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.

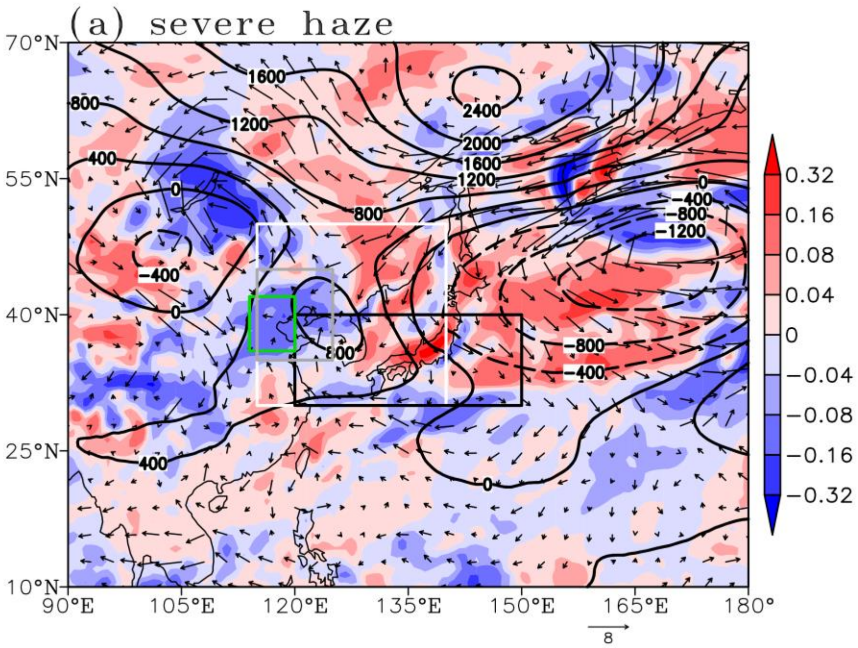
Reply:

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.



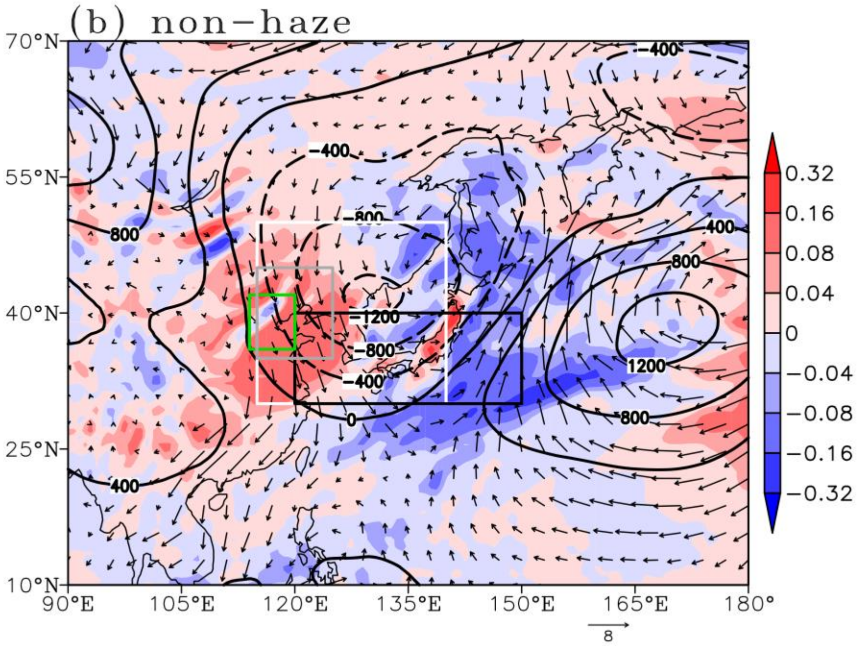


Figure 11. Structure of the AANA on (a) severe haze episodes and (b) non-haze episodes in December 2017: Z_{500} (contour, units: $m^2 \cdot s^{-2}$), $\boldsymbol{V}_{850}$ (arrow, units: $m \cdot s^{-1}$) and $\boldsymbol{\omega}_{500}$ (shading, units: $Pa \cdot s^{-1}$). The anomalies here were calculated 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	
	$AANAI_{\omega500}$	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^{**}
	$AANAI_{\omega500}$	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^{**}
	$AANAI_{\omega500}$	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
	$AANAI_{\omega500}$	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 $AANAI_{Z500}$ ($AANAI_{V850}$, $AANAI_{\omega 500}$) 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	
	$AANAI_{\omega500}$	0.27	
2015	$AANAI_{Z500}$	-0.46	-0.65*
	$AANAI_{V850}$	0.64*	0.72**
	$AANAI_{\omega500}$	0.28	0.46
2016	$AANAI_{Z500}$	-0.53*	-0.56*
	$AANAI_{V850}$	0.47	0.60**
	$AANAI_{\omega500}$	0.20	0.55*
2017	$AANAI_{Z500}$	-0.66**	-0.59*
	$AANAI_{V850}$	0.12	0.05
	$AANAI_{\omega500}$	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

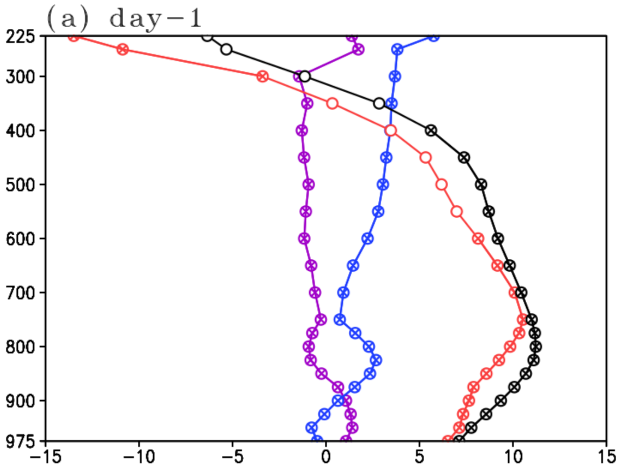
episodes and did not predominate in the changes of lower level temperature (Figure 7).

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.



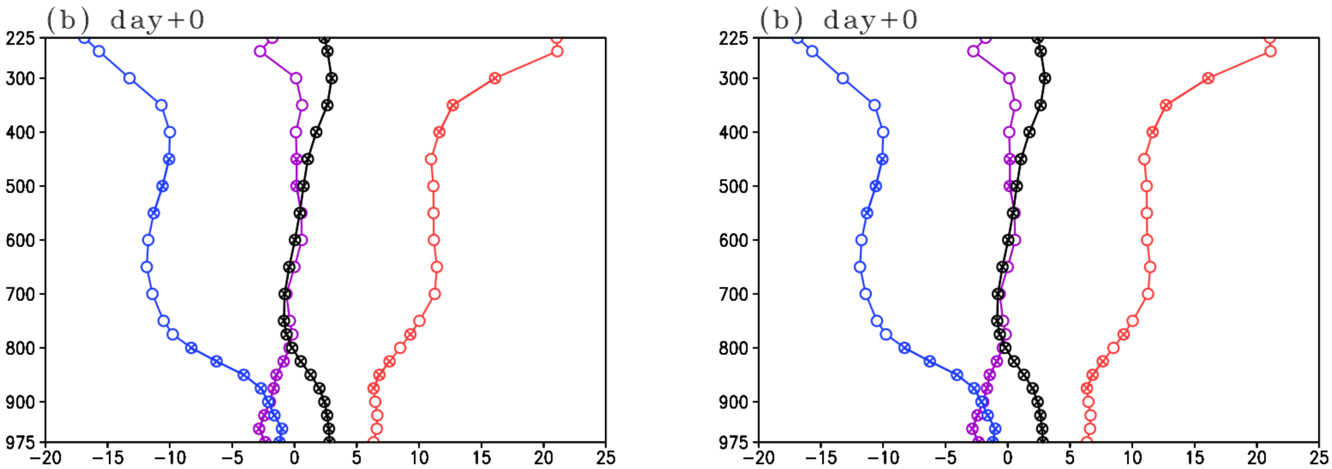


Figure 7. The differences of temperature changes (units: $10^{-5}\mathrm{K}\cdot\mathrm{s}^{-1}$) between severe haze and non-haze events over the BTH region. "Day+0" refers to the first day of severe haze and non-haze events. "Day-1" refers to one day before the first day of severe haze and non-haze 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 over~~in~~ 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 over~~in~~ 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 incursions~~activity~~ 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 aforementioned~~mentioned~~ 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 region~~the 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 dimension~~from 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"

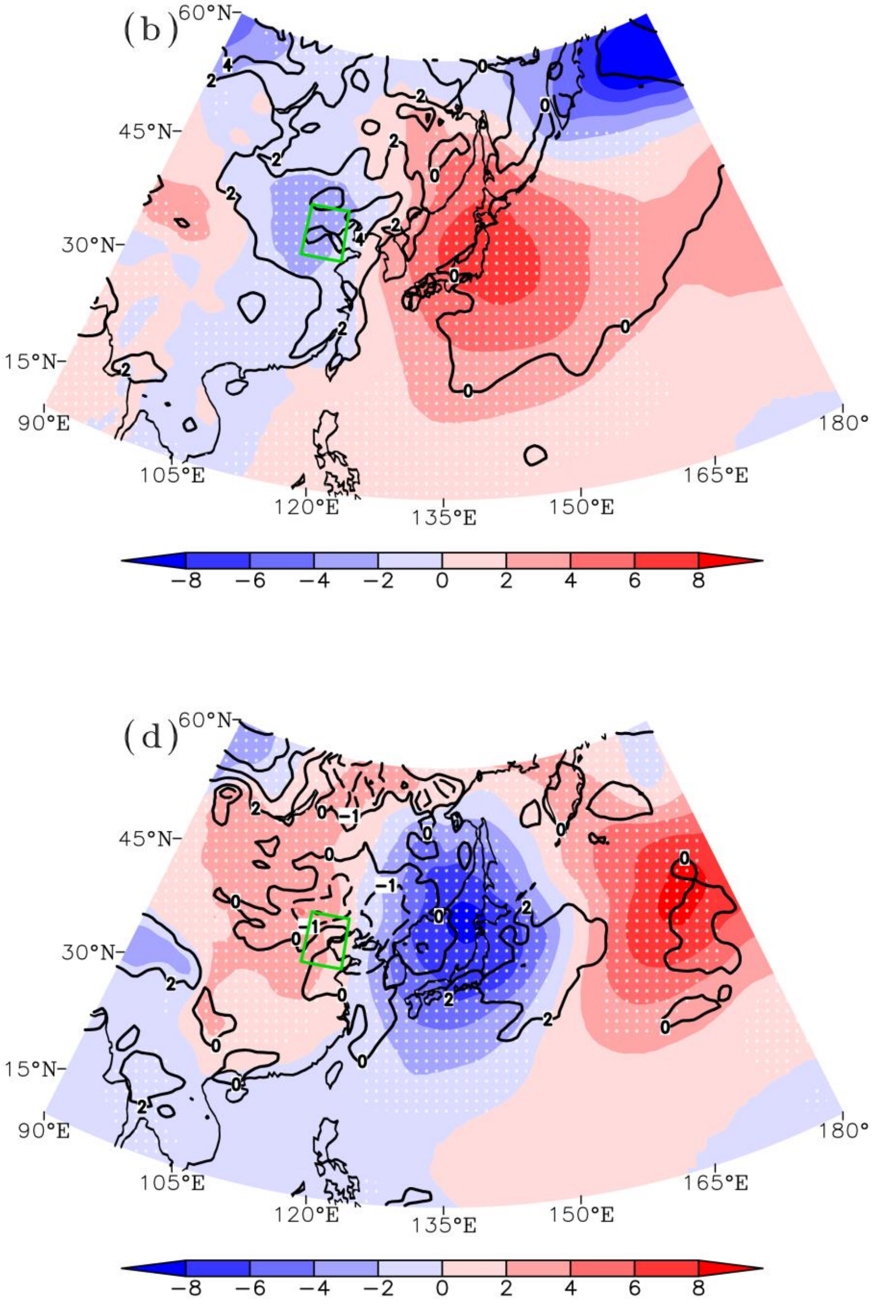


Figure 2. Composite distribution of the atmospheric circulation anomalies on severe haze/non-haze episodes. The anomalies here are calculated with respect to the 1979-2010 climatology. The green (white) box indicates the BTH region (area covered by $AANAI_{Z500}$). (b) SLP (shading, units: hPa) and SAT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

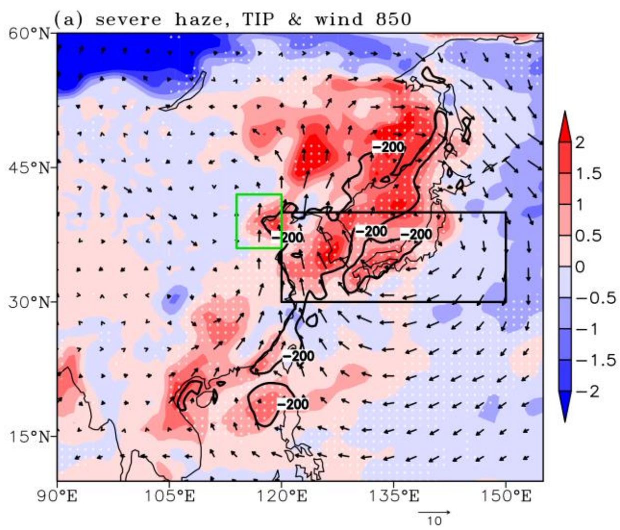
1. The PBLH climatology is relatively low in the winter, and the mean state of PBLH in December over the BTH region is 430.7m according to the ERA-interim data. It is almost impossible to plot the mean positions for the PBLH during severe haze (266.7m) and non-haze (813.7m) episodes in the vertical profile 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"



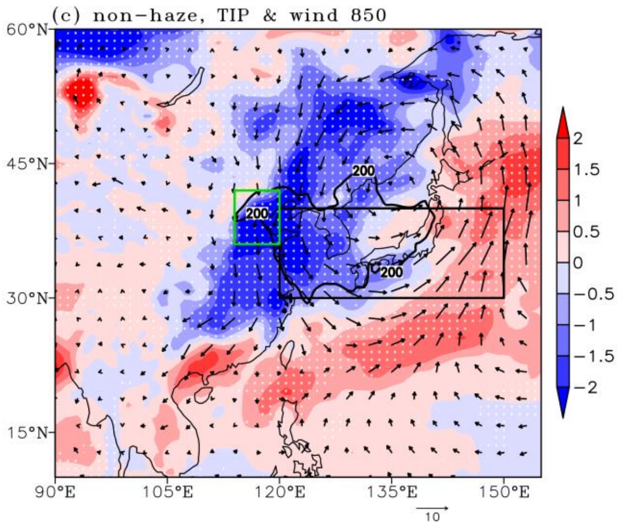


Figure 3. Composite distribution of local atmospheric circulation anomalies on severe haze/non-haze episodes. The anomalies here are calculated with respect to the 1979-2010 climatology. The green (black) box indicates the BTH region (area covered by AANAI$_{V850}$). (a) $\boldsymbol{V}_{850}$ (arrow, 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

References:

Corfidi, S. F., Corfidi, S. J., and Schultz, D. M.: Elevated Convection and Castellanus: Ambiguities, Significance, and Questions. *Wea. Forecasting*, **23**, 1280-1303, doi:10.1175/2008WAF2222118.1, 2008.

Hu, Y. L., Wang, S. G., Ning, G. C., et al.: A quantitative assessment of the air pollution purification effect of a super strong cold-air outbreak in January 2016 in China. *Air Qual. Atmos. Health.*, **11**, 907-923, doi:10.1007/s11869-018-0592-2, 2018.

Lackmann, G.: Midlatitude synoptic meteorology: dynamics, analysis, and forecasting, American Meteorological Society, Boston, America, 5-10, 2011.

Liu, X. E. and Guo, X. L.: Role of Downward Momentum Transport in the Formation of Severe Surface Winds, *Atmospheric and Oceanic Science Letters*, **5**, 379-383, doi:10.1080/16742834.2012.11447020, 2012.

Shen, L., Jacob, D. J., Mickley, L. J., et al.: Insignificant effect of climate change on winter haze pollution in Beijing, *Atmos. Chem. Phys.*, **18**, 17489-17496, doi:10.5194/acp-18-17489-2018, 2018..

Wallace, J. M. and Hobbs, P. V.: Atmospheric science: an introductory survey. 2nd ed., Elsevier Academic Press, Amsterdam, 283, 2006.

Reply letter to the anonymous referee #2

Major Comments As noted in my initial evaluation, this manuscript presents a potentially practical index, based on synoptic-scale data, to assess the likelihood and duration for marked haze/pollution events over parts of China (the Beijing-Tianjin-Hebei region). The presentation is generally good. The paper could, however, be improved by further attention to translation from Chinese into English. In addition, there are statements regarding the influence of anomalous anticyclonic conditions (as determined by the authors' index) on local circulations and the vertical transport of pollutants that I find confusing. The statements may, in part, simply reflect difficulties in translation. They might, however, also reflect some misunderstanding regarding the generally accepted roles that anticyclonic and cyclonic environments play in the regional accumulation of low-level pollution aerosols. Those parts of the text and figures that relate to these and a few other important issues have been highlighted using bold italics in the Specific Comments section below. The illustrations are, for the most part good, although Figure 2 could be improved by enlargement, and information (certain contours) appear to be missing in Figures 7 and 8.

Specific Comments (numbers refer to lines in the manuscript)

14. (Abstract) Replace "conductive" with "conducive," "lower" with "shallower," and add comma after "layer."

Reply:

The error has been corrected.

Revisions:

In "Abstract"

examined the impacts of the AANA. The results indicated that local meteorological conditions were conduc~~t~~ive to severe haze (such as weaker surface winds, a stronger temperature inversion, a shallower~~lower~~ boundary layer, and higher relative humidity)

17. (Abstract) Unclear what is meant by "the horizontal direction." Also, the sentence that begins, "The AANA induced anomalous..." is unclear. This statement is directly related to the "somewhat confusing statements" in the body of the manuscript mentioned in Major Comments (above).

Reply:

As a synoptic-scale circulation in the mid-latitude area, the AANA was associated with anomalous horizontal and vertical motions. The reflection of the AANA on the horizontal wind fields was an anticyclonic circulation. In the meanwhile, the AANA was a high-pressure system in the free troposphere. It often corresponded with anomalous vertical flows beneath its control areas, and could modulate vertical motion changes in the synoptic-scale environments. This part has been reworded in a more clearly way.

Revisions:

In "Abstract"

……During severe haze episodes, the AANA remained strong in the mid-upper troposphere, generating anomalous southeasterly winds near the surface. This effect not only promoted the accumulation of pollutants due to the unique topographical conditions in the BTH region, but also caused warm advection in lower levels, which was the main cause of the formation and development of temperature inversion layer. As a synoptic-scale circulation, the AANA was accompanied by anomalous vertical motions in the surrounding areas, which weakened the meridional circulation over the BTH region. The intrusions of the clean air from upper levels to the surface and the downward transportation of westerly momentum were suppressed, resulting in weaker northerly winds near the surface and a shallower boundary layer. 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.

19. (Abstract) Add "a" before "shallower."

20. (Abstract) Replace "stable" with "persistent."

Reply:

Some revisions were made.

Revisions:

In "Abstract"

~~transportation of westerly momentum was also restrained~~, resulting in weaker ~~surface~~ northerly winds near the surface and a shallower boundary layer. The thermally indirect zonal circulation between the BTH region and western Pacific triggered by the AANA provided a persistent~~stable~~ source of moisture to the BTH region, which strengthened the development of severe

21. (Abstract) How does abundant moisture weaken turbulence?

Reply:

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

Revisions:

In "Abstract"

haze by promoting the growth of fine particles ~~and weakening turbulence~~. The advance and retreat of the AANA ~~were~~often

28. It is not entirely clear what is meant by the word "haze." I suggest adding a short sentence to clarify the intended meaning (e.g., is the subject pollutant / restrictor of visual range here more akin to "smog," or is the term being used to refer to the presence of sulfate-containing aerosols that more commonly appear over eastern Asia and North America in summer; perhaps by "haze" you mean both phenomena).

Reply:

The advice was adopted. Some revisions were added.

Revisions:

In "Introduction"

……Haze is a weather phenomenon, which could restrict the visual range and increase the risk of traffic accidents; and haze is also a type of serious air pollution that is detrimental to people's health (Hu et al., 2015; Wang et al., 2016). Haze events in China are mainly caused by the fine particulate matter (PM), which contains primary pollutants and sulfate or nitrate aerosols (Wang et al., 2016; Cai et al., 2017; Shen et al., 2018).

29. Change "level" to "levels."

Reply:

The error has been corrected.

Revisions:

In "Introduction"

range and serious pollution levels, which are detrimental to people's life and health (Hu et al., 2015; Wang et al., 2016). Notably,

30. Change "have" to "has."

Reply:

The error has been corrected.

Revisions:

In "Introduction"

the number of haze days in the BTH region hasve increased, and the affected area has shown an interdecadal expanding trend

35. The assumption implied here is that the rate of occurrence continues to increase; if that is the case, replace "occurred" with "occur."

Reply:

This part has been reworded.

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).

39. Not certain of meaning of "...were detected within20 days..." Do you mean "lasted about 20 days"?

Reply:

The intended meaning was that within 20 days, two severe and persistent haze events occurred. One haze event lasted for 5 days, while the other lasted for 9 days. Relatively short breaks existed between these two severe haze events.

43. "Cause" might be a better word choice than "reason."

Reply:

Some revisions were made.

Revisions:

In "Introduction"

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

57. Suggest "a weaker" instead of "the weaker;" also, I suggest introducing

the acronym “EAWM” here instead of in line 62.

Reply:

The advice was adopted. Some revisions were made.

Revisions:

In “Introduction”

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

60. Eliminate “the” 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

62. Add “have” after “studies.”

Reply:

Some revisions were made.

Revisions:

In “Introduction”

studies have indicated that weak East Asian winter monsoon ~~(EAWM)~~ could modulate the AANA (Li et al. 2015; Yin et al.

69. Eliminate “the” after “study focused on.”

70. Add comma after “2014-2016.”

Reply:

Some revisions were made.

Revisions:

In “Introduction”

indexes (Wang and Jiang, 2004; He and Wang, 2012). Considering that the air quality measurement network in China is relatively recently developed, t~~T~~his study focused on ~~the~~ severe haze in the BTH region during the months of December in the years 2014-2016~~the period of December 2014-2016~~, and explicated the characteristics of the AANA and its relationship with

73. Is there a reason why only December (vs. other winter month) data were used? Should state why only December data were used, and consider using data

from other winter months to enlarge dataset.

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.

4. 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.
5. 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.
6. 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.

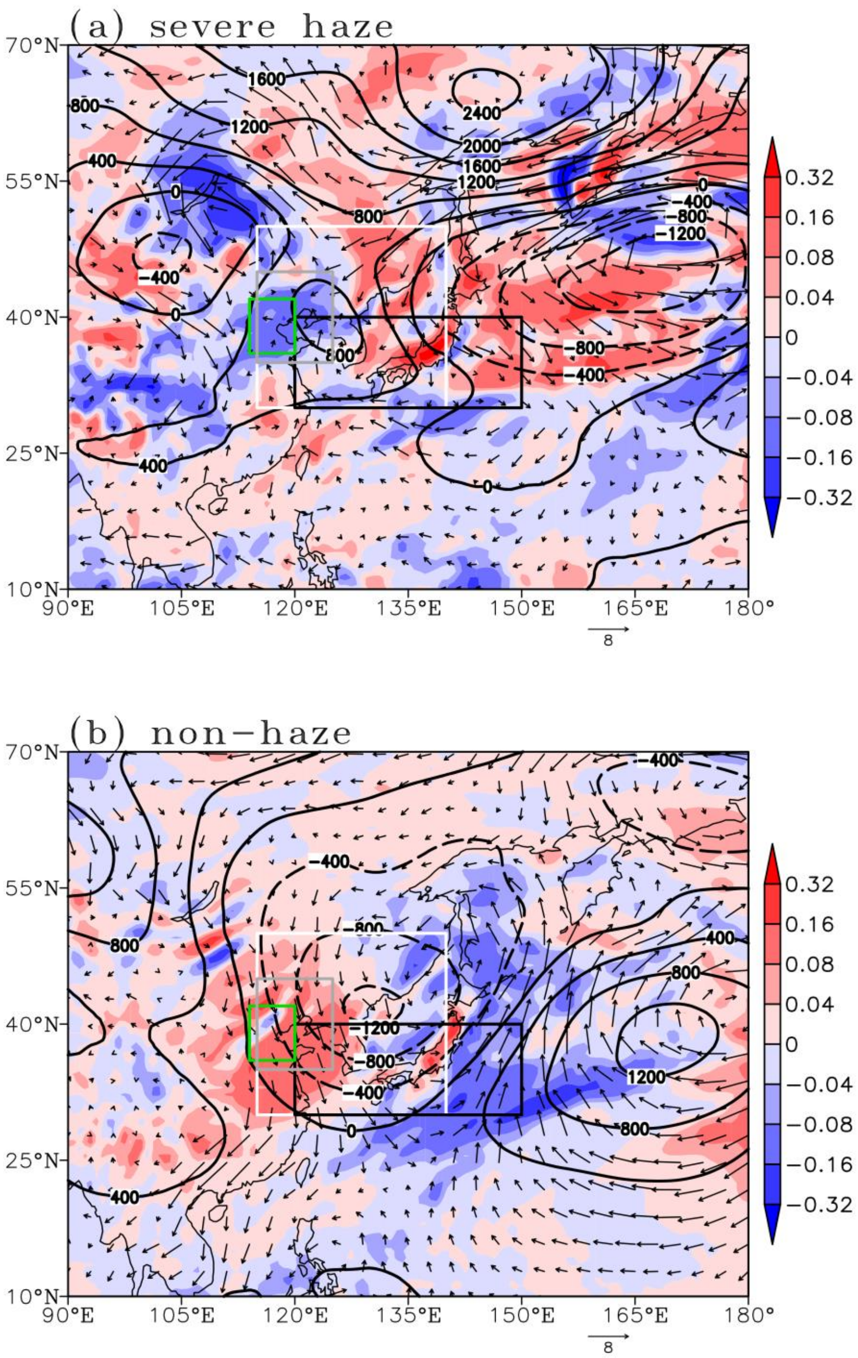


Figure 11. Structure of the AANA on (a) severe haze episodes and (b) non-haze episodes in December 2017: Z_{500} (contour, units: $m^2 \cdot s^{-2}$), $\boldsymbol{V}_{850}$ (arrow, units: $\mathrm{m} \cdot \mathrm{s}^{-1}$) and $\boldsymbol{\omega}_{500}$ (shading, units: $\mathrm{Pa} \cdot \mathrm{s}^{-1}$). 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 $AANAI_{\omega 500}$, 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).

77. Not certain what is meant by "vertical wind" here; if I am correct, I think you mean vertical motion (i.e., as is indicated in the parentheses, omega)?

Reply:

Some revisions were made to describe this point more explicitly.

Revisions:

In "Data and method"

sea level pressure (SLP), U and V components of wind at 200 hPa, 850 hPa and the surface, vertical velocity~~vertical wind~~

84. Add an "s" to "polygon" and eliminate "the" after "built."

Reply:

The error has been corrected.

Revisions:

In “Data and method”

~~created~~made up Thiessen polygons to calculate the weighted average of $PM_{2.5}$ concentration and built ~~the~~ time series at

88. Not certain of the meaning of “haze progresses.”

Reply:

The error has been corrected.

Revisions:

……Most previous studies investigated haze events in units of hours or days and the variations among haze pollution processes were not taken into account.

89. Change “remained” to “remain.”

Reply:

The error has been corrected.

Revisions:

In “Data and method”

pollution in a few cases but remain~~ed~~ insignificant in others. In this way, the relationship between haze pollution and

90-91. Replace “synoptic processes” with “synoptic-scale environments.” Also in line 91, could the second use of the word “process” be better if replaced by “events”?

92 and 94. Ditto comment for lines 90-91 regarding use of the word “process.”

Reply:

The haze pollution processes are the synoptic processes defined for haze events. In other words, each haze pollution process in this text was sorted out according to the $PM_{2.5}$ concentration data that describing the pollution levels of haze events. This part has been reworded.

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.

101. Change "pollutions" to "pollution events."

Reply:

Some revisions were made.

Revisions:

In "Results"

were 55.4 $\mu g \cdot m^{-3}$, 79.1 $\mu g \cdot m^{-3}$, and 70.9 $\mu g \cdot m^{-3}$, respectively. These results demonstrated that haze pollutions in December wasere serious and fluctuated strongly. The first and third quartiles of the series were 54.0 $\mu g \cdot m^{-3}$ and

107. "Quickly" relative to what? Assuming that it is (was) relative to the observed behavior in 2015 and 2016, add the word "relatively" before "quickly." Also, consider replacing "lowering down" with "decreasing."

Reply:

Some revisions were made to describe this point more explicitly.

Revisions:

In "Results"

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.~~

114. Suggest replacing "the negative patterns of the" with "a relatively weak."

Reply:

Some revisions were made.

Revisions:

In "Results"

from the upper to the lower troposphere, which could be verified by the ~~negative~~relatively weak geopotential height patterns

115. Eliminate "the" before "mid-level" and add an "s" to "mid-level."

Reply:

The error has been corrected.

Revisions:

In "Results"

over the Siberia and the Aleutian Islands at ~~the~~ mid-levels (Figure 2a), the decline in northerly winds near the surface (Figure

119. Replace "the cold air stayed inactive," etc., with "cold air intrusions were suppressed, and their southward movement into the BTH region decreased."

Reply:

Some revisions were made.

Revisions:

In "Results"

weakened and that the BTH region was mainly occupied by zonal circulation. Thus, cold air intrusions were suppressed, and their southward movement into the BTH region decreased~~the cold air stayed inactive, and its frequency of moving southward and entering into the BTH region decreased~~ (Chen and Wang, 2015; Yin and Wang, 2017b). The decline in prevailing northerly

121. Suggest replacing "wind" with "flow."

Reply:

Some revisions were made.

Revisions:

In "Results"

~~wind~~flow near the surface was strengthened by the reduction in the land-sea pressure differences. The negative anomalies of

122. What is a "meion"? Replace "in" with "over."

Reply:

"Meions" are the centers of the negative anomalies. We have rephrased the word to describe this point more explicitly.

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 positiveSLP in the Western

123. Change middle part of line to read “...SLP over the western Pacific anomalously high” (or to something similar).

Reply:

Some revisions were made.

Revisions:

In “Results”

……while the SLP anomaly in the Western Pacific was positive (Figure 2b).

124. The mechanism by which increased southeasterly component to the low-level flow restricted the dispersion of pollutants is not immediately apparent; please briefly explain.

Reply:

Considering that the BTH region is located in the southeast of the Taihang-Yanshan mountains, southeasterly winds could restrict the dispersion of pollutants. Some revisions were made to describe this point more explicitly.

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.

125. Add “the” after “brought by.”

Reply:

Some revisions were made.

Revisions:

In “Results”

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

127. Change "made the cold air activity" to "made cold-air invasions more frequent."

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

130. Change "activity" to "invasions."

Reply:

Some revisions were made.

Revisions:

In "Results"

general, the weakening of the EAWM restricted the cold air invasions activity and had an impact on local weather conditions,

135. Change "mentioned" to "aforementioned."

Reply:

Some revisions were made.

Revisions:

In "Results"

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

137. I think what you mean to say here is that "...we evaluated the influence of AANA on the regional atmospheric environment."

Reply:

Some revisions were made to describe this point more explicitly.

Revisions:

In "Results"

……Thus, we evaluated the AANA as a key circulation pattern influencing severe haze in the BTH region.

138. Add "in" before "the white box."

139. Add "in" before "the black box."

140. Add "in" before "the white box."

Reply:

Some revisions were made.

Revisions:

In "Results"

AANAI$_{Z500}$ (defined as Z_{500} anomalies over 115-140°E, 30-50°N, i.e., in the white box in Figure 2a), AANAI$_{V850}$ (defined as wind speed anomalies at 850 hPa over 120-150°E, 30-40°N, i.e., in the black box in Figure 3a) and AANAI$_{\omega500}$ (defined as ω_{500} anomalies over 115-125°E, 35-45°N, i.e., in the white box in Figure 6a) to describe the intensity of the AANA in the mid

142. Add a comma before "since."

Reply:

Some revisions were made.

Revisions:

In "Results"

2004; He and Wang, 2012), since the AANA was an important manifestation of the weaker EAWM (Figure 2a). However, here

143. Change "the anomaly field" to "anomaly fields."

144. Add an "s" to "circulation."

Reply:

The error has been corrected.

Revisions:

In "Results"

we defined these indexes through ~~the~~ anomaly fields to analyze anomalous atmospheric circulations, differing from the EAWM

147. Change "from the horizontal direction" to "at two pressure levels."

Reply:

Some revisions were made.

Revisions:

In "Results"

……Considering that the AANAI$_{Z500}$ and AANAI$_{V850}$ only represented the intensity of the AANA in the horizontal dimension, we further introduced AANAI$_{\omega500}$ to investigate the vertical structure of the AANA.

151. Add an “s” to “mid-level.” Also change “From the horizontal direction, etc....” to “At the surface, the AANA could generate weak southerly winds (Figure 3a).”

153. Change “Taihang-Yanshan mountain” to “the Taihang-Yanshan mountains.” Also change “beneficial to” to “encouraged.”

Reply:

This part has been reworded.

Revisions:

In “Results”

……When severe haze took place, the AANA could be identified from the lower to the upper levels, especially at mid-troposphere (Figure 6a). The AANA could generate southeasterly winds near the surface (Figure 3a), which was encouraged to the accumulation of pollutants and water vapor.

154. Add an “s” to “wind.”

Reply:

The error has been corrected.

Revisions:

In “Results”

to the accumulation of pollutants and water vapor. Southeasterly winds gathered pollutants from the surrounding area and

155. Consider indicating the location of Bohai Bay either in the text or in Figure 3 to clarify geographical references for readers.

Reply:

Some revisions were made.

Revisions:

In “Results”

……Southeasterly winds gathered pollutants from the surrounding areas and provided a steady supply of fine particles for haze pollution in the BTH region, while bringing moisture from the Western Pacific to the BTH region **via Bohai Bay**.

156. Change “aroused” to “induced.”

Reply:

Some revisions were made.

Revisions:

In “Results”

Bayfrom the Western Pacific to the Bohai Bay. With the weak convergence inducedaroused by the anomalous low surface

159. Add an “s” to “speed” and the word “a” before “drier environment.”

Reply:

The error has been corrected.

Revisions:

In “Results”

restrained the transport of water vapor (Figure 3d). Higher wind speeds and a drier atmosphere were conducive to the dispersion

161. Change “special” to “unique.” Change “topography condition” to “topographical conditions.”

162. Change “wind” to “flow.”

Reply:

Some revisions were made.

Revisions:

In “Results”

exceeding the 99% confidence level (Table 3). Thus, because of the specialunique topographical conditionstopography condition in the BTH region, the anomalous southeasterly windflow caused by the AANA facilitated the formation and

163. Add a comma after “particles.” Well-stated; the sentence (ending in “persistent and serious”) provides a good, succinct summary of the situation.

Reply:

This part has been reworded.

Revisions:

In “Results”

……Thus, because of the unique topographical conditions in the BTH region, the anomalous southeasterly flows caused by the AANA facilitated the formation and aggregation of haze particles. The emergence of temperature inversion layer enhanced the atmospheric stability, leading to more persistent and serious haze events.

165. Changed "verified" to "occurred" or "were focused over."

Reply:

Some revisions were made.

Revisions:

In "Results"

were ~~verified~~ focused over~~in~~ Northeast Asia and coastal regions of eastern China, while positive anomalies were mainly located

166-167. I think you mean to say, "...the mid-level reflection of AANA stimulates anomalous ascending motion..." I am not certain what is meant by "in the rear" and "in the front." In the rear or front of what? I think you mean "with respect to the AANA," but consider briefly clarifying the point of reference.

170. Change "at the back" to "to the rear."

Reply:

Some revisions were made to describe this point in a more clearly way.

Revisions:

In "Results"

……Thus, the mid-level reflection of AANA was accompanied by anomalous synoptic-scale ascending (descending) motions to the rear (front) of the AANA.

171-172. Change "appeared to have a conflict with" to "appear to contradict." Not sure what is meant by "the insufficient speculation;" please clarify. Eliminate "would" after "The following sections."

Reply:

Some revisions were made.

Revisions:

In "Results"

……Our results appeared to contradict with the insufficient speculation by Yin and Wang (2017b), which simply concluded the sinking motion generated by the AANA as the overall state. The following sections explain how the associated vertical circulation affected severe haze in the BTH region.

174. Not sure of the meaning of "range;" do you mean that it (the anomalous ascending motion) extended through the depth of the troposphere?

Reply:

Some revisions were made to describe this point in a more clearly way.

Revisions:

In "Results"

……The anomalous synoptic-scale ascending motion associated with the AANA extended through the depth of the troposphere (Figure 8).

175-176. I am not certain how wind anomalies "appeared as weak and narrow ascending motion...which broke the local circulation." This is one of the "confusing statements" mentioned in the Major Comments section that should be clarified prior to publication.

177. Not certain of the meaning of "was restrained at 500-800 hPa." "500-800" implies a fairly thick layer, not a single level. I also do not know what constitutes "confrontation" between updrafts and downdrafts. Consider rewording this sentence; also, change "the upper level" to "upper levels."

Reply:

Figure S1 showed the climatology of the meridional circulation over the BTH region. The warm air rises over the Equator, that subsequently flows poleward in upper levels and sinks in the subtropics. The BTH region is located beneath the downward branch of the meridional circulation. Acknowledging this point, when the anomalous synoptic-scale ascending motion associated with the AANA prevailed in the local area, the meridional circulation was greatly weakened. The anomalous ascending flow at mid-levels was relatively stronger than that in lower levels. This phenomenon led to weak ascending motions in the lower troposphere (i.e., 500-800 hPa), even though sinking motions still prevailed over the BTH region (Figure 9a). Some of the word choices in the origin version were inaccurate and this part has been reworded.

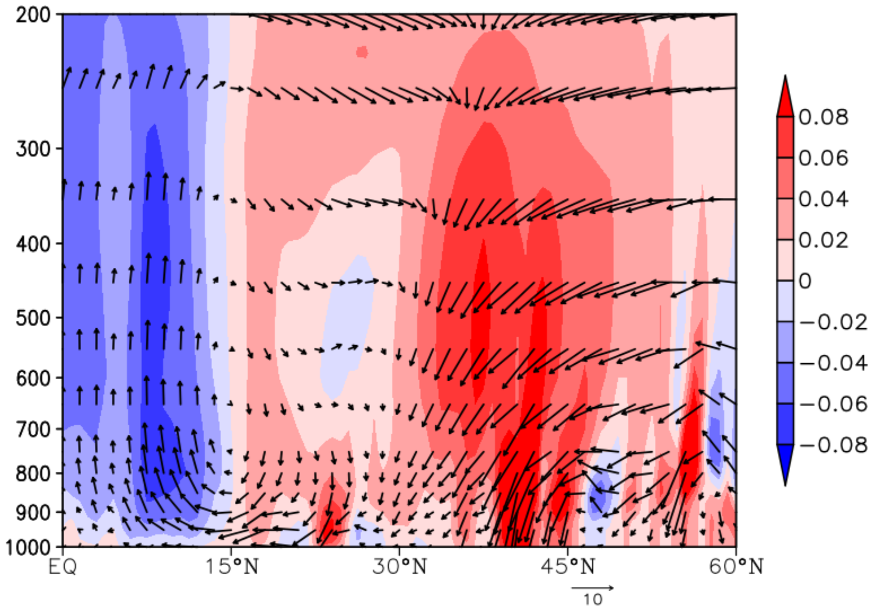


Figure S1. The 1979-2010 climatology of the local meridional circulation (114°-120°E mean). Omega, shading, units: $Pa \cdot s^{-1}$; wind, arrow, omega magnified 100 times, units: $m \cdot s^{-1}$. To make the horizontal velocity and the vertical velocity in the same order, the vertical velocity (omega) here is magnified 100 times.

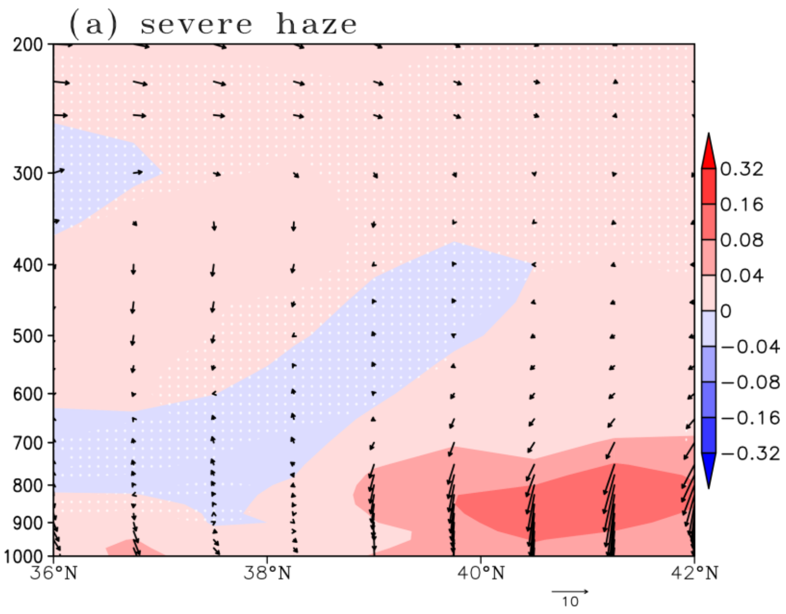


Figure 9. Vertical circulation on severe haze episodes (composite synoptic processes): (a) meridional circulation averaged over the BTH region (114°-120°E) on severe haze episodes (omega, shading, units: $Pa \cdot s^{-1}$; wind, arrow, omega magnified 100 times, units: $m \cdot s^{-1}$); the white dots indicate that omega exceeded the 95% confidence level. To make the horizontal velocity and the vertical velocity in the same order, the vertical velocity (omega) here is magnified 100 times.

Revisions:

In “Results”

……The anomalous synoptic-scale ascending motion associated with the AANA extended through the depth of the troposphere (Figure 8). Considering of the climate mean state over the BTH region (i.e., descending motion; Figure S1), the anomalous ascending flow weakened the vertical motion in the local area when severe haze occurred, and even generated weak ascending motions in the lower troposphere (i.e., 500-800 hPa; Figure 9a). 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). The strong warm advection mentioned above (Figure 7) represented the decline in the dry air intrusion (Sun et al., 2017). As a result, the invasion of cold and dry air from upper levels to the surface was relatively weak, which provided favorable conditions for the formation of severe haze (Sun et al., 2017; Hu et al., 2018).

179. I can understand how weakening of the downward transport of westerly flow from aloft can foster the build-up of pollutants near the surface, but I not see how the presence of anomalous ascending motion in the mid and upper levels necessarily “confined” downward westerly momentum transport. What likely physical processes were involved?

Reply:

The downward transportation of westerly momentum often corresponds with strong sinking motions, and it could bring about strong northerly winds near the surface over the BTH region. These effects are encouraged to the horizontal and vertical dispersion of the pollutants. During severe haze events, the emergence of anomalous ascending motions in the middle-upper atmosphere greatly weakened the normal meridional circulation. Thus, the sinking motion over the BTH region became weaker and the momentum exchange between the upper and lower atmosphere was greatly inhibited. Some revisions were made to describe this point in a more clearly way.

Revisions:

In "Results"

……The anomalous ascending motion in the middle troposphere not only weakened the normal sinking flow, but also confined the downward transportation of westerly momentum (i.e., $\frac{\partial u\omega}{\partial P}$>0, Figure 9b), which led to weaker northerly winds near the surface (Lu et al., 2010; Liu and Guo, 2012).

183-184. Perhaps I am not cognizant of the scale of the anomalous vertical motions being discussed here. But I do not understand how synoptic-scale vertical motions — anomalous or otherwise — can impact the vertical air motions such that they overpower vertical motions that predominantly occur in response to vertical density differentials (i.e., to the vertical stratification). It is well-known that regional inversions often arise as a result of persistent synoptic-scale subsidence, and that such inversions sometimes are associated with haze and pollution events. Ascending motions tend to destabilize stratified thermal environment, so it is a bit difficult to accept the notion given that the diagnosed ascending motions somehow "restrict" the descent of ("cold") air from higher levels of the atmosphere, thereby encouraging the build-up of pollutants. As the offered interpretation runs counter to that which is commonly understood — and because this part of the paper is central to the overall argument being made regarding the value of the AANA index — further discussion and clarification of the ideas presented in this paragraph are warranted.

Reply:

1. Sinking motions still prevailed over the BTH region (Figure 9a). The anomalous ascending motions did not overpower the vertical motions that predominantly occur in response to the vertical stratification.
2. 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 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).

3. The anomalous vertical flow provided favorable synoptic-scale environments for the development of severe haze by confining the clean air intrusion and the downward momentum from upper levels (Sun et al., 2017; Hu et al., 2018). Due to the anomalous ascending flow associated with the AANA, the sink of cold air from upper levels over the BTH region was greatly weakened (Figure 9a). The strong warm advection (Figure 7) represented the decline in the dry air intrusion (Sun et al., 2017). As a result, the invasion of cold and dry air from the upper atmosphere to the surface was relatively weak. Vertical motion changes also confined the downward transportation of westerly momentum, leading to weaker northerly winds near the surface (i.e., stronger warm advection; Figure 7). 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 of the word choices were inaccurate in the origin version and this part has been reworded in a more clearly way.

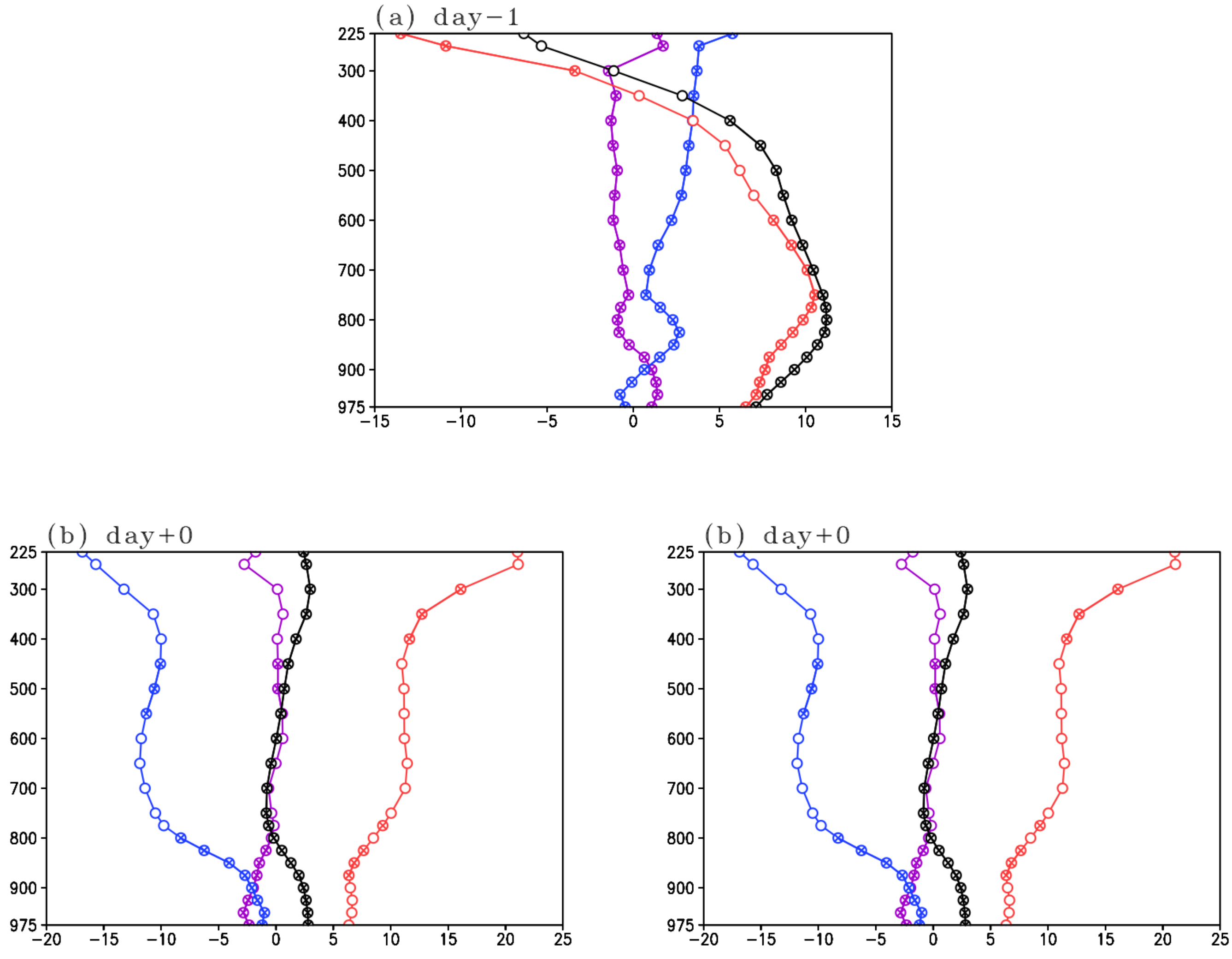


Figure 7. The differences of temperature changes (units: $10^{-5}\mathrm{K}\cdot\mathrm{s}^{-1}$) between severe haze and non-haze events over the BTH region. "Day+0" refers to the first day of severe haze and non-haze events. "Day-1" refers to one day before the first day of severe haze and non-haze 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.

188-189. Change "the atmospheric environment capacity" to "the atmosphere's capacity for pollution aerosols."

Reply:

This part has been reworded.

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.

195. What is the "normal vertical circulation" in the BTH region?

Reply:

The normal vertical circulation has been presented in Figure S1. Please see the preceding section.

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.

Reply:

I agree that the emergence of temperature inversion layer could discourage the air in lower levels from connecting with the air in upper levels. Your suggestions help us build a better understanding on the impacts of anomalous vertical motions. Some revisions were added to clarify this point. Still though, the role of anomalous ascending motions over the BTH region could not be neglected. The existence of anomalous ascending motions provided favorable synoptic-scale environments by confining the clean air intrusion and the downward momentum from upper levels. This part has been clarified in the preceding section.

Revisions:

In "Results"

……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.

……Moreover, the aforementioned temperature inversion layer could lead to weaker turbulence, which discouraged the ascending motion in lower levels from connecting with the air in upper levels.

204. Add an "s" to "levels."

205. Not sure "generated advection inversion" means. Is it that the relatively warm oceanic air moves inland atop the shallow, cool layer based at the surface?

206. Add the word "a" before "thermal inversion."

207. Add an "s" to updrafts.

Reply:

This part has been reworded.

Revisions:

In "Results"

……Consequently, the anomalous ascent was weak near the surface relative to the anomalies in the lower and middle troposphere. Weak updrafts near the surface could not make the pollutants disperse in the vertical direction (Sun et al., 2017; Yin and Wang, 2018). Moreover, the aforementioned temperature inversion layer could lead to weaker turbulence, which discouraged the ascending motion in lower levels from connecting with the air in upper levels.

209. It is not immediately apparent why the circulation is indirect; adding a few words to support this observation would be helpful (a similar comment could be made for direct circulation noted in line 200). Also, consider rewording sentence that begins "Drier atmosphere" as "The resulting drier atmosphere..."

Reply:

In the boreal winter, the local zonal circulation appears as ascending motions over the relatively warm sea and descending motions over the relatively cold land (Figure S2). This could be regarded as a thermally direct circulation. Some revisions were made to describe this point more explicitly.

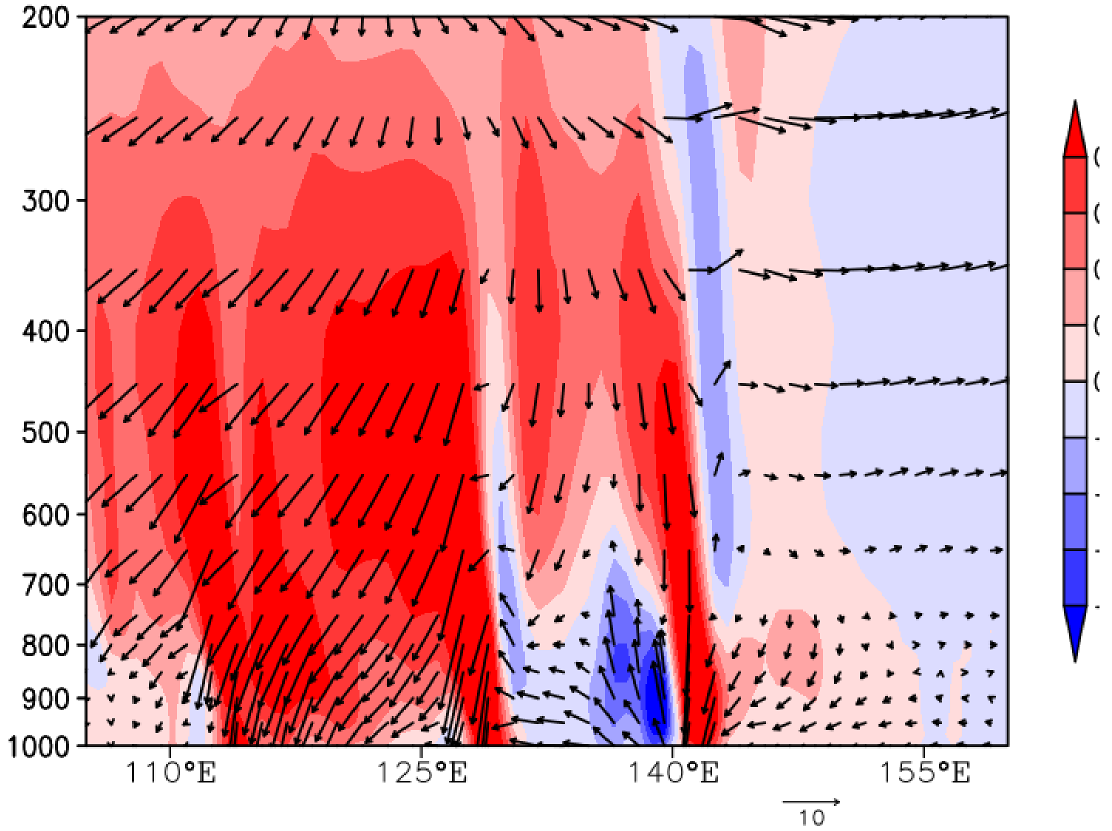


Figure S2. The 1979-2010 climatology of the local zonal circulation (36°-42°E mean). Omega, shading, units: $Pa \cdot s^{-1}$; wind, arrow, omega magnified 100 times, units: $m \cdot s^{-1}$. To make the horizontal velocity and the vertical velocity in the same order, the vertical velocity (omega) here is magnified 100 times.

Revisions:

In "Results"

……Note that the AANA modulated a thermally indirect zonal circulation between the BTH region and Western Pacific (i.e., ascending motions over the land and descending motions over the sea; the mean state over this region in the boreal winter is ascending motions over the relatively warm sea and descending motions over the relatively cold land, see Figure. S2), which acted as an important water vapor path (Figure 8b).

……During non-haze events, the thermally direct vertical circulation (i.e., ascending motions over the sea and descending motions over the land) could be verified beneath the control area of the AANA, through which pollutants and water vapor were transported to the ocean.

211. Change “stable” to “persistent” or “reliable.”

Reply:

Some revisions were made.

Revisions:

In “Results”

and sea triggered by the AANA provided a persistent~~stable~~ source of water vapor for severe haze, and the resulting higher RH

214. Change “forecast” to “forecasting.”

Reply:

The error has been corrected.

Revisions:

In “Results”

quality forecasting. Before severe haze episodes, Northeast Asia was mainly occupied by cyclonic circulation, which had the

215. Change “in” to “over” before Lake Baikal.

Reply:

The error has been corrected.

Revisions:

In “Results”

tendency of weakening over time (Figure 10a–c). This effect was caused by the strengthening of positive anomalies over~~in~~ Lake Baikal. The eastward propagation~~forward motion~~ of positive anomalies over~~in~~ Lake Baikal was a precursory signal of

219-220. Low-level convergence cannot “supply” water vapor. Likewise, there is no process of which I am aware by which convergence at low-levels can “motivate” (cause?) sinking motion and lower PBLHs.

Reply:

This insufficient conclusion has been eliminated.

Revisions:

formation of severe haze. ~~One day after severe haze, T~~the AANA moved to the east continually after the first day of severe haze (Figure 10e-f). ~~, and the main supply of water vapor began to change from southeasterly wind to low-level convergence (Figure 10f). Meanwhile, convergence in the low level could motivate sinking motion and lead to lower PBLH, which might trigger persistent haze.~~ Three days after severe haze, the AANA was ~~broken~~replaced by a cyclonic circulation and haze

222. Change “rebuilt of” to “rebuilding of a.”

Reply:

The error has been corrected.

Revisions:

In “Results”

pollution tended to dissipate ~~-~~(Figure 10g). The rebuil~~d~~ting of a cyclonic circulation ~~in~~over the BTH region represented the

227. Change “the” before “cyclonic circulation” to “a.”

Reply:

This part has been reworded.

Revisions:

In “Results”

……One day after the non-haze day, the anomalous descending motion was enhanced with the development of the cyclonic circulation (Figure 10l).

228. Change “and then it was forced to move” to “that subsequently moved.”

Reply:

This part has been reworded.

Revisions:

In “Results”

……Subsequently, the cyclonic circulation moved eastward by the positive anomaly over Lake Baikal (Figure 10n).

236. Add an “s” to “winds,” an “a” before “stronger,” and a comma after

Reply:

The error has been corrected.

Revisions:

In “Conclusions and discussions”

analyzed. The results indicated that the AANA was closely related to weaker surface winds, a stronger temperature inversion, a ~~lower~~ shallower boundary layer~~PBLH~~, and higher ~~relative humidity~~RH in the BTH region, which were of importance in the

237. Eliminate “From the horizontal direction.”

Reply:

Some revisions were made.

Revisions:

In "Conclusions and discussions"

formation of severe haze. ~~From the horizontal direction, t~~The AANA motivated southeasterly winds in the lower troposphere,

239. Change "updraft" to "vertical motions."

Reply:

This part has been reworded.

Revisions:

In "Conclusions and discussions"

……As a synoptic-scale system, the AANA was accompanied by anomalous vertical motions in the surrounding areas.

240. Change "broke" to "weakened."

Reply:

This part has been reworded.

Revisions:

In "Conclusions and discussions"

……This weakened the local meridional circulation and the invasions of cold and dry air from higher levels. This phenomenon was a key factor in promoting severe haze.

241. Change "of" after "factor" to "in promoting." Also, change "ascending" to "anomalous vertical." Recall, however, in the summary you present here, the comments given above for lines 183-199.

Reply:

This part has been reworded.

Revisions:

In "Conclusions and discussions"

……As a synoptic-scale system, the AANA was accompanied by anomalous vertical motions in the surrounding areas. This weakened the local meridional circulation and the invasions of cold and dry air from higher levels. Meanwhile, the anomalous vertical motion restrained the downward transport of momentum and resulted in lower surface wind speeds, weaker turbulence and a shallower boundary layer, which were highly detrimental to pollutant dispersion.

243. Related to comment made for line 209, it is difficult to envision how a land-sea circulation is indirect without a bit more clarification.

Reply:

Some revisions were made to describe this point more explicitly.

Revisions:

In “Conclusions and discussions”

……The AANA also modulated a thermally indirect circulation between land and sea, which acted as the main moisture path.

248. Change “the” to “a” after “contrast.” Also, add a comma after “non-haze day,” and change “for” after “non-haze day” to “resulting in.”

Reply:

Some revisions were made.

Revisions:

In “Conclusions and discussions”

……In contrast, a transition from anticyclonic circulation to cyclonic circulation occurred a day before the non-haze day, resulting in the rapid movement of polar cold air.

253. Add an “s” to “winds” and an “a” before “stronger.” As a review for readers, you might consider briefly restating the relationship between the (well-known) EAWM and the AANA here.

Reply:

Some revisions were made.

Revisions:

In “Conclusions and discussions”

……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).

256. Eliminate “in the horizontal direction.”

257. Add "of the AANA area" after "front."

258. Add an "s" to "winds," an "a" before "Stronger," and an "a" before "shallower."

Reply:

This part has been reworded.

Revisions:

In "Conclusions and discussions"

……The AANA not only motivated southeasterly winds near the surface but also modulated anomalous vertical motions. These synoptic-scale environments led to conducive local meteorological conditions for severe haze, including weaker surface winds, a stronger temperature inversion, a shallower boundary layer and higher RH.

260-275. Interesting observations regarding the different statistical relationships observed. But given the relatively small number of cases involved, it is difficult to draw definitive conclusions.

Reply:

After adding the samples in December 2017, strong correlations between haze and meteorological factors remained (Table 4&5). This verified that the relationship revealed in this study are robust and reliable in the different years, and the AANA indexes could capture the relationship between severe haze in the BTH region and the synoptic-scale environments. This part has been reworded.

Revisions:

In "Conclusions and discussions"

……In the different years, the relationship between the AANA and severe haze in the BTH region expressed different features but remained strong. In 2014, 2016 and 2017, the SPCCs between the $PM_{2.5}$ concentration and $AANAI_{Z500}$ were 0.81, 0.79 and 0.73, respectively, all passing the 99% confidence level (Table 4). These results indicated that the AANA could play an important role in the formation of severe haze over the BTH region in 2014, 2016 and 2017. However, the SPCC between the $PM_{2.5}$ 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. The SPCC between the $PM_{2.5}$ concentration and $AANAI_{V850}$ ($AANAI_{\omega 500}$) was -0.61 (-0.66), exceeding the 95% confidence level (Table 4). In addition, there were some differences on how the AANA affected severe haze. In 2014, the AANA strengthened the severe haze mainly by enhancing TIP anomalies and surface RH, whose SPCC with the $AANAI_{Z500}$ were 0.62 and 0.57, respectively (Table 5). The AANA could promoted weaker surface winds, higher surface RH and a shallower boundary layer in 2015. The SPCCs between the $AANAI_{V850}$ and surface wind speed, surface RH and ERA PBLH anomalies were 0.74 -0.70 and 0.64, respectively (Table 5). Similar situation could be detected in 2016 and 2017 (Table 5). These results proved that the AANA indexes could capture the relationship between severe haze in the BTH region and the synoptic-scale environments. 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.

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	AANAI$_{500}$	AANAI$_{850}$	AANAI$_{\omega 500}$	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*

262. Not sure that “indicative” is the correct word here. I’m also not sure that the word is needed; I think it could be eliminated.

Reply:

Some revisions were made.

Revisions:

In “Conclusions and discussions”

……These results indicated that the AANA could play an important role in the formation of severe haze over the BTH region in 2014, 2016 and 2017.

……The evolution processes of the AANA on severe haze/non-haze episodes illustrated that the intensity of the AANA could play an important role in the emergence and dissipation of severe haze.

275. Add an “s” to “levels.”

276. Change “wind” to “flow.”

Reply:

Some revisions were made.

Revisions:

In “Conclusions and discussions”

further research to confirm. Higher relative humidityRH over the BTH region could be verified in the upper levels (200-300 hPa; Figure 8b) because evaporated water vapor over the ocean could be brought transported to the air over the land by anomalous easterly windflows. Further research remains necessary to explore how higher relative humidityRH in the upper

279. Unless I have interpreted your data section incorrectly, “the period of December 2014-2016” should be rephrased as “the months of December in the years 2014-2016.”

Reply:

Some revisions were made.

Revisions:

In “Conclusions and discussions”

……However, the severe haze/non-haze events analyzed in this study were limited to the months of December in the years 2014-2016.

Figures Fig. 1 In caption, add an “s” to lines,” and add a comma and the word “respectively” after “episodes.”

Reply:

Some revisions were made.

Revisions:

In “Figure 1”

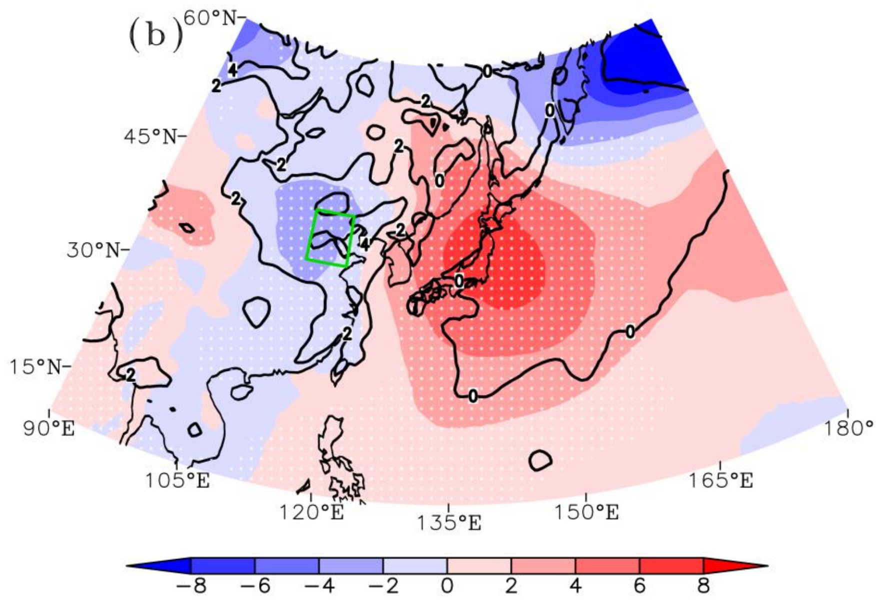
Figure 1. The six-hour variation of mean $PM_{2.5}$ concentration over the BTH region (units: $\mu g \cdot m^{-3}$) in December 2014, December 2015 and December 2016. The time series (concentrations) corresponding to the red/blue lines represent the occurrence time (threshold values) of severe haze/non-haze episodes, respectively.

Fig. 2. While the images can be enlarged for viewing with electronic media, the present images need some enlargement for print publication. Also consider somewhat thickening the underlying geographical outlines for ease of view.

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:



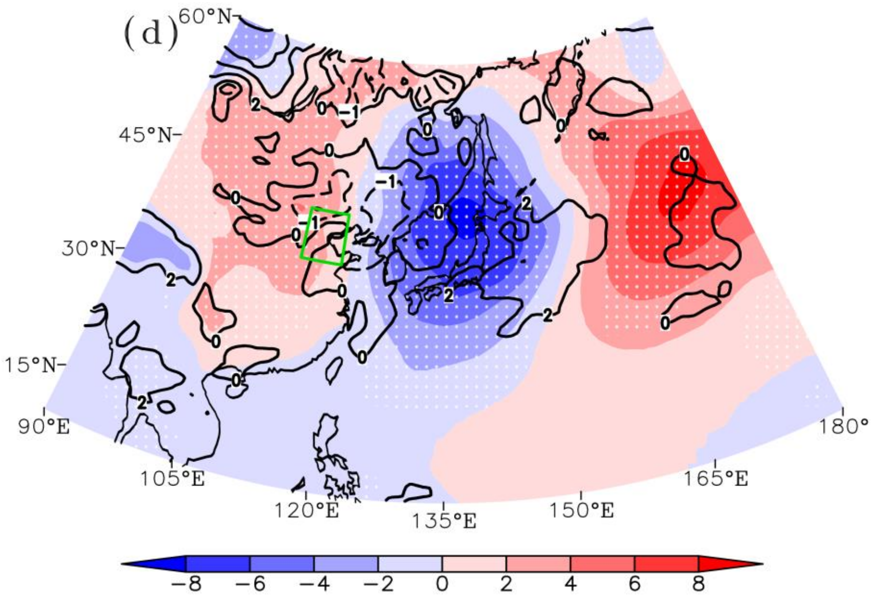


Figure 2. Composite distribution of the atmospheric circulation anomalies on severe haze/non-haze episodes. The anomalies here are calculated with respect to the 1979-2010 climatology. The green (white) box indicates the BTH region (area covered by $AANAI_{Z500}$). (b) SLP (shading, units: hPa) and SAT (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. 6 In caption, add an "s" to "mid-level."

Reply:

Some revisions were made.

Revisions:

In "Figure 6"

Figure 6. Structure of the AANA in the mid-levels: Z_{500} (contour, units: $m^2 \cdot s^{-2}$) and $\boldsymbol{\omega}_{500}$ (shading, units: $Pa \cdot s^{-1}$). The anomalies here are calculated with respect to the 1979-2010 climatology. The green (gray) box indicates the BTH region (area covered by $AANAI_{\omega500}$). (a) severe haze episodes, (b) non-haze episodes. The white dots indicate that the $\boldsymbol{\omega}_{500}$ anomalies exceeded the 95% confidence level.

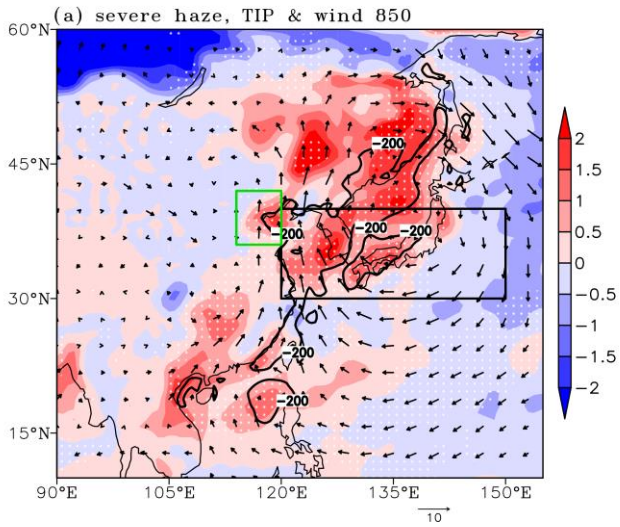
Fig. 7. The meaning of the green lines in parts "a" and "c" not indicated in caption. More significantly though (and forgive me here), I find this figure confusing. Parts "a" through "d" purport to show wind anomalies, but the

captions for each part mention "omega." Parts "a" and "c" purport to show contoured PBLH anomalies, but I can find no contours in either figure parts. As this figure is important to supporting the thesis of the paper, some clarification of the figure caption would improve the presentation. This figure (and the related text in the manuscript) represents one of the areas of "confusing statements" mentioned in the Major Comments section.

Reply:

1. The green line was used to present the PBLH anomaly averaged over 114°-120°E (the BTH region) in the origin version. Now, the PBLH anomaly was plotted in the Figure 3(a) and (c) with bold black contours.
2. The "omega" should be the "omega vertical velocity". The intended meaning of this figure was to plot the meridional circulation and zonal-vertical circulation in the control area of the AANA. The vectors in Figure 8a (Figure 8b) represented the vertical and meridional (zonal) components. Note that, the vertical velocity here was magnified 100 times to make the horizontal velocity and the vertical velocity in the same order. The original values of the vertical velocity were plotted with shading. The figure caption has been reworded in a more clearly way.

Revisions:



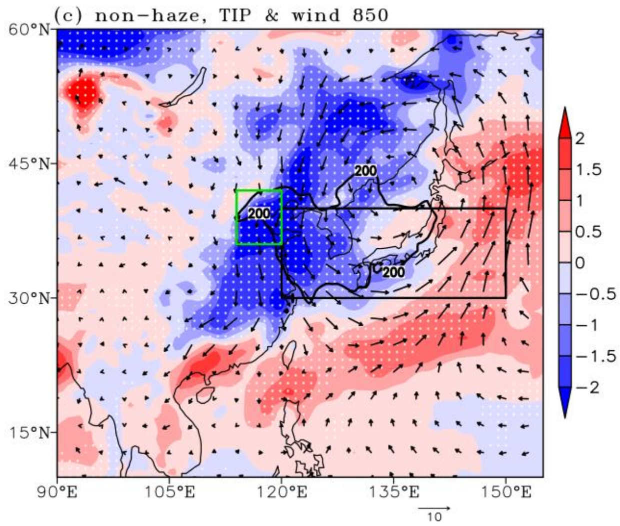
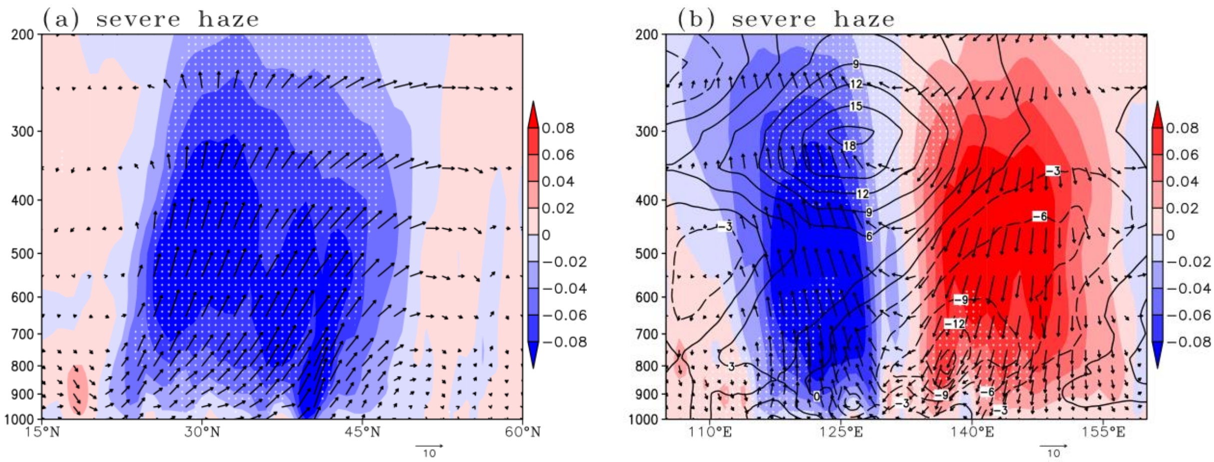


Figure 3. Composite distribution of local atmospheric circulation anomalies on severe haze/non-haze episodes. The anomalies here are calculated with respect to the 1979-2010 climatology. The green (black) box indicates the BTH region (area covered by AANAI$_{V850}$). (a) $\boldsymbol{V}_{850}$ (arrow, 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.



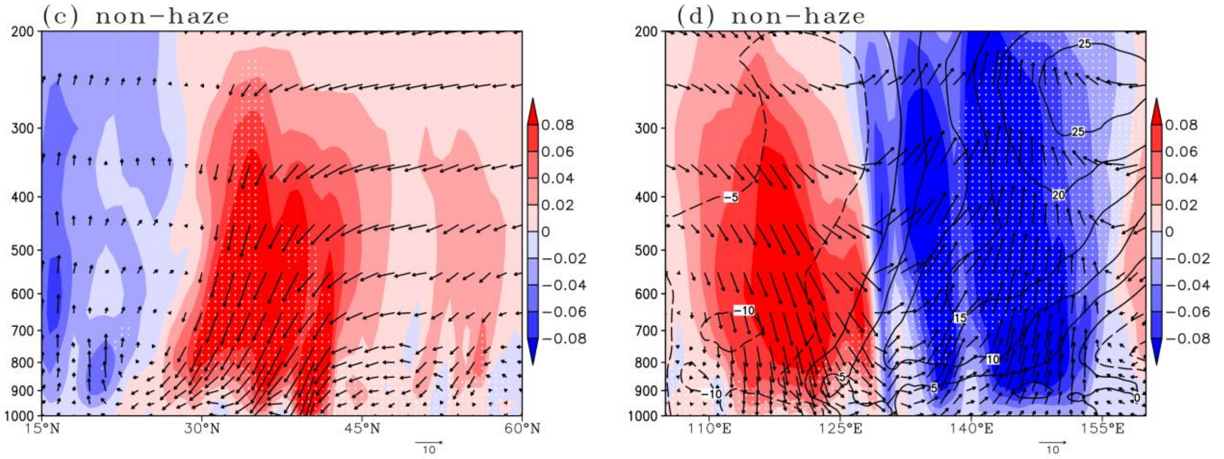


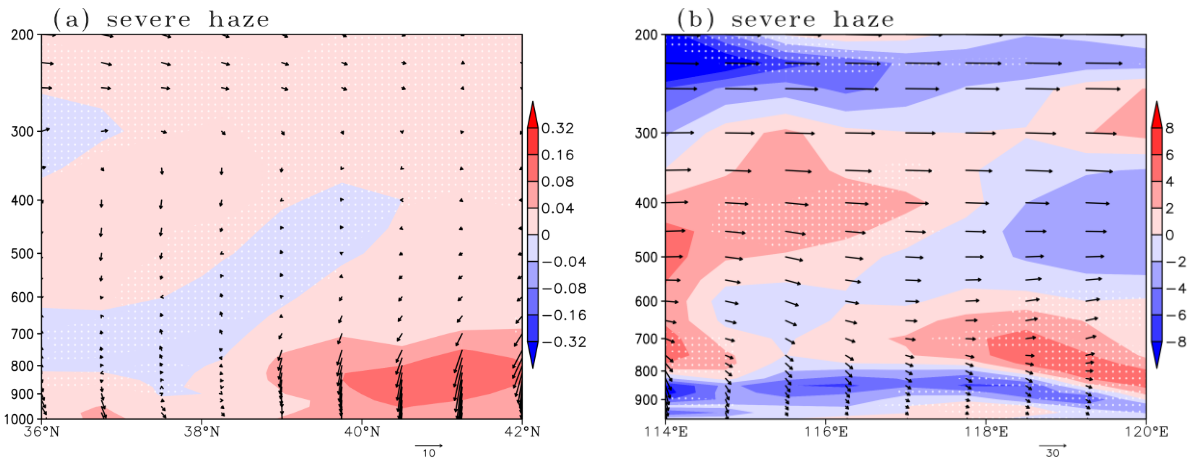
Figure 8. Vertical circulation on severe haze/non-haze episodes (composite anomalies): (a) meridional circulation averaged over the AANA (115 °-125 °E) on severe haze episodes (vertical velocity, shading, units: $Pa \cdot s^{-1}$; the vectors represent the vertical and meridional components); the white dots indicate that the vertical velocity exceeded the 95% confidence level. (b) zonal-vertical circulation averaged over the AANA (30 °-40 °N) on severe haze episodes (vertical velocity, shading, units: $Pa \cdot s^{-1}$; the vectors represent the vertical and zonal components) and RH anomalies (contour, units: %); the white dots indicate that the RH exceeded the 95% confidence level. (c) meridional circulation averaged over the AANA (115 °-125 °E) on non-haze episodes (vertical velocity, shading, units: $Pa \cdot s^{-1}$; the vectors represent the vertical and meridional components); the white dots indicate that the vertical velocity exceeded the 95% confidence level. (d) zonal-vertical circulation averaged over the AANA (30 °-40 °N) on non-haze episodes (vertical velocity, shading, units: $Pa \cdot s^{-1}$; the vectors represent the vertical and zonal components) and RH (contour, units: %); the white dots indicate that the RH exceeded the 95% confidence level. The anomalies here are calculated with respect to the 1979-2010 climatology. To make the horizontal velocity and the vertical velocity in the same order, the vertical velocity (omega) here was magnified 100 times.

Fig. 8. In caption, consider changing "Pressure-meridional" in parts "b" and "d" to "Pressure-longitude" to better correspond with terminology used in parts "a" and "c." As with Figure 7, I am also somewhat confused by this one. If I understand things correctly, parts "a" and "c" depict mean profiles of the wind along a longitudinal band between 114 and 120 E. If what is shown is indeed wind, why is "omega" mentioned in the captions for both parts "a" and "c"? Further, do the orientations of the arrows indicate the directions (i.e., azimuths) of the wind? Parts "b" and "d" purport to be the mean wind along the latitudinal band between 36 and 42 N. Again, however, there is reference to "omega" in the caption for both parts. Vertical transport of westerly momentum is shown only along the latitudinal swaths given in parts "b" and "d," but not along the longitudinal swaths given in parts "a" and "c." Is there a reason for this? Again, as this figure also is important to the thesis of the paper, some clarification would improve the presentation.

Reply:

1. The “omega” should be the “omega vertical velocity”. The intended meaning of this figure was to plot the meridional circulation and zonal-vertical circulation over the BTH region. The vectors in Figure 9a (Figure 9b) represent the vertical and meridional (zonal) components. Thus, the orientations of the arrows here indicate the directions of the wind. Note that, the vertical velocity here was magnified 100 times to make the horizontal velocity and the vertical velocity in the same order. The original values of the vertical velocity were plotted with shading. The figure caption has been reworded in a more clearly way.
2. Considering of the existence of the westerly jet stream at the tropopause, the momentum exchange between the free troposphere and the lower troposphere was mainly via sinking motions that bring down the westerly momentum. Thus, it would be more understandable if the vertical transport of westerly momentum was plotted with the zonal-vertical circulation that was made up of the vertical and zonal components rather than the meridional circulation.

Revisions:



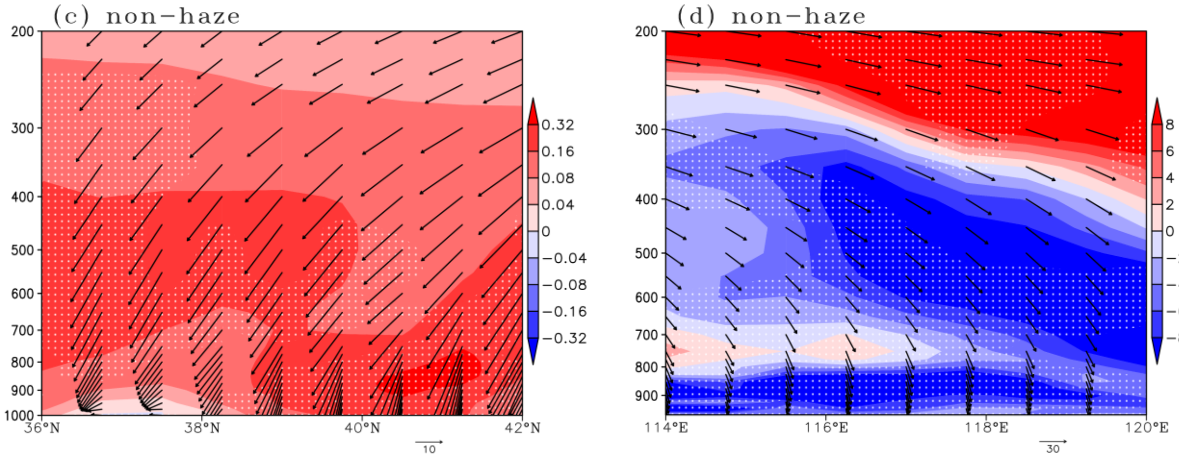


Figure 9. Vertical circulation on severe haze/non-haze episodes (composite synoptic processes): (a) meridional circulation averaged over the BTH region (114°-120°E) on severe haze episodes (vertical velocity, shading, units: $Pa \cdot s^{-1}$; the vectors represent the vertical and meridional components); the white dots indicate that vertical velocity exceeded the 95% confidence level. (b) zonal-vertical circulation (36°-42°N mean) on severe haze episodes (the vectors represent the vertical and zonal components) and the vertical transport of westerly momentum (shading, units: $10^{-5} m \cdot s^{-2}$); the white dots indicate that the vertical transport of westerly momentum exceeded the 95% confidence level. (c) meridional circulation averaged over the BTH region (114°-120°E) on non-haze episodes (vertical velocity, shading, units: $Pa \cdot s^{-1}$; the vectors represent the vertical and meridional components); the white dots indicate that vertical velocity exceeded the 95% confidence level. (d) zonal-vertical circulation (36°-42°N mean) on non-haze episodes (the vectors represent the vertical and zonal components) and the vertical transport of westerly momentum (shading, units: $10^{-5} m \cdot s^{-2}$); the white dots indicate that the vertical transport of westerly momentum exceeded the 95% confidence level. To make the horizontal velocity and the vertical velocity in the same order, the vertical velocity (omega) here was magnified 100 times.

References:

Corfidi, S. F., Corfidi, S. J., and Schultz, D. M.: Elevated Convection and Castellanus: Ambiguities, Significance, and Questions. *Wea. Forecasting*, **23**, 1280-1303, doi:10.1175/2008WAF2222118.1, 2008.

Hu, Y. L., Wang, S. G., Ning, G. C., et al.: A quantitative assessment of the air pollution purification effect of a super strong cold-air outbreak in January 2016 in China. *Air Qual. Atmos. Health.*, **11**, 907-923, doi:10.1007/s11869-018-0592-2, 2018.

Lackmann, G.: Midlatitude synoptic meteorology: dynamics, analysis, and forecasting, American Meteorological Society, Boston, America, 5-10, 2011.

Liu, X. E. and Guo, X. L.: Role of Downward Momentum Transport in the Formation of Severe Surface Winds, *Atmospheric and Oceanic Science Letters*, **5**, 379-383, doi:10.1080/16742834.2012.11447020, 2012.

Shen, L., Jacob, D. J., Mickley, L. J., et al.: Insignificant effect of climate change on winter haze pollution in Beijing, *Atmos. Chem. Phys.*, **18**, 17489-17496, doi:10.5194/acp-18-17489-2018, 2018..

Wallace, J. M. and Hobbs, P. V.: Atmospheric science: an introductory survey. 2nd ed., Elsevier Academic Press, Amsterdam, 283, 2006.