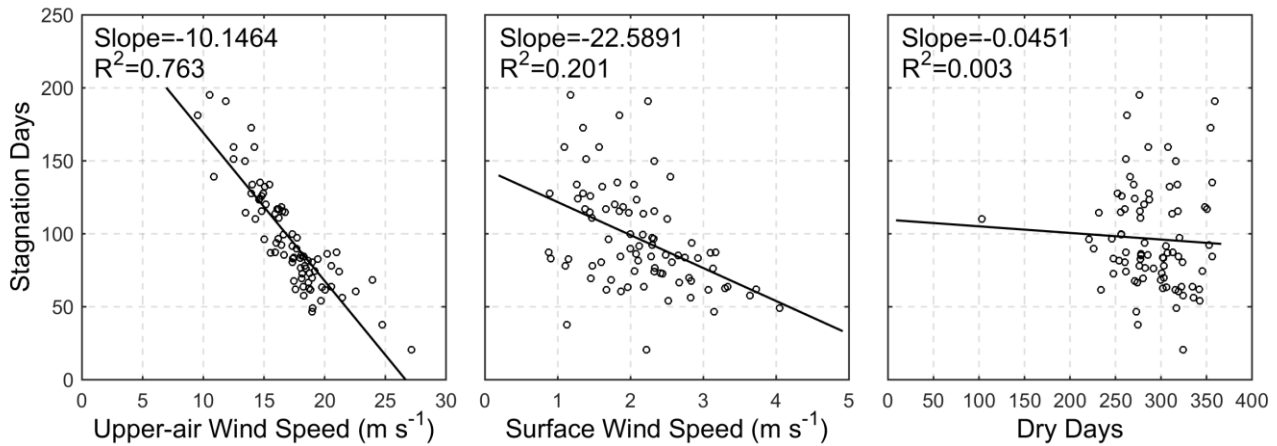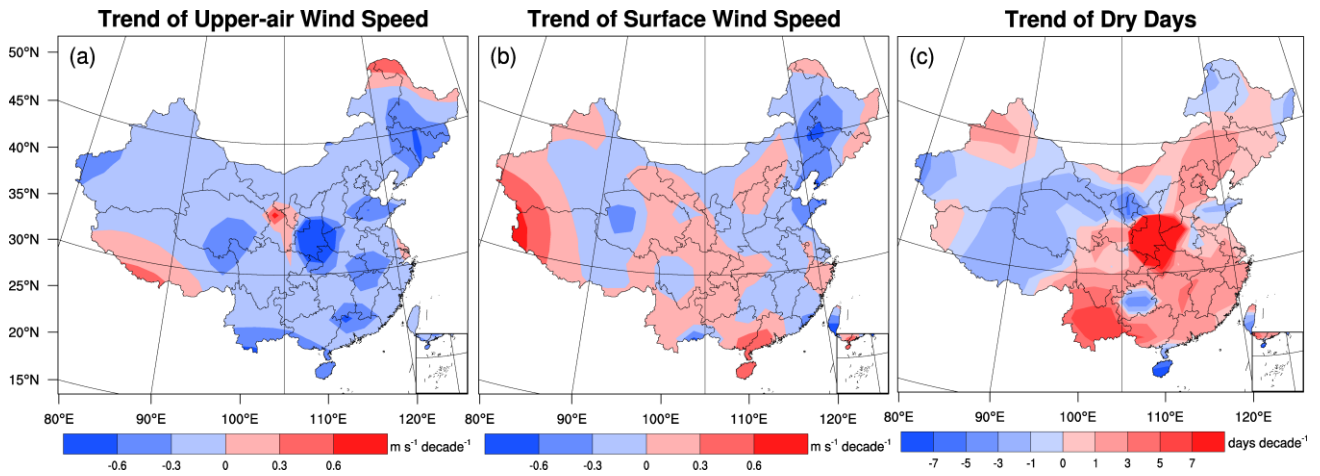
Figure 7. Annual mean upper-air wind speed (a), surface wind speed (b) and dry days (c) in China (1985–2014).
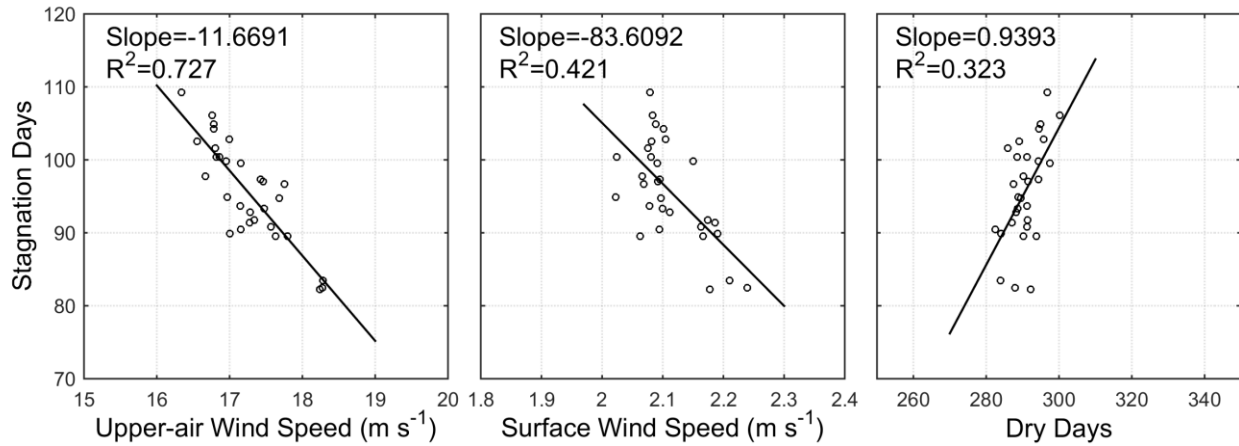

Figure 8. Dependence of spatial distribution of stagnation days on three components (upper-air wind speed, surface wind speed and dry days). Linear regression coefficients between annual mean stagnation days at 81 stations and each corresponding component are shown.

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

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