Reply letter to the anonymous referee #1

This paper examines the connection between the large-scale mid-tropospheric circulation over Northeast Asia and air quality in one of the most heavily populated parts of China. The analysis is generally well constructed; however, some aspects of the methodology are not sufficiently documented, some of the confidence levels appear to be overstated given the limitations of the data involved, and some of the interpretations need further clarification. I include a few suggestions along these lines below. The content is within the scope of ACP and a revised version of the paper could be a valuable contribution to research on this topic, helping to address some outstanding questions on how the large-scale circulation influences air quality in Beijing and surrounding areas. However, major revisions will likely be necessary for the paper to meet that standard.

Major comments:

1, Why only December? This is not clearly explained in the text, and seems a strange choice given that only three years of data are used.

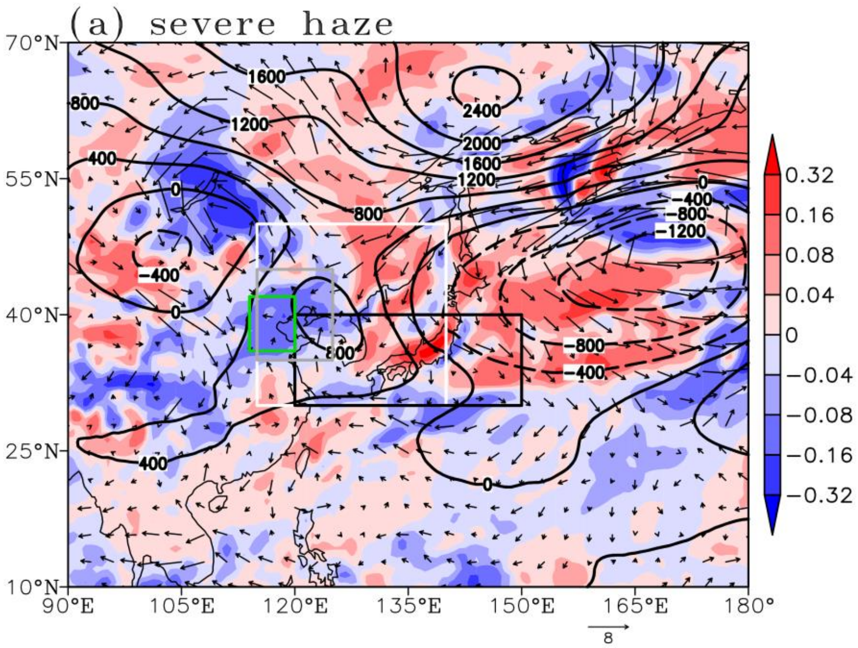
Reply:

We have further clarified why December data in 2014, 2015 and 2016 were used. Some revisions were added. The situation in December 2017 was discussed in the discussion, serving as an independent verification. This confirmed that our results are robust and reliable.

1. This study was a continuation of previous research on the relationship between Eurasian snow cover and December haze days in China (Yin and Wang, 2018). We have further revealed how the anomalous anticyclonic circulation affected severe haze pollution in the BTH region through its impact on local meteorological conditions.
2. According to previous studies, severe haze events in North China are most frequent in boreal winter (i.e., December, January and February), especially in December (Chen and Wang, 2015). Besides, the strong inter-annual variation of December haze days in Central North China occurs after the mid-1990s, and it is different from that in other winter months (Yin and Wang, 2018). Here, we took a close look at the

December severe haze events to explain its association with the large-scale circulation from the sub-seasonal time scale.

3. Open access to the $PM_{2.5}$ concentration data is available only after 2014 and the data in 2018 have not been fully updated. It is well acknowledged that the fine particulate matter (PM) is the main cause of severe haze (Wang et al., 2016; Cai et al., 2017). However, the air quality measurement network in China is relatively recently developed and the $PM_{2.5}$ concentration data are available only after 2014. Since our studies lasted for a relatively long time and the data were not updated in time, we did not take the sample of December 2017 within the scope of our research in the original version. Now, we have further discussed the situation in December 2017, serving as an independent verification. In December 2017, there were 2 severe haze events, 5 non-haze events and 7 non-severe haze events. The SPCC between mean $PM_{2.5}$ concentration and $AANAI_{Z500}$ was 0.73, exceeding the 99% confidence level. The AANA detected in December 2017 was much weaker relative to the overall state during the months of December in the years 2014-2016, which might explain why severe haze (non-haze) was less (more) frequent in December 2017. These results confirmed that our conclusions are robust and reliable.



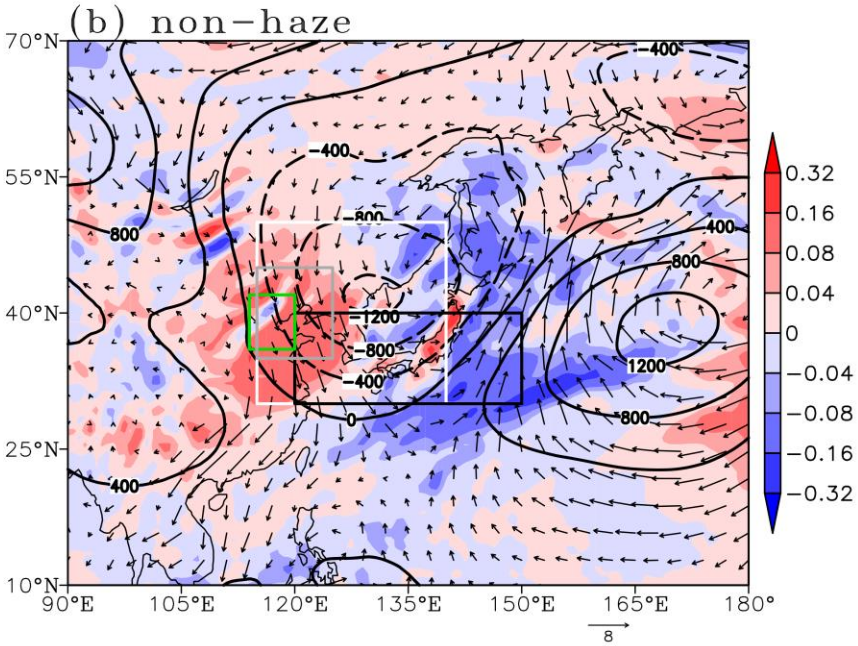


Figure 11. Structure of the AANA on (a) severe haze episodes and (b) non-haze episodes in December 2017: Z_{500} (contour, units: $m^2 \cdot s^{-2}$), $\boldsymbol{V}_{850}$ (arrow, units: $m \cdot s^{-1}$) and $\boldsymbol{\omega}_{500}$ (shading, units: $Pa \cdot s^{-1}$). The anomalies here were calculated with respect to the 1979-2010 climatology. The green box indicates the BTH region. The white, black and gray boxes indicate the area covered by $AANAI_{Z500}$ $AANAI_{V850}$ and $AANAI_{\omega500}$, respectively.

Revisions:

In "Introduction"

……Considering that the air quality measurement network in China is relatively recently developed, this study focused on severe haze pollution in the BTH region during the months of December in the years 2014-2016, and explicated the characteristics of the AANA and its relationship with severe haze, while making comparison with non-haze episodes. The situation in December 2017 were also discussed to verify the relationship revealed in this study.

In "Discussion"

……The situation in December 2017 backed up our conclusions. Even though the haze events were not as serious as those in previous years, the AANA could be detected at the mid-level when severe haze occurred (Figure 11a). BTH region was occupied by anomalous southerly winds near the surface and anomalous ascending motions in upper levels. The strong cyclonic circulation over Northeast Asia might explain why the haze pollution was less severe in December 2017 (Figure 11b).

2, Details and/or citations for how the 'synoptic process mean' and 'synoptic process correlation coefficient' are calculated are missing from the paper. It is possible to infer the definition and application of a 'synoptic process' for PM2.5 from table 1 and figure 1, but this should be made more explicit to help readers put the results into the context of previous studies. It is less clear what a synoptic process means in the context of the AANA (tables 3 and 5). Does this comprise the same set of events as for PM2.5, or are these defined based on the intensity of the AANA instead?

Reply:

1. We have explained the synoptic process mean and the synoptic process correlation coefficient in a more accurate way. Some revisions were added.
2. The synoptic process mean (SPM) data were rebuilt by averaging the mean $PM_{2.5}$ concentration, all the meteorological data and the AANA indexes during each severe haze, non-haze and non-severe haze pollution processes. All the synoptic process correlation coefficients (SPCCs) were calculated basing on the SPM data to represent the relationship between haze and meteorological factors during different types of haze events.

Revisions:

In "Data and method"

……Most previous studies investigated haze events in units of hours or days and the variations among haze pollution progresses were not taken into account. Some meteorological factors might be closely related to haze pollution in a few cases but remain insignificant in others. In this way, the relationship between haze pollution and meteorological factors might be overemphasized. Meanwhile, some meteorological factors, such as the PBLH and RH, showed strong temporal variations, which might call their statistical relationship with haze pollution into question. Thus, neglecting the small time-scale disturbances within each synoptic-scale environment could help to obtain the physical insight (Lackmann, 2011).

In “Table 3”

Table 3. The SPCCs between $AANAI_{Z500}$ ($AANAI_{V850}$, $AANAI_{\omega500}$) and regional meteorological indexes. “*” represents that the SPCC exceeded the 95% confidence level, and “**” represents that the SPCC exceeded the 99% confidence level. The synoptic process correlation coefficients (SPCCs) were calculated basing on the SPM data, which were rebuilt by averaging all the meteorological data and the AANA indexes during each severe haze (14), non-haze (12) and non-severe haze (24) process. The sample size was 50.

SPCC	Visibility	Surface wind speed	Surface RH	TIP anomalies	ERA PBLH anomalies
$AANAI_{Z500}$	-0.71**	-0.38**	0.73**	0.58**	-0.50**
$AANAI_{V850}$	0.59**	0.25	-0.56**	-0.41**	0.40**
$AANAI_{\omega500}$	0.51**	0.11	-0.50**	-0.30*	0.22

3, The definition of synoptic processes for PM2.5 is potentially problematic, particularly with respect to interpretation of the level of confidence to assign to the results. Specifically, the authors should probably (1) define a minimum duration for a synoptic process and (2) allow for brief interruptions in a given synoptic process.

• Following the standard definition of ’synoptic’ (see, e.g., Bluestein, 1992) and the composite evolution shown in figure 10, the minimum duration for (1) should probably be at least 12-24 hours (i.e., events should cover at least two reanalysis timesteps, and preferably 3-4).

• The allowance for brief interruptions would help to ensure mutual independence among the data points, given the persistence of meteorological conditions. A decent starting point would be to combine any two events of the same sign with less than 24 hours between them into a single point.

Note that applying these two criteria would effectively cut the sample size in

half, which may call some of the statistical relationships into question even before considering potential changes in the values of the correlation coefficients. Even without these adjustments, tables 4 and 5 appear to be overstating the confidence levels associated with variability in each year, most especially for PBLH.

Reply:

1. We have applied these two criteria to define each synoptic process for haze. Some revisions were added.
2. The SPM data included **three** types of events for haze: severe haze, non-haze and non-severe haze. In December 2014, December 2015 and December 2016, there were 14 severe haze events, 12 non-haze events and 24 non-severe haze events. The total sample size was **50**. The samples in December 2017 were also included to verify the relationship revealed in this study. Note that the statistical relationships remained even after the aforementioned adjustments on the definition of synoptic processes for haze. The SPM data could remove the potential influence of the day-to-day and diurnal variations and maintain the physical relations between haze and meteorological factors.

Revisions:

In "Data and method"

……To better describe the relationships and mechanisms manifesting among different haze pollution processes, new data called synoptic process mean (SPM) data were rebuilt. According to the $PM_{2.5}$ concentration, the synoptic-scale environments were divided into three groups: severe haze, non-haze and non-severe haze (i.e., $PM_{2.5}$ concentration $\subseteq [50,150]\ \mu g \cdot m^{-3}$). Two criteria were used to ensure each type of haze pollution process was typical and mutual independent: (1) a haze pollution process should have a minimum duration for at least 12 hours (i.e., two timesteps; a timestep represents 6 hours); (2) if any two haze pollution processes of the same type were detected within 24 hours (i.e., four timesteps), these two processes would be merged into one. The SPM data applied time averaging method to calculate the mean $PM_{2.5}$ concentration and all the meteorological data during each haze pollution process. Based on the SPM data, the synoptic process correlation coefficients (SPCCs) were calculated in the units of haze pollution processes, rather than in units of hours or days. This method maintains the physical relations between haze and meteorological factors while removing the potential influence of the day-to-day and diurnal variations inside each synoptic-scale environment.

In "Table 4"

Table 4. The SPCCs between the mean $PM_{2.5}$ concentration over the BTH region and key indexes in December 2014, December 2015, December 2016 and December 2017. "*" represents that the SPCC exceeded the 95% confidence level, and "**" represents that the SPCC exceeded the 99% confidence level. The synoptic process correlation coefficients (SPCCs) were calculated basing on the SPM data, which were rebuilt by averaging the mean $PM_{2.5}$ concentration, all the meteorological data and the AANA indexes during each severe haze, non-haze and non-severe haze process. The sample sizes in 2014, 2015, 2016 and 2017 were 18, 14, 18 and 15, respectively. Note that the PBLH from the FNL data is available only after 2015.

SPCC	AANA I_{500}	AANA I_{850}	AANA $I_{\omega 500}$	Visibility	Surface wind speed	Surface RH	TIP anomalies	ERA PBLH anomalies	FNL PBLH
2014	0.81**	-0.72**	-0.77**	-0.76**	-0.36	0.75**	0.69**	-0.65**	
2015	0.53	-0.61*	-0.66*	-0.94**	-0.53*	0.92**	0.37	-0.63*	-0.72**
2016	0.79**	-0.62**	-0.70**	-0.9**	-0.52*	0.87**	0.80**	-0.63**	-0.70**
2017	0.73**	-0.33	-0.58*	-0.89**	-0.68**	-0.86**	0.68**	-0.73**	-0.68**

In "Table 5"

Table 5. The SPCCs between $AANAI_{Z500}$ ($AANAI_{V850}$, $AANAI_{\omega 500}$) and regional meteorological indexes in December 2014, December 2015, December 2016 and December 2017. "*" represents that the SPCC exceeded the 95% confidence level, and "**" represents that the SPCC exceeded the 99% confidence level. The synoptic process correlation coefficients (SPCCs) were calculated basing on the SPM data, which were rebuilt by averaging all the meteorological data and the AANA indexes during each severe haze, non-haze and non-severe haze process. The sample sizes in 2014, 2015, 2016 and 2017 were 18, 14, 18 and 15, respectively. Note that the PBLH from the FNL data is available only after 2015.

Year	SPCC	Visibility	Surface wind speed	Surface RH	TIP anomalies	ERA PBLH anomalies	FNL PBLH
2014	$AANAI_{Z500}$	-0.64**	-0.10	0.57*	0.62**	-0.39	
	$AANAI_{V850}$	0.35	-0.09	-0.38	-0.27	0.22	
	$AANAI_{\omega 500}$	0.46	-0.01	-0.45	-0.45	0.27	
2015	$AANAI_{Z500}$	-0.66*	-0.68**	0.64*	0.07	-0.46	-0.65*
	$AANAI_{V850}$	0.75**	0.74**	-0.70**	-0.22	0.64*	0.72**
	$AANAI_{\omega 500}$	0.67**	0.35	-0.79**	-0.24	0.28	0.46
2016	$AANAI_{Z500}$	-0.70**	-0.46	0.69**	0.67**	-0.53*	-0.56*
	$AANAI_{V850}$	0.69**	0.46	-0.60**	-0.56*	0.47	0.60**
	$AANAI_{\omega 500}$	0.64**	0.26	-0.80**	-0.45	0.20	0.55*
2017	$AANAI_{Z500}$	-0.74**	-0.57*	0.65**	0.72**	-0.66**	-0.59*
	$AANAI_{V850}$	0.17	0.03	0.01	0.16	0.12	0.05
	$AANAI_{\omega 500}$	0.48	0.40	-0.39	-0.41	0.62*	0.58*

4, Speaking of PBLH, the small correlations here may be in part due to the use of PBLH values from ERA-Interim, which are based on a Richardson number formulation that tends to underestimate PBLH and its spatiotemporal variability (e.g., von Engeln and Teixeira, 2013). Other work suggests that the tendency for ERA-Interim to underestimate PBLH may be less of an issue during winter over this part of China (Guo et al, 2016), but a close look at their results still suggests that there may be issues in capturing the day-to-day and diurnal variations that this study relies on. If the statistical relationships do not hold up, it might

Reply:

To better capture the relationship between severe haze and PBLH, the following methods were used:

1. Calculating the PBLH anomaly. Specific to the climatology, we used the four times daily data during the months of December in the years 1979-2010 from ERA-Interim and calculated the mean state of PBLH at 02:00, 08:00, 14:00 and 20:00 (Beijing local time). The PBLH anomaly was calculated according to the PBLH climatology in each timestep. The could help to eliminate the potential influence of diurnal variations and highlight the characteristics of anomaly field.
2. Rebuilding the SPM data to calculate the SPCC. The synoptic process mean data were rebuilt by averaging the mean $PM_{2.5}$ concentration and the PBLH anomaly

during each severe haze, non-haze and non-severe haze process. Considering that each process for haze usually lasted for more than 4 timesteps (a timestep represents 6 hours), most of the day-to-day variations could be removed. In this way, the physical relations between haze and PBLH maintained.

3. Using the FNL data from NCEP to support our results. Note that the FNL data are only available after 2015. We calculated the SPCC between mean $PM_{2.5}$ concentration and PBLH from FNL data in December 2015, December 2016, December 2017, and they were -0.72, -0.70, -0.68, respectively (Table R1). The relationship between the AANA indexes and PBLH from FNL data also remained strong in these years (Table R2). These results confirmed that our conclusions are not dependent on the reanalysis dataset.

Some revisions were added to clarify the relationship between haze and PBLH.

Table R1. The SPCCs between the mean $PM_{2.5}$ concentration over the BTH region and ERA PBLH anomalies (FNL PBLH) in December 2014, December 2015, December 2016 and December 2017. "*" represents that the SPCC exceeded the 95% confidence level, and "**" represents that the SPCC exceeded the 99% confidence level. The synoptic process correlation coefficients (SPCCs) were calculated basing on the SPM data, which were rebuilt by averaging the mean $PM_{2.5}$ concentration, ERA PBLH anomalies (FNL PBLH) during each severe haze, non-haze and non-severe haze process. The sample sizes in 2014, 2015, 2016 and 2017 were 18, 14, 18 and 15, respectively. Note that the PBLH from the FNL data is available only after 2015.

SPCC	ERA PBLH anomalies	FNL PBLH
2014	-0.65**	
2015	-0.63*	-0.72**
2016	-0.63**	-0.70**
2017	-0.73**	-0.68**

Table R2. The SPCCs between $AANAI_{Z500}$ ($AANAI_{V850}$, $AANAI_{\omega500}$) and ERA PBLH anomalies (FNL PBLH) in December 2014, December 2015, December 2016 and December 2017. "*" represents that the SPCC exceeded the 95% confidence level, and "**" represents that the SPCC exceeded the 99% confidence level. The synoptic process correlation coefficients (SPCCs) were calculated basing on the SPM data, which were rebuilt by averaging ERA PBLH anomalies (FNL PBLH) and the AANA indexes during each severe haze, non-haze and non-severe haze process. The sample sizes in 2014, 2015, 2016 and 2017 were 18, 14, 18 and 15, respectively. Note that the PBLH from the FNL data is available only after 2015.

Year	SPCC	ERA PBLH anomalies	FNL PBLH
2014	$AANAI_{Z500}$	-0.39	
	$AANAI_{V850}$	0.22	
	$AANAI_{\omega 500}$	0.27	
2015	$AANAI_{Z500}$	-0.46	-0.65^{*}
	$AANAI_{V850}$	0.64^{*}	0.72^{**}
	$AANAI_{\omega 500}$	0.28	0.46
2016	$AANAI_{Z500}$	-0.53^{*}	-0.56^{*}
	$AANAI_{V850}$	0.47	0.60^{**}
	$AANAI_{\omega 500}$	0.20	0.55^{*}
2017	$AANAI_{Z500}$	-0.66^{**}	-0.59^{*}
	$AANAI_{V850}$	0.12	0.05
	$AANAI_{\omega 500}$	0.62^{*}	0.58^{*}

Revisions:

In "Data and method"

……Considering that ERA-Interim might have problems capturing the day-to-day and diurnal variations of PBLH over North China (von Engeln and Teixeira, 2013; Guo et al, 2016), the NCEP GDAS/FNL Global Surface Flux data were applied to make a comparison. The anomaly fields were calculated with respect to the mean climatology in December from 1979 to 2010. Considering of the strong diurnal variations of some meteorological factors, such as the PBLH, temperature and RH, the climatology here were calculated separately for 02:00, 08:00, 14:00 and 20:00 in Beijing local time.

In "Conclusions and discussions"

……It is worth noting that the tendency for ERA-Interim to underestimate PBLH (von Engeln and Teixeira, 2013) may be less of an issue during winter over North China (Guo et al, 2016). We have further calculated the SPCCs between AANA indexes and FNL PBLH (Table 5), which confirmed that our conclusions are not dependent on the reanalysis dataset.

5, The explanation for the relationship between vertical motion and the BL temperature inversion ("ascending motion inhibits invasion of cold air from the

upper atmosphere . . . propitious to the formation of thermal inversion layer in the lower level"; l.183-184) seems counterintuitive. One would expect mid-tropospheric subsidence and associated adiabatic warming to more effectively promote the development of an inversion layer at the BL top, as opposed to ascent. This might be reconciled by considering the north–south slope of isentropic surfaces in this mid-latitude region and how AANA-related variations in omega project onto the cross-isentropic component of the horizontal flow, as hinted by the authors around l.157-159 (concerning the role of horizontal advection in strengthening the temperature inversion). Perhaps composite analysis of the temperature budget at 925 hPa would help? Either way, this point requires further discussion and clarification.

Reply:

1. We have further diagnosed the local temperature changes according to the thermodynamic energy equation (Wallace and Hobbs, 2006). The results indicated that horizontal advection was the main cause of temperature inversion (Figure 7a&b), and the dissipation process for haze pollution was accomplished through cold and dry air invasions from upper levels (Figure 7c). At the day before the first day of severe haze events, the local temperature changes mainly generated by warm advection were stronger at 850 hPa than those at 1000 hPa (Figure 7a). Even though anomalous vertical motions had negative effects on the changes of temperature at the first day of severe haze events, the positive horizontal advection still prevailed in lower levels and the local temperature changes remained positive (Figure 7b). This was propitious to the emergence and development of temperature inversion layer and the increase in atmospheric stability during severe haze events (Figure 3a). At the day after the first day of severe haze events, the negative temperature changes mainly induced by the sink of cold and dry air broke the inversion layer (Figure 7c). This effect was conducive to the vertical dispersion of pollutants. It is worth noting that the anomalous ascending flow associated with the AANA greatly weakened the vertical motion over the BTH region (Figure 9a). This effect might explain why the subsidence and associated adiabatic warming became weaker during severe haze

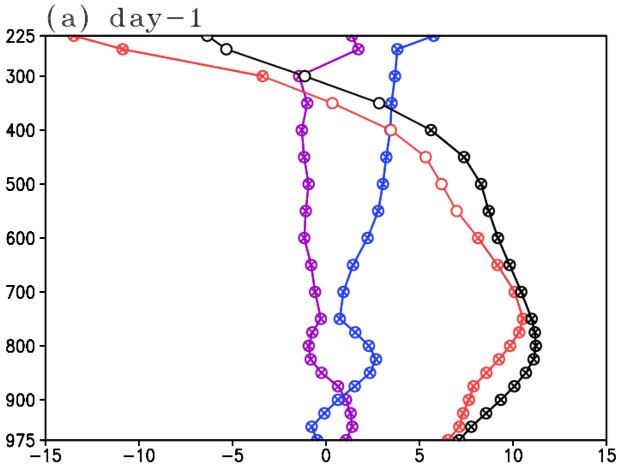
episodes and did not predominate in the changes of lower level temperature (Figure 7).

2. The suggestion from anonymous referee #2 provided new insight into how anomalous ascending flows associated with the AANA affected severe haze pollution. Due to the emergence of inversion layer, the anomalous ascending motion could not connect with the air that lying beneath the stable layer (Corfidi et al. 2008). However, the anomalous vertical flow still provided favorable synoptic-scale environments for the development of severe haze by confining the clean air intrusion and the downward momentum from upper levels. These factors were conducive to the development of inversion layer. Once anomalous ascending flows weakened and descending motions prevailed over the BTH region, the sink of clean air from upper levels tended to break the inversion layer (Figure 7c). In the meanwhile, the downward transportation of westerly momentum could be strengthened, which led to stronger northerly winds near the surface and enhance cold advection over the BTH region (Figure 7c). These effects represented the dissipation process for haze pollution.

Some revisions were made to explain this part in a more clearly way.

Review by anonymous reviewer #2

196-199. The idea that ascending motions somehow limit vertical mixing is, again, counterintuitive and requires further explanation. I might well be missing something in my reading of this section. But another interpretation of the data that occurs to me involves what might be described as the "temporal footprint" of the AANA pattern. In short, a persistent ANNA over the BTH region leaves it with a stable thermal stratification that is conducive to the build-up of pollution aerosols — namely, a shallow PBL capped by a strong inversion. The strong ascending mid-level vertical motions that appear on the "back sides" of the AANA patterns then are unable to strongly "connect" with the air that lying beneath the inversion. Similar environments can give rise to "elevated thunderstorms" (e.g., Corfidi et al. 2006), wherein boundary-layer air is unable to support deep convective development, but the arrival of strong mid-level ascent on the "back side" of a large, deep anticyclone releases convective instability that evolves at the mid-levels. I do feel that the preceding interpretation is more strongly supported by accepted synoptic and mesoscale meteorological theory than is the notion (proffered in line 196) that "clean air in the upper atmosphere" is somehow "restricted" from descending to the surface. Another interpretation that occurs to me in reading this section is that the vertical motions resulting from vertical stratification somehow are being conflated with those that arise from AANA synoptic-scale pattern that is the main subject of your investigation.



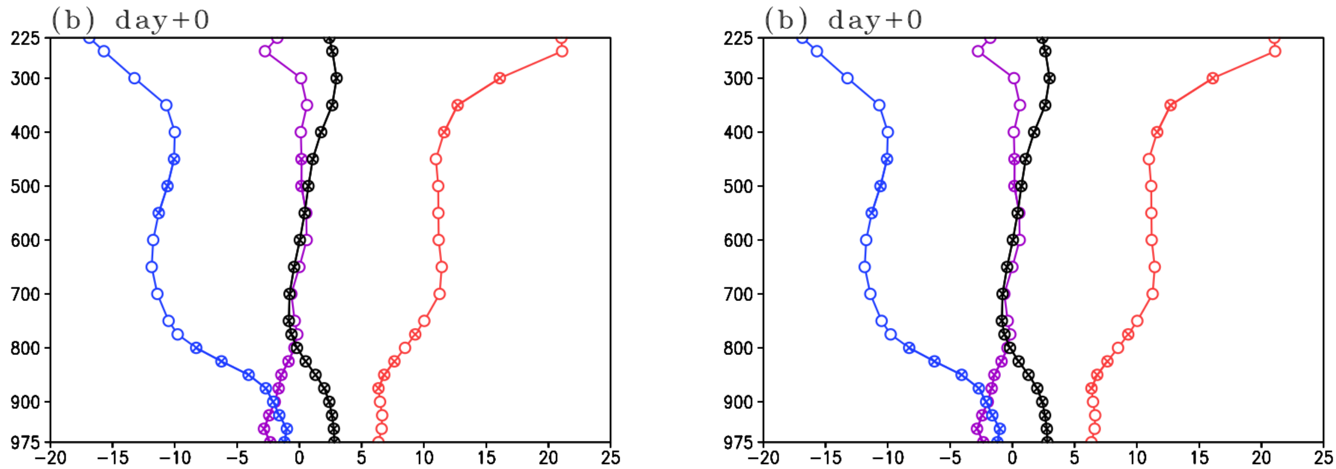


Figure 7. The differences of temperature changes (units: $10^{-5}\mathrm{K}\cdot\mathrm{s}^{-1}$) between severe haze and non-haze events over the BTH region. "Day+0" refers to the first day of severe haze and non-haze events. "Day-1" refers to one day before the first day of severe haze and non-haze events. Day+1 refers to one day after the first day of severe haze and non-haze events. The black line represents the local temperature changes (i.e., $\frac{\partial T}{\partial t}$). The red line represents the horizontal temperature advection (i.e., $-\boldsymbol{V}\cdot\nabla\mathrm{T}$). The blue line represents the combined effect of adiabatic compression and vertical advection (i.e., $(\frac{\kappa T}{P}-\frac{\partial T}{\partial P})\omega$, $\kappa = R/C_p = 0.286$; Wallace and Hobbs, 2006). The purple line represents the effect of diabatic heating process (i.e., $\frac{J}{C_p}$, J represents diabatic heating rate; this term was obtained through residual calculation) "ⓧ" indicates that the differences of the term between severe haze and non-haze exceeded the 95% confidence level.

Revisions:

In "Results"

……In addition, the warm advection over the BTH region induced by southeasterly winds could be verified in the middle and lower troposphere (Figure 7). Strong warm advection at mid-levels was also consistent with the decline in the EAWM. Specifically, the local temperature changes mainly generated by warm advection were stronger at 850 hPa than those at 1000 hPa at the day before the first day of severe haze events. Even though anomalous vertical motions had negative effects on the change of temperature at the first day of severe haze events, the positive horizontal advection still prevailed in lower levels and the local temperature changes remained positive (Figure 7). These effects were propitious to the formation and development of temperature inversion layer and the increase in atmospheric stability (Figure 3a). The SPCC between the $AANAI_{Z500}$ and TIP was 0.58 and exceeded the 95% confidence level (Table 3).

……Even though sinking motions still prevailed over the BTH region, the sink of cold air from upper levels was greatly weakened due to the anomalous ascending flow (Figure 9a). This effect might explain why the subsidence and associated adiabatic warming weakened during severe haze episodes and did not predominate in the changes of lower level temperature (Figure 7).

……It is worth noting that the emergence of inversion layer in the BTH region resulted in a more stable atmosphere, and thus the aforementioned anomalous ascending flow could not connect with the air that lying beneath the stable layer (Corfidi et al. 2008). However, the anomalous vertical flow still provided favorable synoptic-scale environments by confining the clean air intrusion and the downward momentum from upper levels. Once anomalous ascending flows weakened and descending motions prevailed over the BTH region, the sink of clean air from upper levels tended to break the inversion layer (Figure 7c). This effect could also strengthen the downward momentum and northerly winds near the surface. Subsequently, the BTH region was mainly controlled by the cold advection (Figure 7c). These factors represented the dissipation process for haze pollution.

6, Some of the secondary conclusions are not well supported; e.g., the statement that "severe haze had the tendency of becoming more persistent in recent years" (l.107-108) based on only three years' worth of December data.

Reply:

This insufficient conclusion has been eliminated and this part has been reworded.

Revisions:

In "Results"

The duration time of severe haze events (9.3 timesteps) was relatively longer than that of non-haze events (8.9 timesteps), especially in 2015 and 2016.

reasonable. There were 148 severe haze and 1220 non-haze events in December 2014-2016 (Table 1). The duration time of severe haze events (9.3 timesteps) was relatively longer than that of non-haze events (8.9 timesteps), especially in 2015 and 2016. –Severe haze broke out rapidly in most cases, but the dissipation processes varied in different years. The $PM_{2.5}$ concentration decreased relatively quickly in 2014, while it remained at high concentration levels before decreasinglowering down in 2015 and 2016. –Thus, severe haze had the tendency of becoming more persistent during the period of 2014-2016.

7, The text is readable and understandable, but some word choices are not quite appropriate and the text would benefit from editing for English. Please see technical comments below.

Specific and technical comments:

l.13: 'conductive' → 'conducive' (see also l.230)

Reply:

The error has been corrected.

Revisions:

In "Abstract"

examined the impacts of the AANA. The results indicated that local meteorological conditions were conductive to severe haze

In "Results"

northwesterly wind (Figure 10k). The anomalous northerly wind was conductive to the dissipation of pollutants. One day after

l.22: this sentence implies that increased moisture is responsible for weakening turbulence – is this the intended meaning?

Reply:

This insufficient conclusion has been eliminated and this part has been reworded.

Revisions:

In "Abstract"

……The thermally indirect zonal circulation between the BTH region and western Pacific triggered by the AANA provided a persistent source of moisture to the BTH region, which strengthened the development of severe haze by promoting the growth of fine particles.

l.22: suggest 'were' → 'often'

Reply:

Some revisions were made.

Revisions:

In “Abstract”

……The advance and retreat of the AANA often corresponded with the emergence and dissipation of severe haze, illustrating that the AANA could be an effective forecast indicator for air quality.

l.29: ‘the characteristics of’ could be removed; also, the meaning of ‘wide range’ here is not clear – large spatial extent?

Reply:

Some revisions were made.

Revisions:

In “Introduction”

……In recent years, the Beijing–Tianjin–Hebei (BTH, located at 36°-42°N, 114°-120°E) region has witnessed several severe haze events with long duration, large spatial extent and serious pollution levels.

l.33: suggest ‘for’ → ‘via’

Reply:

Some revisions were made.

Revisions:

In “Introduction”

……mainly via the reduction in SO_2 and NO_2 concentrations.

l.35: ‘increasing frequency’ – does this statement still hold true after the winter of 2017-2018?

Reply:

This part has been reworded in a more accurate way.

Revisions:

In “Introduction”

……However, the decline in $PM_{2.5}$ concentration was not obvious, and the occurrence of severe haze events in the BTH region showed strong inter-annual variations, especially in the winter (Chen and Wang, 2015; Yin and Wang, 2018).

l.43: ‘effect’ → ‘effects’

Reply:

The error has been corrected.

Revisions:

In “Introduction”

The basic ~~reason~~cause of haze pollution is excessive emission (Wang et al., 2013; Zhang et al., 2013). The synergistic effects

l.57: ‘the weaker’ → ‘a weaker’

Reply:

The error has been corrected.

Revisions:

In “Introduction”

could be strengthened by ~~the~~a weaker East Asian winter monsoon (EAWM) and the positive phase of the East Atlantic-West

l.59: ‘the’ not needed before ‘anticyclonic anomalies’

Reply:

Some revisions were made.

Revisions:

In “Introduction”

Research on persistent and severe haze pollution in the BTH region has demonstrated that ~~the~~ anticyclonic anomalies in

l.74: ‘of’ → ‘from’

Reply:

The error has been corrected.

Revisions:

In “Data and method”

relative humidity (RH). Hourly $PM_{2.5}$ concentration data from~~of~~ 80 national air quality stations over the BTH region were

l.81: ‘created’ → ‘applied’?

Reply:

Some revisions were made.

Revisions:

In “Data and method”

……here we made up Thiessen polygons to……

l.100-101: ‘pollutions ... were’ → ‘pollution ... was’

Reply:

The error has been corrected.

Revisions:

In “Results”

were 55.4 μg · m^{-3}, 79.1 μg · m^{-3}, and 70.9 μg · m^{-3}, respectively. These results demonstrated that haze pollution~~s~~ in December was~~ere~~ serious and fluctuated strongly. The first and third quartiles of the series were 54.0 μg · m^{-3} and

l.113: ‘negative patterns’ – negative patterns in what variable?

Reply:

Some revisions were added.

Revisions:

In “Results”

……could be verified by the relatively weak geopotential height patterns over the Siberia and the Aleutian Islands at mid-levels……

l.118: ‘cold air stayed inactive’ – suggest something like ‘cold air intrusions were suppressed’

Reply:

The advice was adopted. Some revisions were added.

Revisions:

In “Results”

……Thus, cold air intrusions were suppressed, and their southward movement into the BTH region decreased (Chen and Wang, 2015; Yin and Wang, 2017b).

l.121: what are meions?

Reply:

“Meions” are the centers of the negative anomalies. We have rephrased the word to describe it more explicitly.

Revisions:

In “Results”

……with two negative centers located over the Siberian plain and Bering Strait……

l.121: 'in' → 'over'?

Reply:

The error has been corrected.

Revisions:

In "Results"

the SLP were obvious over the middle-high latitude area in the Eurasian continent, with two ~~meions~~ negative centers located overin the Siberian plain and Bering Strait, while the SLP anomaly in the Western Pacific was positive~~SLP in the Western~~

l.122: 'SLP in the Western Pacific was a positive anomaly' 'SLP anomaly in the Western Pacific was positive'

Reply:

Some revisions were made.

Revisions:

In "Results"

the SLP were obvious over the middle-high latitude area in the Eurasian continent, with two ~~meions~~ negative centers located overin the Siberian plain and Bering Strait, while the SLP anomaly in the Western Pacific was positive~~SLP in the Western~~

l.123: 'southeaster' → 'southeasterly winds' (see also l.152, l.241)

Reply:

Some revisions were made.

Revisions:

In "Results"

restricting the dispersion of pollutants. Moreover, the warm air brought by the –southeasterly wind strengthened the intensity

the Taihang-Yanshan mountains~~Taihang-Yanshan mountain~~, the anomalous southeasterly wind was ~~beneficial~~ encouraged to

southeasterly wind also generated temperature inversion through warm advection, which strengthened the stability of lower

l.126: 'activity' → 'incursions'?

Reply:

Some revisions were made.

Revisions:

In "Results"

Thus, the cold air incursionsactivity became more frequent, resulting in stronger surface winds and lower surface relative

l.135: 'mentioned' → 'aforementioned'

Reply:

Some revisions were made.

Revisions:

In "Results"

The aforementionedmentioned southeasterly wind, abundant moisture and strong temperature inversion that induced

l.136: what is the intended meaning of 'marked' here? maybe change to something like 'a key circulation pattern influencing severe haze in the BTH region'?

Reply:

The advice was adopted. Some revisions were made.

Revisions:

In "Results"

severe haze were all closely related to the AANA (Figure 4–5). Thus, we evaluated the AANA as a key circulation pattern influencing severe haze in the BTH regionthe marked influencing atmospheric circulation. Here, we defined three indexes:

l.145: 'from the horizontal direction' → 'in the horizontal dimension'

Reply:

The error has been corrected.

Revisions:

In "Results"

the $AANAI_{Z500}$ and $AANAI_{V850}$ only represented the intensity of the AANA in the horizontal dimensionfrom the horizontal

l.152: 'mountain' → 'mountains'

Reply:

This part has been reworded.

Revisions:

In "Results"

……Considering that the BTH region is located in the southeast of the Taihang-Yanshan mountains, wind anomalies could restrict the dispersion of pollutants.

……The AANA could generate southeasterly winds near the surface (Figure 3a), which was encouraged to the accumulation of pollutants and water vapor.

l.154: 'from the Western Pacific to the BTH region via Bohai Bay' might help to make the connection clearer for readers less familiar with the local geography

Reply:

The advice was adopted. Some revisions were made.

Revisions:

In "Results"

a steady supply of haze particles while bringing moisture from the Western Pacific to the BTH region via Bohai Bayfrom the

l.182: remove 'Actually' – would also be helpful here to make the connection between warm advection and humidity more explicit in the text, since the reference is to dry air intrusions rather than cold air intrusions

Reply:

The advice was adopted. Some revisions were made.

Revisions:

In "Results"

Actually, TThe strong warm advection mentioned above

l.199: I am not sure 'upper troposphere' is the appropriate term to use here – perhaps 'free troposphere' or just 'higher levels' would work better? (see also l.244)

Reply:

This part has been reworded.

Revisions:

In "Results"

……The descending motion from upper levels was restrained due to the anomalous ascending flow, even though sinking motions still prevailed over the BTH region (Figure 9a).

l.207-208: this sentence ('ascending motion in the lower level declined') appears to conflict with the conclusions in the previous paragraph ('the AANA generated ascending motion in its rear' and following sentences), as well as figure

8 which appears to show anomalous ascent extending basically all the way down to the surface – I think the intended meaning may be that the anomalous ascent is weak close to the surface relative to the anomalies in the lower and middle troposphere, but this is not communicated by the current text.

Reply:

The advice was adopted. Some revisions were made to describe it more explicitly.

Revisions:

In "Results"

……Higher RH near the surface also restrained evaporation, which restricted the development of turbulence (Betts, 1997). Consequently, the anomalous ascent was weak near the surface relative to the anomalies in the lower and middle troposphere.

l.219: suggest replacing 'forward motion' with 'eastward propagation'

Reply:

The advice was adopted. Some revisions were made.

Revisions:

In "Results"

……The eastward propagation of positive anomalies over Lake Baikal was a precursory signal of severe haze.

l.255-256: correlations with visibility are included in several tables, but not really discussed in the text – what in this work supports the contention here that PM2.5 concentrations better represent the characteristics of haze episodes than visibility? Should remove or elaborate on this point

Reply:

Haze is not only a weather phenomenon, but also a type of serious air pollution that is detrimental to people's health (Hu et al., 2015; Wang et al., 2016). It is well acknowledged that the fine particulate matter (PM) is the main cause of severe haze (Wang et al., 2016; Cai et al., 2017). Thus, the $PM_{2.5}$ concentration could represent the characteristics of haze pollution better, comparing with visibility used in previous researches (Chen and Wang, 2015; Yin et al., 2015a; Yin et al., 2015b). The visibility data were included to draw a comparison with previous researches. Some revisions were made to make this point more explicitly.

Revisions:

In “Conclusions and discussions”

……It is well acknowledged that the fine PM is the main cause of severe haze in China (Wang et al., 2016; Cai et al., 2017). Compared with visibility used in previous researches (Chen and Wang, 2015; Yin et al., 2015a; Yin et al., 2015b), the $PM_{2.5}$ concentration could represent the characteristics of haze pollution better. Thus, the severe and non-haze events analyzed in this research were sorted out according to $PM_{2.5}$ concentration, while the visibility data were included to draw a comparison with previous researches. The basic results that stronger AANA, corresponding to a weaker EAWM, could lead to severe haze by generating weaker surface winds, a stronger temperature inversion and higher RH were in agreement with previous findings (Yin et al., 2015a; Yin and Wang, 2017b). Strong correlations between AANA indexes and visibility also existed (Table 3 and table 5).

l.256: here it might be worth reiterating the connection between EAWM and AANA, since the latter is the focus of this work (e.g., something like ‘...stronger AANA, corresponding to a weaker EAWM...’)

Reply:

The advice was adopted. Some revisions were made.

Revisions:

In “Conclusions and discussions”

sorted out according to $PM_{2.5}$ concentration. The basic results that stronger AANA, corresponding to a weaker EAWM, could lead to severe haze by generating weaker surface winds, a stronger temperature inversion and higher ~~relative humidity~~RH were

l.264-269: any speculations on why the statistical relationships were confined to the lower tropospheric components of the AANA in 2015? ENSO influence on the mid-tropospheric circulation perhaps?

Reply:

The advice was adopted. Some revisions were added.

Revisions:

In “Conclusions and discussions”

……However, the SPCC between the PM2.5 concentration and the $AANAI_{Z500}$ was 0.53 in 2015, and it failed to pass the confidence test. It might be associated with the influence of ENSO on the mid-tropospheric circulation. Although the AANA was not evident in the mid-level, it still emerged in the lower troposphere and had an impact on severe haze.

l.282-283: here again the question: why were severe haze/non-haze events limited to December 2014–2016 here? acknowledging that the air quality measurement network is relatively recently deployed, are data unavailable for this region in other winter months, or for the most recent winter?

Reply:

The $PM_{2.5}$ concentration data in China are available only after 2014. The access to the $PM_{2.5}$ concentration data and the reanalysis data has time delays. Since our studies lasted for a relatively long time and the data were not updated in time, we only investigated the severe haze in December 2014, December 2015 and December 2016 in the original version. Now, the data in December 2017 have been updated, and we have further discussed the situation during this period, serving as an independent verification. However, the sample of December 2018 was not taken into consideration in this text due to the limitation of data access. Some revisions were added to clarify this point.

Revisions:

In "Introduction"

……Considering that the air quality measurement network in China is relatively recently developed, this study focused on severe haze pollution in the BTH region during the months of December in the years 2014-2016, and explicated the characteristics of the AANA and its relationship with severe haze, while making comparison with non-haze episodes. The situation in December 2017 were also discussed to verify the relationship revealed in this study.

In "Discussion"

……The situation in December 2017 backed up our conclusions. Even though the haze events were not as serious as those in previous years, the AANA could be detected at the mid-level when severe haze occurred (Figure 11a). BTH region was occupied by anomalous southerly winds near the surface and anomalous ascending motions in upper levels. The strong cyclonic circulation over Northeast Asia might explain why the haze pollution was less severe in December 2017 (Figure 11b).

Table 2: even with n = 38, the correlation with PBLH does not reach the critical threshold for 99% confidence (0.41) – are sample sizes being counted differently?

Reply:

The SPM data included three types of events for haze: severe haze, non-haze and non-severe haze. After applying the aforementioned criteria to define the haze pollution processes, the total sample size was **50**. In December 2014, December 2015 and December 2016, there were 14 severe haze events, 12 non-haze events and 24 non-severe haze events in total. The SPCC between the mean $PM_{2.5}$ concentration and ERA PBLH anomalies was -0.60, exceeding the 99% confidence level. Some revisions were added to make this point more clearly.

Revisions:

In “Table2”

Table 2. The SPCCs between the mean $PM_{2.5}$ concentration over the BTH region and key meteorological indexes. All the SPCCs exceeded the 99% confidence level. The visibility, surface wind speed and surface relative humidity (RH) were based on the observation data and calculated as the mean over the BTH region. The temperature inversion potential (TIP, defined as T_{850}-T_{1000}) anomalies were calculated as the mean over the BTH region and with respect to the 1979-2010 climatology. The planetary boundary layer height (PBLH) anomalies were calculated as the mean over the BTH region and with respect to the 1979-2010 climatology. **The synoptic process correlation coefficients (SPCCs) were calculated basing on the SPM data, which were rebuilt by averaging the mean $PM_{2.5}$ concentration, all the meteorological data and the AANA indexes during each severe haze (14), non-haze (12) and non-severe haze (24) process. The sample size was 50.**

Index	AANA I_{Z500}	AANA I_{V850}	AANA$I_{\omega 500}$	Visibility	Surface wind speed	Surface RH	TIP anomalies	ERA PBLH anomalies
SPCC	0.64	-0.64	-0.70	-0.83	-0.42	0.72	0.56	-0.60

Table 3: should clarify the definition of synoptic processes for AANA

Reply:

The advice was adopted. Some revisions were added.

Revisions:

In "Table 3"

Table 3. The SPCCs between AANAI_{Z500} (AANAI_{V850}, AANA$I_{\omega 500}$) and regional meteorological indexes. "*" represents that the SPCC exceeded the 95% confidence level, and "**" represents that the SPCC exceeded the 99% confidence level. **The synoptic process correlation coefficients (SPCCs) were calculated basing on the SPM data, which were rebuilt by averaging all the meteorological data and the AANA indexes during each severe haze (14), non-haze (12) and non-severe haze (24) process. The sample size was 50.**

Tables 4-5: confidence levels again appear to be overstated here, particularly for PBLH, again raising the question of how the number of degrees of freedom in these tests is specified

Reply:

The SPM data included three types of events for haze: severe haze, non-haze and non-severe haze. The samples in December 2017 were also included to verify the relationship revealed in this study. The sample sizes in December 2014, December 2015, December 2016 and December 2017 were 18, 14, 18 and 15, respectively. The SPCC between the mean $PM_{2.5}$ concentration and ERA PBLH anomalies in December 2014, December 2015, December 2016 and December 2017 were -0.65, -0.63, -0.63 and -0.73, respectively, all exceeding the 95% confidence level (Table R1). The strong correlations between the mean $PM_{2.5}$ concentration and FNL PBLH in different years also supported out results. Some revisions were added to make this point more clearly.

Revisions:

In “Table 4”

Table 4. The SPCCs between the mean $PM_{2.5}$ concentration over the BTH region and key indexes in December 2014, December 2015, December 2016 and December 2017. “*” represents that the SPCC exceeded the 95% confidence level, and “**” represents that the SPCC exceeded the 99% confidence level. The synoptic process correlation coefficients (SPCCs) were calculated basing on the SPM data, which were rebuilt by averaging the mean $PM_{2.5}$ concentration, all the meteorological data and the AANA indexes during each severe haze, non-haze and non-severe haze process. **The sample sizes in 2014, 2015, 2016 and 2017 were 18, 14, 18 and 15, respectively.** Note that the PBLH from the FNL data is available only after 2015.

In “Table 5”

Table 5. The SPCCs between $AANAI_{Z500}$ ($AANAI_{V850}$, $AANAI_{\omega500}$) and regional meteorological indexes in December 2014, December 2015, December 2016 and December 2017. “*” represents that the SPCC exceeded the 95% confidence level, and “**” represents that the SPCC exceeded the 99% confidence level. The synoptic process correlation coefficients (SPCCs) were calculated basing on the SPM data, which were rebuilt by averaging all the meteorological data and the AANA indexes during each severe haze, non-haze and non-severe haze process. **The sample sizes in 2014, 2015, 2016 and 2017 were 18, 14, 18 and 15, respectively.** Note that the PBLH from the FNL data is available only after 2015.

Fig 2: it is basically impossible to make out the contours for surface air temperature anomalies in (b) and (d) – suggest moving them to fig 3 or removing them entirely.

Reply:

The figure has been plotted in a more clearly way. This could help to make out the situation in the BTH region. Some revisions were made.

Revisions:

In “Figure 2”

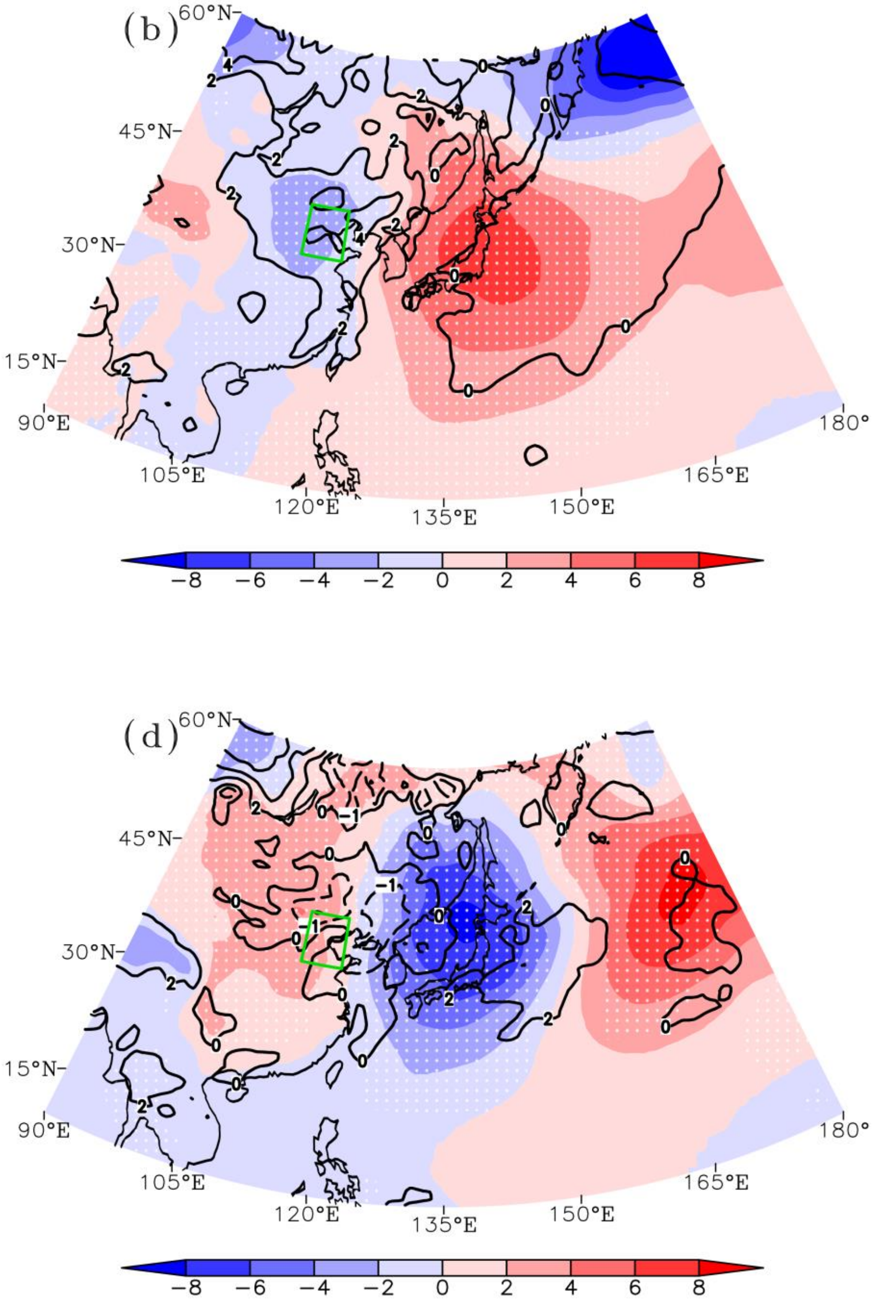


Figure 2. Composite distribution of the atmospheric circulation anomalies on severe haze/non-haze episodes. The anomalies here are calculated with respect to the 1979-2010 climatology. The green (white) box indicates the BTH region (area covered by $AANAI_{Z500}$). (b) SLP (shading, units: hPa) and SAT (contour, units: K) on severe haze episodes; the white dots indicate that the SLP anomalies exceeded the 95% confidence level. (d) SLP (shading, units: hPa) and SAT (contour, units: K) on non-haze episodes; the white dots indicate that the SLP anomalies exceeded the 95% confidence level.

Fig 8: the PBLH anomalies are potentially misleading when plotted like this against the deeper circulation anomalies, especially without more information regarding the typical location of the PBLH. could the anomalies over BTH specifically perhaps be moved to figure 7 (maybe using a linear scale in pressure rather than log-p to increase the vertical space near the surface), marking mean positions for the PBLH during haze / non-haze episodes as red / blue horizontal lines? this would also help to put the thermal advection in the context of the boundary layer depth, which may help in explaining the TIP changes relative to vertical motion changes.

Reply:

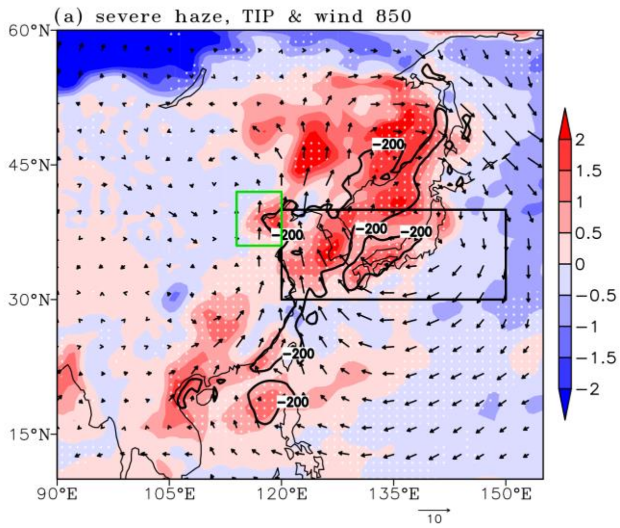
1. The PBLH climatology is relatively low in the winter, and the mean state of PBLH in December over the BTH region is 430.7m according to the ERA-interim data. It is almost impossible to plot the mean positions for the PBLH during severe haze (266.7m) and non-haze (813.7m) episodes in the vertical profile even using a linear scale in pressure. Now, the PBLH anomaly was plotted in the Figure 3(a) and (c) with bold black contours, and the PBLH anomaly over the BTH region was lower than -200m. Some revisions were made to further explain this point.
2. According to the Richardson number formulation, the boundary layer depth depends not only on the atmospheric stratification, but also on the momentum exchange between upper levels and lower levels. The impact of vertical motion changes on PBLH was also important, which was associated with the inhibited downward momentum. This part has been clarified in the text. Note that the stable layer mainly generated by the warm advection could extend to 850 hPa during severe haze events (Figure 7a). The height of stable layer was far over the boundary layer height. It might be inappropriate if we only discussed the relationship between thermal advection and boundary layer depth.

Revisions:

In "Results"

……Weaker turbulence could be verified by a shallower planetary boundary layer (Figure 3a). The PBLH over the BTH region was only 266.7m during severe haze episodes (the mean state of PBLH in December is 430.7m according to the ERA-interim data). This reduced the atmosphere's capacity for pollution aerosols and had adverse effects on the dispersion of pollutants. The SPCC between the PBLH anomalies and the $PM_{2.5}$ concentration was -0.60, passing the 99% confidence level (Table 2). It is worth noting that the emergence of inversion layer in the BTH region resulted in a more stable atmosphere, and thus the aforementioned anomalous ascending flow could not connect with the air that lying beneath the stable layer (Corfidi et al. 2008). However, the anomalous vertical flow still provided favorable synoptic-scale environments by confining the clean air intrusion and the downward momentum from upper levels. Once anomalous ascending flows weakened and descending motions prevailed over the BTH region, the sink of clean air from upper levels tended to break the inversion layer (Figure 7c). This effect could also strengthen the downward momentum and northerly winds near the surface. Subsequently, the BTH region was mainly controlled by the cold advection (Figure 7c). These factors represented the dissipation process for haze pollution.

In "Figure 3"



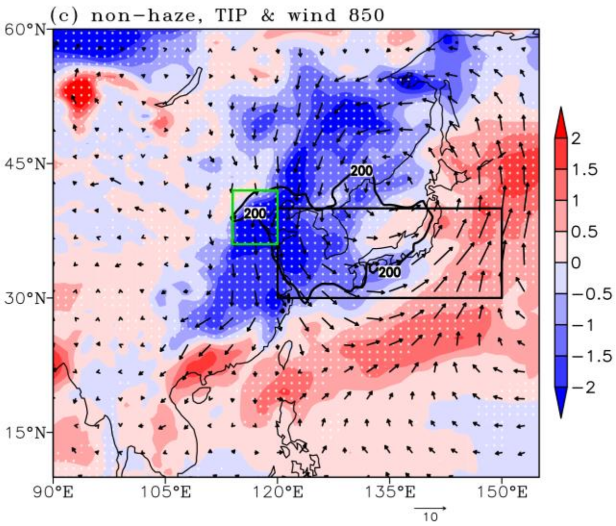


Figure 3. Composite distribution of local atmospheric circulation anomalies on severe haze/non-haze episodes. The anomalies here are calculated with respect to the 1979-2010 climatology. The green (black) box indicates the BTH region (area covered by AANAI$_{V850}$). (a) $\boldsymbol{V}_{850}$ (arrow, units: $\mathrm{m \cdot s^{-1}}$), PBLH (contour, units: m) and temperature inversion potential (T_{850}-T_{1000}, shading, units: K) on severe haze episodes; the bold black contours plotted represent the PBLH anomaly was lower than -200m; the white dots indicate that the temperature inversion potential anomalies exceeded the 95% confidence level. (c) $\boldsymbol{V}_{850}$ (arrow, units: $\mathrm{m \cdot s^{-1}}$), PBLH (contour, units: m) and temperature inversion potential (T_{850}-T_{1000}, shading, units: K) on non-haze episodes; the bold black contours plotted represent the PBLH anomaly was greater than 200m; the white dots indicate that the temperature inversion potential anomalies exceeded the 95% confidence level.

Title: recommend removing ‘the’ before ‘anticyclonic anomalies’

Reply:

Some revisions were made.

Revisions:

In “Title”

The Relationship between Anticyclonic Anomalies in Northeast Asia and Severe Haze in the Beijing-Tianjin-Hebei Region

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