Response to reviewer's comments

Anonymous Referee #1:

General comments:

The manuscript discusses a pollution event that produced a "haze front" over Beijing, China on 24 December 2015. The haze front is a sharp change in visibility on the boundary of warm dry clean air meeting cool moist polluted air over the city. The warm air mass was created by a foehn wind blowing down from the mountains to the north and west of Beijing. The interaction between the two air masses is analysed in detail using meteorological variables, and particular matter measurements from a number of sites across the city. The authors then conclude with statistics of how often this sort of event occurs. These events can have a large impact on air quality in Beijing and can potentially be applied to other cities with a similar geographical layout. I am not aware of a similar publication into haze fronts caused by foehn winds. The manuscript reads well and the English is good, but there are some sections that need changing. Great use of many different measurement platforms. As there are a lot of sites, Table 1 and the map in Figure 1 really help for orientation. But some of the figures need some work (see below). The supplemental figures are helpful for providing a broader picture.

We sincerely thank the reviewer for in-depth comments and helpful suggestions. We have responded to all the comments point-by-point and made corresponding changes in the manuscript. Following are detailed responses to all the comments.

I could not find a video (mentioned during the submission).

We are very sorry for forgetting to upload the video during the submission. This video will be submitted as a supplement along with the revised manuscript.

Specific comments:

Define the time zone LST (I assume it's local time)

The time zone LST (Local Standard Time) is Beijing time. We have defined the time zone LST in the manuscript.

PM2.5: sometimes the 2.5 is subscript or normal script

Thank you. All of 2.5 in PM2.5 have been set as subscripts in the manuscript.

Mini-MPL: sometimes you refer to the Mini-MPL as Min-MPL

Thank you. All 'Min-MPL' has been changed to 'Mini-MPL'.

Table 1:

- observation heights missing

Thank you. This has been corrected.

- AOT AWS is missing

Thank you. This has been corrected.

Section 3.1 needs to discuss the meteorological conditions in a bit more detail.

- You show a number of weather charts, but don't really explain what the relevance is to the haze front case study. The upper level trough is not really relevant here.

Thank you. We have added more explanations to this section. We also have adjusted the sequence of Section 3.1 as Referee #2 suggested. In brief, the upper air flows were dominated by northwesterly winds. And before the impact of the synoptic system, surface winds were weak. This synoptic pattern was one of typically frequent unfavorable conditions which exacerbate air pollution.

- You don't reference the 850 mb charts in the main text. What height is the 850 mb surface? This is useful when comparing to the wind profiler data (Fig. 2d). But ultimately the surface wind is weak and doesn't really correlate with the upper level data in the morning. Figure 10 also shows very low wind speeds in the morning before the foehn arrives. Looking at Figure S1a there doesn't seem to be any evidence of a cold front or dominant wind direction.

The height of 850 mb at Beijing is ~ 1500 m above the ground level. The winds at this height in Figure 2d agree well with the winds at same height in Figure 3c and 3d. We agree with you that the cold front marked in Figure 3e, which was automatically plotted by the software, seems not obvious and unwarranted. Therefore, we have re-plotted the map without the cold front.

- Figure 3: if possible add some dots to show measurement sites if they are not too close together. Maybe same as Figure 4 (IUM, IAP and GXT). As a minimum a dot showing the centre of Beijing.

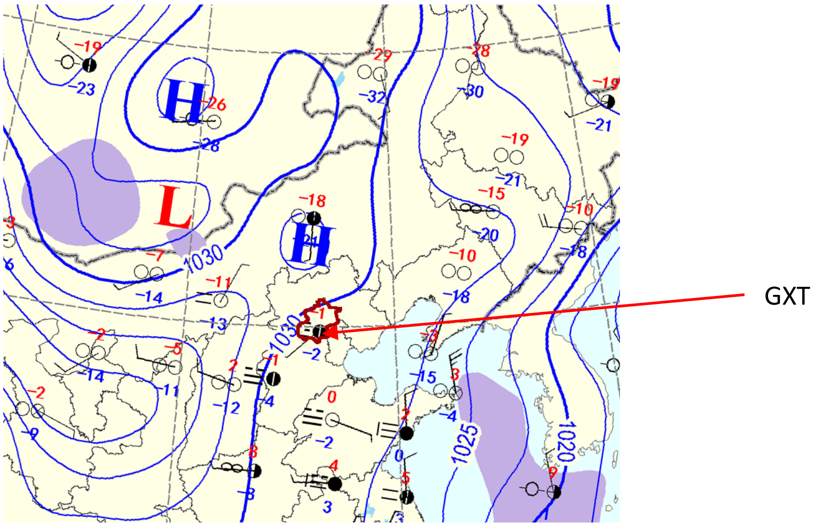
Thank you for the comment. It is hard to distinguish sites in such small maps. So we have made the boundaries of Beijing bold and brown on the maps.

Also, in the caption it should be '850 mb'.

The caption has been corrected.

- Line 158 says the flow is weak south-westerly in Figure 2c, but looks weak northeasterly to me in Figure 3f. Which one is it?

The flow is southwesterly in Figure 3f. Please see an enlarged figure below. The black dot pointed by a red arrow is the GXT site with ~ 1 m/s southwesterly surface wind.



- The radiosonde profile in Figure 2c also shows up the vertical extent of the haze front at GXT nicely.

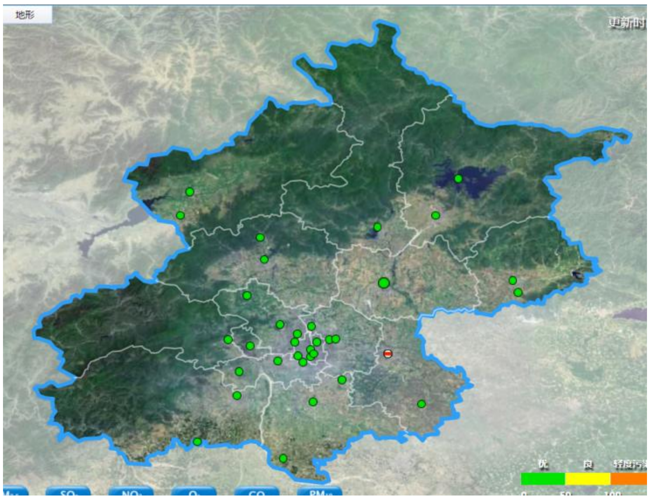
Thank you for the comment.

- Figure 2a: Is it possible to add some sort of distribution of hourly PM2.5 values from the different sites (percentiles)? The event is highly variable.

We are not sure about how to plot the percentiles in Figure 2. An alternative way is to plot hourly PM2.5 value for all three representative sites and three-sites mean value. Please see the new Figure 2a.

Also, what area does the average PM2.5 cover?

The average PM2.5 is the mean PM2.5 concentration of 35 sites in Beijing shown on the below site map and the new Figure 1a. Most of the sites are located in plain areas in Beijing.



Source: http://zx.bjmemc.com.cn/getAqiList.shtml?timestamp=1601452931296

Section 3.2:

- Figure 4: it might help to add a narrow line to the images where you can pick out the haze front as it is quite difficult to see at first (similar to Figure 6)

Thank you for the comment. We have added red lines to illustrate the haze front in Figure 4.

- Figure 5b: The text says that the wind direction changes suddenly at t2 (ie. 16:21 LST) (line 177) but I can't see this in the figure. Are the wind directions in the plot correct?

The wind directions in the plot are correct. As a result of using wind data observed at Chedougou (CDG) site, ~ 1 km north of the IUM, the wind direction changes at CDG didn't match the PM2.5 concentration changes at IUM very well. In fact, there is an AWS collocated with the Mini-MPL at the top of the IUM building, which observed wind direction and wind speed but with more missing data during the HF passing period. We used wind direction and wind speed data at IUM and redrew the Figure 5b. Besides the wind data observed at the IUM site, you can also find the wind direction changes agreed well with the PM2.5 concentration changes from the supplemental video.

- Figure 5 (caption, line 673): The scanning lidar is at IUM not IAP.

Thank you. This has been corrected.

- Figure 7: can you add the haze front line to this plot? Also, personal preference: maybe flip the colour bar (red as dry and blue as moist)

Thank you for the comment. We have added the haze front line to Figure 7, and flipped the color bar as you suggested.

- line 193: revise the word "surrounded"

Thank you for the comment. We have revised the word "surrounded". The sentence now reads:

"The foehn winds with the warm, dry, and clean air collided with more southerly or southeasterly winds with the cold, wet, and polluted air and resulted in oscillations of the HF line (Fig. 6-7)."

Section 3.3:

- Figure 8 has values every hour and not three-hourly as mentioned in the caption. The use of tendency is a bit confusing. Using it for pressure works, to show the small differences between sites that produce the pressure gradient. Are the tendencies subtracted from the mean of the whole day? Unless the absolute values of temperature and humidity for the different sites are very different, I would find it easier if they were absolute (or at least include the mean values in the plot eg. Tmean[CP]=x.xdegC) as you reference absolute values in the main text.

Thank you for the comment. The pressure tendency we used here is defined as P_{t0}-P_{t0-3}, where P_{t0} is the pressure at t0 (current time in hour) and P_{t0-3} is the pressure at 3 hours before t0. A similar tendency definition was used for the temperature and specific humidity. We agree with your comment that the use of tendency is a bit confusing. Hence, we have re-plotted Figure 8a, 8b and 8c by using the half-hourly pressure anomaly, temperature and specific humidity, respectively. We have marked the time of HF passage at CDG in Figure 8 as Refree #2 suggested. Also, we have revised sentences related to the changes in Figure 8.

- line 223: I think “gusty the foehn” should be “the gusty foehn”.
Thank you. This has been corrected.
Also, what do you mean by “enlarging the coverage”?
By “enlarging the coverage”, we mean to express the enlarged scope or coverage of the UHI after the warm-dry air mass driven by the gusty foehn merged with the UHI.

- line 225: do you mean “the pressure increased significantly compared to the other sites”?
We meant the pressure increased significantly when the haze front passed over the CDG site. But because we modified Figure 8 and found the pressure only increased slightly, we have revised the sentence. It now reads:
“When the HF passed over CDG, the humidity and PM2.5 concentrations significantly increased, the pressure slightly increased, but the temperature slightly decreased (Fig. 8).”

- line 229: Reference that it is IAP Doppler lidar data in the text to make it clear. Otherwise I have to look at the figure to work that out.
Thank you for the comment. We have revised the sentence. The sentence now reads:
“At IAP around noon, the Doppler lidar detected a northwesterly wind and a significantly increased updraft between 450 m and 1250 m height above the surface, and the wind direction below 500 m changed from northeast to northwest (Fig. 9).”

- line 233: Please reword. I think you mean something like: “the temperature was higher and the turbulence was increased mainly between 12:00 LST and 19:00 LST”. The current wording implies that it started low at 12:00 LST and increased steadily to a maximum at 19:00 LST.
Thank you. We have reworded the sentence.

- line 236 and Figure 10: you might benefit from including potential temperature here, as this shows up stability better.
Thank you for the comment. But there are no pressure observations at 15 levels on the IAP tower.

- line 237: Looks like the enhanced pollution wasn’t just below 100 meters. Figure 9 suggests the aerosol went all the way up to 400 meters.
Thank you. We reworded the sentence. The sentence now reads:
“The boundary layer became more stably stratified near the surface, leading to enhanced pollution in the lowest few hundred meters.”

- Figure 11: Are the tower plots correct? I’d expect DR to decrease as you get closer to the ground, but 47 m shows the highest DR.
Thank you for the comment. The tower plots are correct.
The reason that the DR at 47 m is highest is due to the ‘canyon trapping’ effect on shortwave radiation in the urban canopy layer (Oke, 2017). The rugosity of the urban surface contributes to the lower albedo values at higher solar elevation angles as more short-wave radiation enters

the street canyons where it is trapped (Christen and Vogt, 2004; Kotthaus and Grimmond, C.S.B., 2013). The IAP tower is surrounded by 4- to 20-story buildings with heights of 10 to 60 m (Liu et al., 2017; Wang et al., 2019). Some buildings just south of the IAP tower are higher than the pyrgeometers and pyranometers mounted at 47 m on the tower causing the additional shortwave radiation trapping in the street canyon, especially when solar elevation angles are greater (Dou et al., 2018).
Also, it might be easier to read if you list the tower levels in one column in the legend.
Thank you for the comment. We have listed the tower levels in one column in the legend.

- line 240 and Figure 11: do you mean AOT instead of ATZX?
Thank you. Yes. We have changed all "ATZX" into "AOT".

- line 243: The lower PBL height is also to do with the PBL height being suppressed by the overrunning foehn wind, not just the reduced solar radiation at the ground.
Thank you for the comment. According to our observational analysis, there is no evidence that foehn winds affected GXT. Please see in Figure S2a the southern most areas that foehn winds have invaded. Hence, the lower PBL height at GXT is mainly due to less solar radiation and less turbulence, and positive feedback between the PBL height and the aerosol concentration.

Section 4:
- line 302: are mountain-plains winds and mountain breezes the same thing?
Mountain breezes are a part of mountain and valley breezes that refer to the cooler, more-dense air that glides downslope into the valley during nighttime (Ahrens, 2003). Mountain-plain winds result from horizontal temperature differences between the air over a mountain massif and the air over the surrounding plains, producing large-scale winds that blow up or down the outer slopes of a mountain massif (Whiteman, 2000). The scale of mountain-plain winds is larger than the scale of mountain breezes.

- line 319: add the types in brackets (eg. '(Type A)') to the main text to make it more clear.
Thank you. We have reworded the sentences.

- Table 2: rewording for the types: eg. "Type A: polluted cases where PM2.5 concentrations for the CP, AOT and YZ sites had decreased 24 hours after the foehn's occurrence."
Thank you for the comment. We have reworded the table note.

Data availability: Couldn't access http://www.ium.cn/dataCenter/ (Page not found)
Sorry about the invalid link. The link of the datacenter of IUM has been changed into http://www.ium.cn:8088/ in 2020.

Couldn't access http://106.37.208.233:20035/ (Couldn't install Silverlight on my system)

Please visit https://quotsoft.net/air/ where the PM2.5 data sources from the China Environmental Monitoring Station and the Beijing Environmental Protection Testing Center.

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