Manuscript # acp-2017-455

Reply to Referee #1

We are very grateful to all important and helpful comments from the referee. The followings are our responses to each comment in detail.

This study quantifies the relationship among $PM_{2.5}$ concentration, visibility and planetary boundary layer height for long–lasting haze and fog–haze mixed events in Beijing city. They found negative relationships between visibility and $PM_{2.5}$, $PM_{2.5}$ and PBL height. They also found a double inversion layer formed in both typical events, which played critical roles in maintaining and enhancing the long–lasting polluted events. The topic of this paper is interesting and is suitable for publication in this journal. However, some improvements are needed before publication. Following are the major and specific issues:

Major issues:

1. The authors provided a large amount information of the relationships between $PM_{2.5}$, visibility and PBL height. However, these relationships are reported in many previous studies. The new finding in this study about influence double inversion layer on the meteorology and $PM_{2.5}$ needs more attention and discussion.

Reply 1:

Thanks for your constructive suggestions. We added some discussions relevant to our new finding about influence of double inversion layer on the polluted events in the conclusions and discussions section, as "The new finding in this paper has important implications in explaining the frequent long–lasting polluted events in the study region. Generally, a typical pollution event is usually formed under a stable and shallow temperature–inversion condition at low atmospheric layers, and would disappear or obviously decrease when the daytime solar radiation increases. However, in the study region, we found that many severe haze and fog–haze mixed events lasted for several days even for several weeks. Most previous publications attributed the reason as the persistent abnormal weather system or high emissions. However, this study shows that except for the influence of meteorological condition and high emission, the interactions and feedbacks between PBL and aerosol loading linked by radiation process are crucial in enhancing and maintaining these polluted events. These feedbacks could cause an important variation of dynamical/thermal processes in lower troposphere. The formation of double inversion layer and their subsequent change is closely associated with persistent meteorological condition, high aerosol loading and associated radiation process. Due to the complex interactions and feedbacks, a deeper and more stable atmospheric low–level inversion layer is formed and it is hard to break up by daytime solar radiation heating process until the strong wind occurs and removes the high aerosol loading."

Specific issues:

2. Abstract: Causal relationship about 'The air quality and visibility are strongly influenced by aerosol loading and meteorological conditions.' It would be better to revise as 'influenced by aerosol loading, which is driven by meteorological conditions'.

Reply 2:

Thanks for the suggestion. It has been corrected in the revised manuscript.

3. Introduction: Haze in China is a very hot topic and raises a bunch of new studies recently. The authors may cite more recent papers to strengthen this part. Climate change (Cai et al., 2017, Nature Climate), Arctic sea ice loss (Zou et al., 2017, Science Advances) and decadal weakening of winds (Yang et al., 2016, JGR) suggested causes in climate view. Dust-wind interaction (Yang et al., 2017a, Nature Communications) and upwind transport (Yang et al., 2017b, ACP) can also intensify haze in China.

Reply 3:

Thanks for the good suggestion. We have added some recent papers in the introduction section based on your suggestion, as "In addition, the interactions between aerosol pollution and climate change have been substantially addressed in recent publications, for example, anthropogenic climate change (Cai et al., 2017), reduced Arctic sea ice (Wang et al., 2015; Zou et al., 2017), the Tibetan Plateau warming (Xu et al., 2016), influences of ENSO events on haze frequency in eastern China (Gao and Li, 2015), weakened East Asian winter monsoon (Li et al., 2016), decadal weakening of winds (Yang et al., 2016), and enhanced thermal stability of the lower atmosphere (Zhang et al., 2014; Chen and Wang, 2015). The dust–wind interaction (Yang et al., 2017a) and upwind transport (Yang et al., 2017b) could also intensify haze events in China."

4. Page 6 Line 25: Why haze and fog-haze events were defined like this? The author mentioned humidity in the introduction but the fog-haze was not defined based on humidity.

Reply 4:

Thanks for the comment. Actually, the definition we used is from international definition of fog event. Fog is an observed horizontal visibility below 1000 m in the presence of suspended water droplets and/or ice crystals (NOAA, 1995), which means that when the horizontal visibility is below 1000 m, the fog events occur. Since the horizontal visibility for atmospheric haze event is usually larger than 1000 m, only the fog occurs the visibility can decrease to be less than 1000 m. So that is why we use the minimum visibility to define fog and haze events.

Theoretically, when a fog event occurs, the RH has to reach over 100 %. However, it is difficult to measure RH accurately, so in most cases, we use RH value of 90 % or 95 % as criterion to separate fog and haze. In fact, in the study region, when the RH is high enough, the fog and haze are usually co-existed. The haze aerosols can be transformed to fog droplets under certain conditions according to the Köhler curve (Köhler, 1936). It should be noticed that the situations such as heavy rain event or light fog events, which cause the horizontal visibility to be below or above 1000 m are not considered here. In addition, since we focus on long–lasting severe fog and haze event, we also include factors such as the lasting time and $PM_{2.5}$ mass concentration as additional criteria. To be more clearly, the corresponding text have been modified in the manuscript. We also revised Table 1 to include more parameters such as duration and maximum RH of the pollutant events, show as below:

Table 1: The long–lasting haze and fog–haze mixed events from January 2014 to March 2015 in Beijing city

Type	Starting date / time	Ending date / time	Minimum visibility (m)	Duration (h)	Maximum $PM_{2.5}$ (μg m^{-3})	Maximum RH (%)	Weather phenomenon
Haze events	2014.01.21/ 15:00	2014.01.24/ 15:00	1364	73	264	68	–
	2014.04.11/ 22:00	2014.04.14/ 23:00	1113	74	304	89	–
	2015.02.12/ 21:00	2015.02.16/ 10:00	1667	86	263	77	–
	2015.03.04/ 22:00	2015.03.08/ 10:00	1886	83	266	72	–
Fog–haze mixed events	2014.02.19/ 21:00	2014.02.26/ 20:00	647	168/76[b]	269	92	02.26/16:00–21:25 Drizzle rain
	2014.03.22/ 22:00	2014.03.28/ 14:00	664	137/13[b]	417	94	3.28/4:30–6:20 Drizzle rain
	2014.10.06/ 22:00	2014.10.11/ 18:00	500	117/48[b]	391	100	10.08/6:40–7:50 10.08/10:30–11:50 Drizzle rain
	2014.10.16/ 21:00	2014.10.20/ 23:00	964	99/3[b]	322	100	–
	2014.10.22/ 4:00	2014.10.26/ 4:00	258	97/24[b]	379	100	–

2014.10.28/ 23:00	2014.11.01/ 5:00	837	79/1[b]	184	100	10.29/23:00–10.30/00:10 10.31/15:10–16:30 Drizzle rain
2015.01.12/ 17:00	2015.01.16/ 3:00	526	83/8[b]	297	93[a]	01.14/10:00–10:20 snow

[a] the maximum RH of all valid data except missing measurements.

[b] fog–haze mixed event duration / fog duration.

5. Figure 3: Are the both MPL and CL31 at site in Beijing?

Reply 5:

Yes, they are all located in the observational site at the campus of China Meteorological Administration (CMA) in Beijing. CL31 was sited on the roof of a 20 m tall building, and MPL installed in a working container beside the building not far away 10 m. To be more clearly, we have modified the corresponding text in section 2.1 as "The vertical profiles of aerosol in the troposphere and the PBL height could be also obtained from a ground–based MPL installed in a working container 10 m far away from the building at the campus of CMA."

6. Page 8 Line 21: How about these PBL height in haze events?

Reply 6:

Thank you for your questions. The $PM_{2.5}$ concentrations of 100 μg m^{-3}, 200 μg m^{-3}, 300 μg m^{-3} corresponded to the PBL heights of 0.46 km, 0.37 km and 0.28 km, respectively. It has been added in section 3.2 of the revised manuscript.

7. Page 9 Section 3.4.1: Why the authors chose April 2014 as the typical haze? Haze in northern China are more severe in winter season. How about the results for other haze events identified in this study?

Reply 7:

Thank you for your questions. As you said, the haze events in winter season in northern China are usually more severe. As seen in Table 1, there were only four long–lasting haze events during January 2014 to March 2015 in Beijing. The maximum $PM_{2.5}$ concentration was the highest and the corresponding data was relatively complete in the haze event in April 2014, so we choose the case as the type haze event. We have added these descriptions in section 3.4 of the revised manuscript. Our main conclusion about the influence of double inversion layer on the the long–lasting pollution events in Beijing city are also suitable to the cases in Table 1.

8. Page 9 Line 25: The unit of visibility is m here but km in previous figures. Please unify units for the whole figures and manuscript.

Reply 8:

Thanks for the suggestion. The units of visibility and PBL height as ‘m’ for the whole figures and texts are unified in the revised manuscript, shown as below:

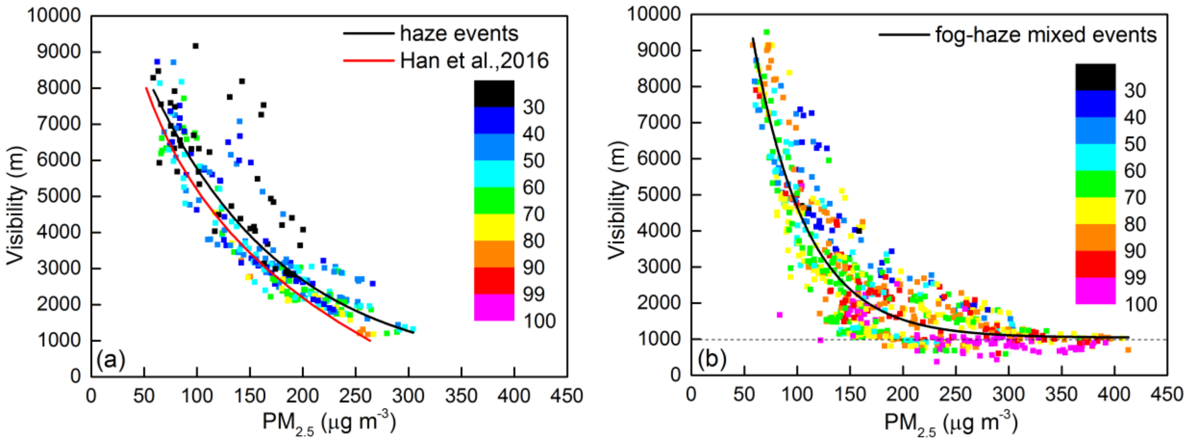

Figure 2: Relationship between the measured visibility and $PM_{2.5}$ mass concentration under different RH conditions for (a) haze and (b) fog–haze mixed events from January 2014 to March 2015 in Beijing city. The black exponential curves present the fits of the squares. The red exponential curve is the fit of daily averaged visibility and $PM_{2.5}$ concentration from October 2013 to September 2014 on stable meteorological days in Han et al. (2016)

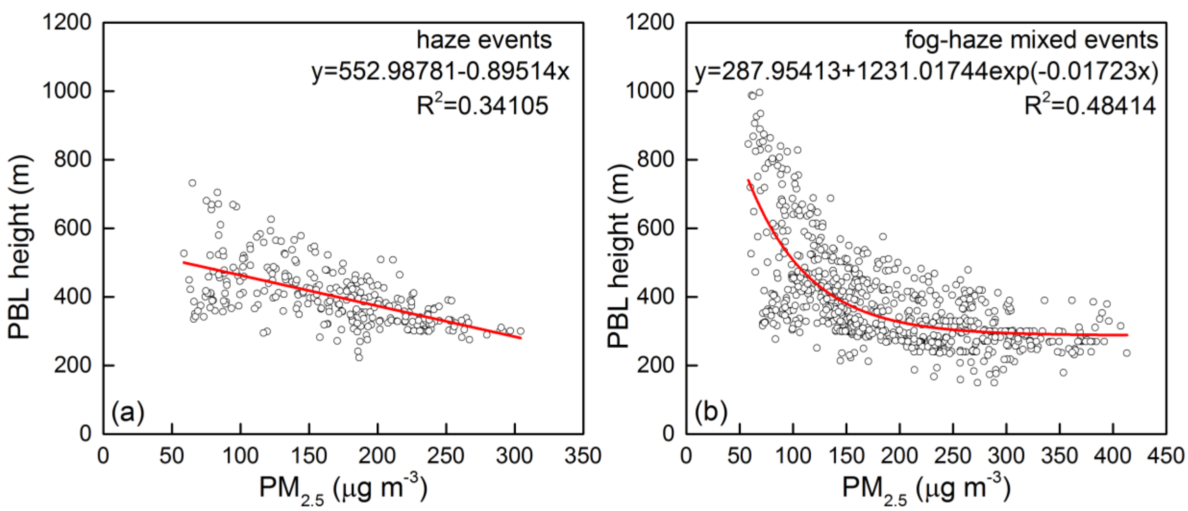

Figure 3: Relationship between PBL height and $PM_{2.5}$ mass concentration for (a) haze and (b) fog–haze mixed events from January 2014 to March 2015 in Beijing city

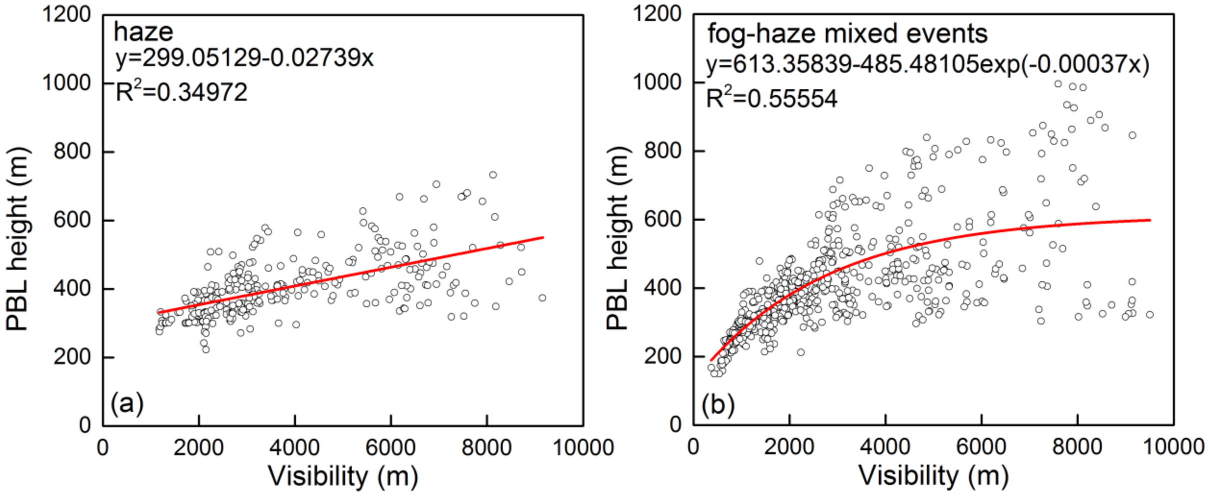

Figure 4: Relationship between visibility and PBL height for (a) haze and (b) fog-haze mixed events from January 2014 to March 2015 in Beijing city

9. Figure 6: I am confused that why PMcoarse did not increase with time. If aerosols are accumulated in the boundary layer due to decrease in PBL, all coarse and fine aerosol concentrations are expected to increase.

Reply 9:

Thanks for the comment. This is caused by the much lower value of PMcoarse than fine aerosol concentration. If we redraw the figures for the haze event and fog–haze mixed event (see below Fig. A and Fig. B), we can find almost the same tendency. The left vertical axis represents the concentration of $PM_{2.5}$ and PM_{10}. The right vertical axis represents the PMcoarse ($PM_{2.5–10}$) concentration. In general, the variation trend of PMcoarse is consistent with that of $PM_{2.5}$ in both two cases, especially in the fog–haze mixed event. In the previous manuscript, we used single vertical axis for the concentration of $PM_{2.5}$, PMcoarse and PM_{10} and the variation of PMcoarse concentration is not clear due to its lower value. Since the variation trend of PMcoarse was generally consistent with that of $PM_{2.5}$ in both two cases, so we have deleted the lines of PMcoarse in Fig. 5 (e) and Fig. 10 (e) in the revised manuscript.

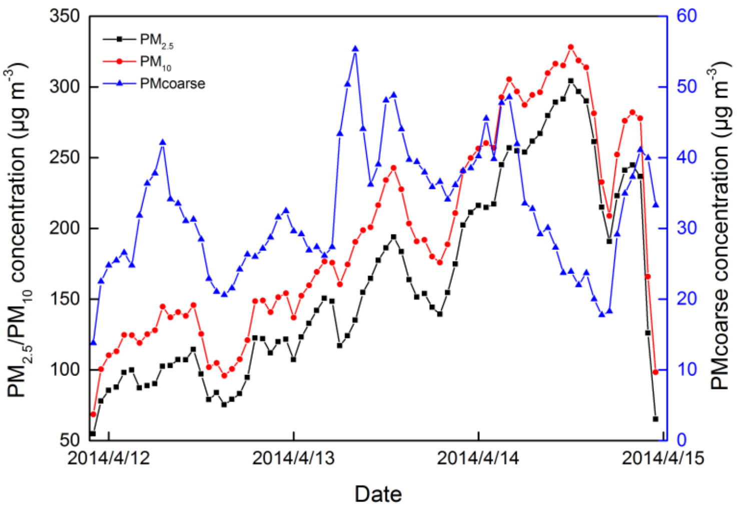

Figure A: Temporal variations of mass concentration of particulate matter observed during the whole haze event in Beijing city.

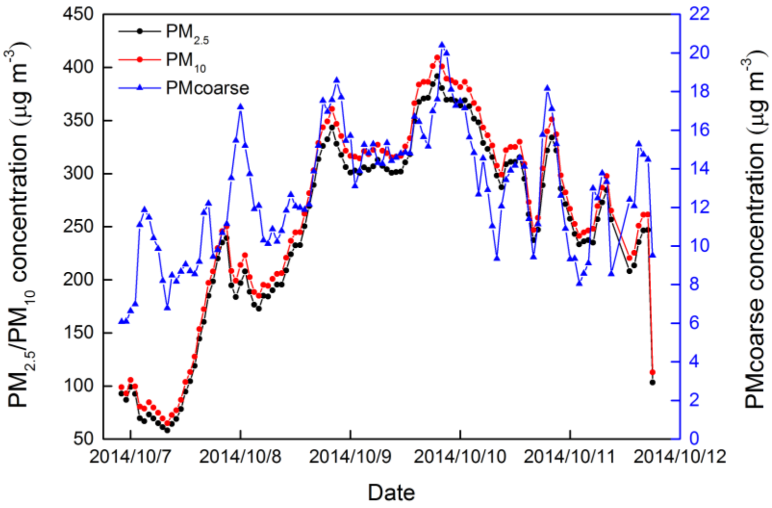

Figure B: Temporal variation of mass concentration of particulate matter observed during the whole fog–haze mixed event in Beijing city.

10. Page 12 Line 6: Why the authors did not choose the same spring season as the haze event analysis above?

Reply 10:

Thanks for the comment. The fog–haze mixed event from 22 to 28 March, 2014 for the same spring season as the haze event was much weaker and shorter-lived than that we selected (Table 1). The fog in selected fog-haze mixed case lasted about 3 days while that for the case with same season only lasted 13 hours. In order to investigate the typical long–lasting fog–haze mixed event, we chose this case. To be more clearly, we have added the message to section 3.4 of the revised manuscript as "In all haze events, the haze event observed from 11 to 14 April was highly polluted with the maximum $PM_{2.5}$ concentration of 304 μg m^{-3} and minimum visibility of 1113 m. For all fog–haze mixed events, the fog duration was considered firstly. Two cases are chosen, in which the fog duration accounted for more than 40 % of the total. One was observed from 19 to 26 February 2014, and the other was occurred from 6 to 11 October 2014. Moreover, the maximum RH reached to 100 % in the fog–haze event occurred from 6 to 11 October 2014, which was chosen as typical fog–haze event for the following study."

Technique issue:

11. Too much figures in the manuscript, the authors may move some into supplement.

Reply 11:

Thanks for the suggestion. We have moved some figures into supplement in the revised manuscript (see Fig. S1, Fig. S2, Fig. S3 and Fig. S4 in the Supplement).

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