Response to Referee #2

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

Mean Features and Trends (acp-2016-1072)

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 comments of Referee #2 are copied below in italics, and followed by our responses. Additional material containing two figures (Figs. R2 and R3 in this Response) is supplied in the Supplement.

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.

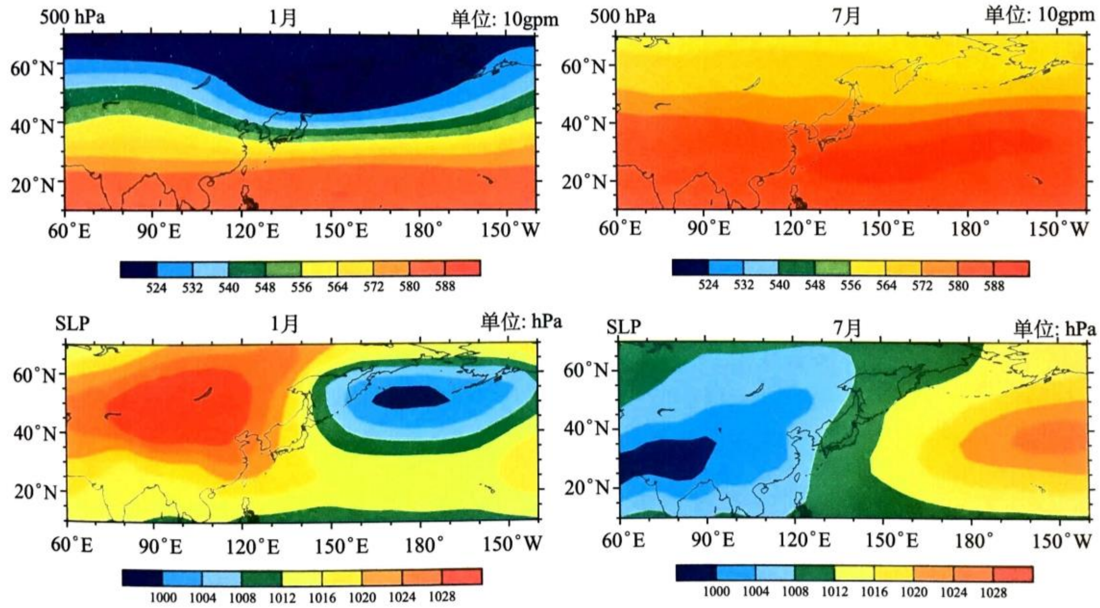

Figure R1. Atmospheric circulation in East Asia. Upper: geopotential height (unit: 10gpm) of 500 hPa in January (left) and July (right). Bottom: sea level pressure (unit: hPa) in January (left) and July (right). This figure is copied from Ding et al. (2013), their Fig. 1.1.

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).

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.

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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.,

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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)?

Response:

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.

Response:

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.

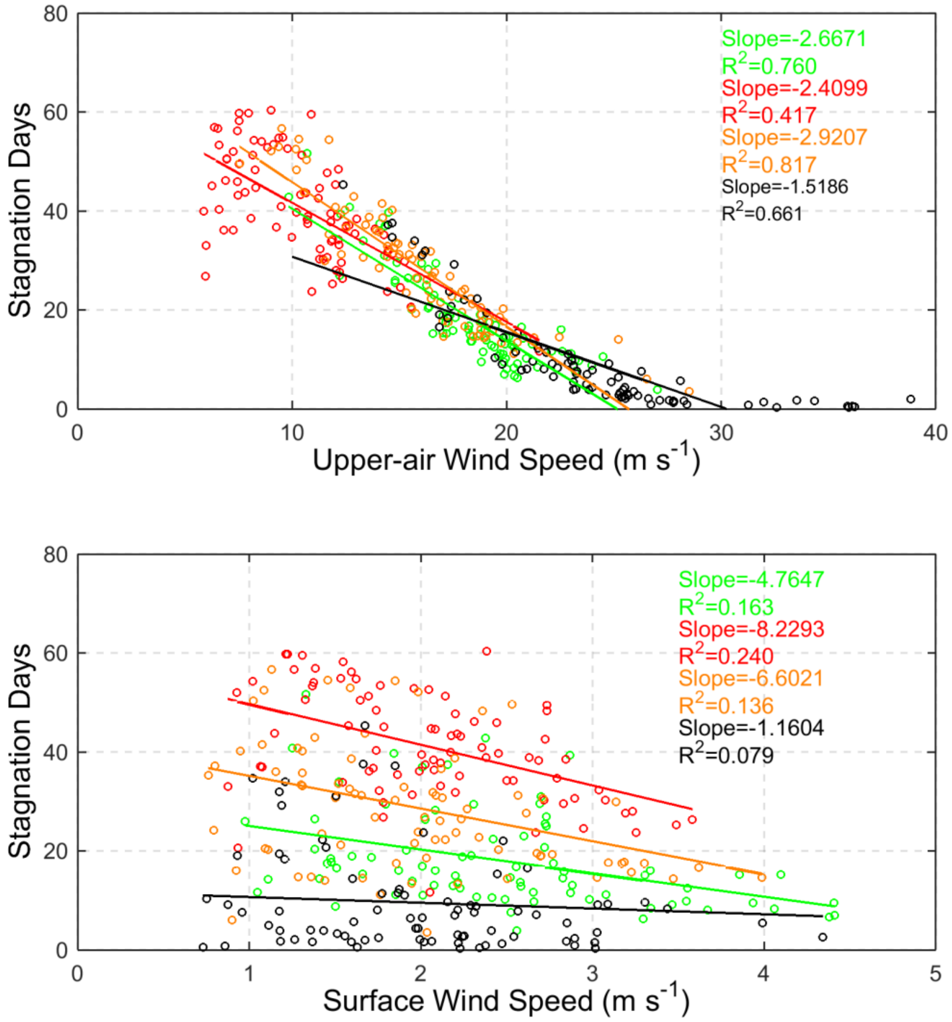

Figure R2. Seasonal dependence of spatial distribution of stagnation days on upper-air wind speed and surface wind speed. Linear regression coefficients between seasonal-mean stagnation days at 81 stations and each corresponding component are shown. Green: spring (MAM); red: summer (JJA); orange: autumn (SON); black: winter (DJF).

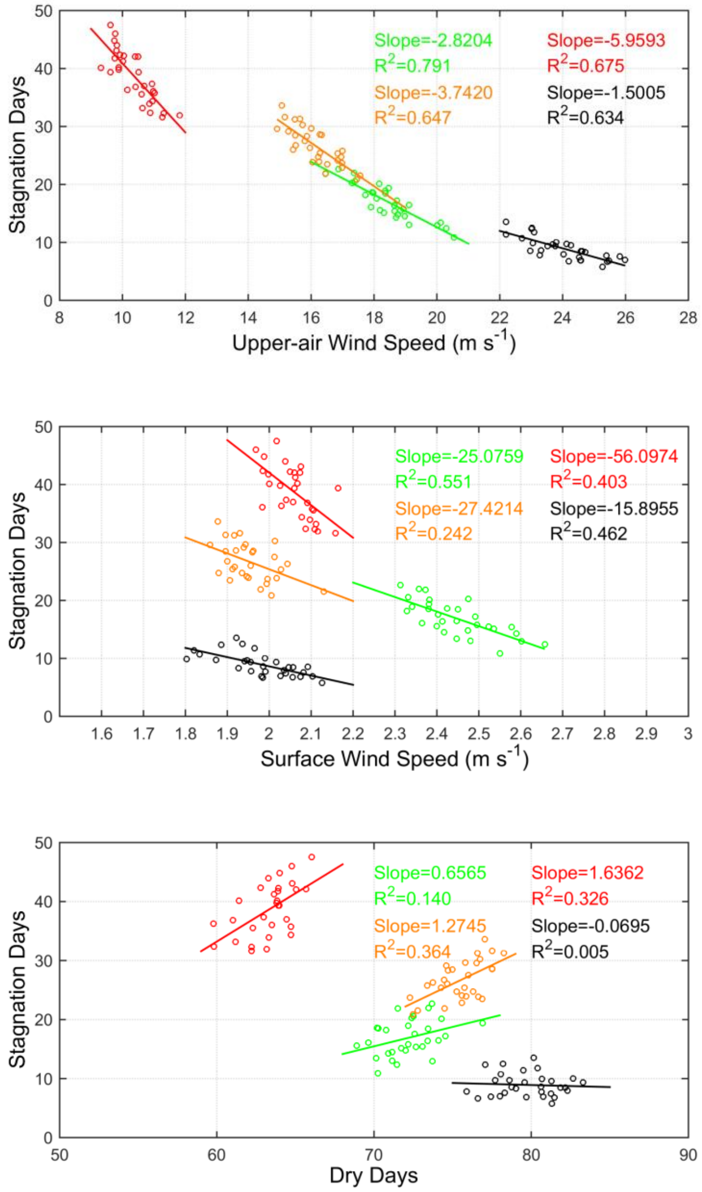

Figure R3. Same as Fig. R2, but for the seasonal trends of stagnant days. Linear regression coefficients between national-averaged stagnant days in different seasons over 30-year period and corresponding components (upper-air wind speed, surface wind speed and dry days) are shown. Green: spring (MAM); 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 the air stagnation days and a time series of 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, and this part of results are not included in the revised manuscript.

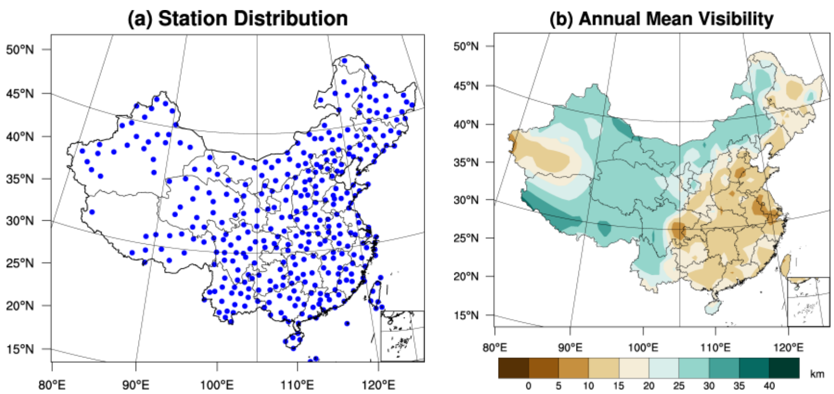

Figure R4. Spatial distribution of (a) visibility observation stations and (b) annual mean visibility throughout China (1985–2014).

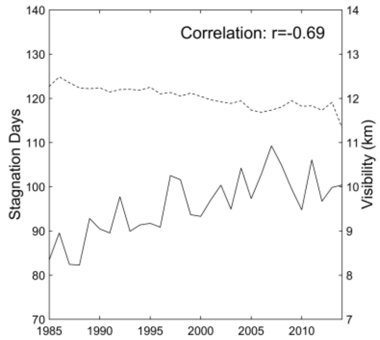

Figure R5. Time series of national averaged stagnant days and visibility during 1985–2014. Solid line: stagnation days; dashed line: visibility. Linear regression correlation between them are shown.

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.