Reply letter to the anonymous Referee #2

Received and published: 14 October 2016

In this work, the authors discussed the possible mechanisms of the severe haze pollution over the North China Plain in winter. Three teleconnection patterns (EA/WR, WP and EU) might have led to stable meteorological conditions that contributed to severe haze events over the North-Central North China Plain in 2014. Using SVD analysis, several external forcings were pointed out to have enhanced certain teleconnection patterns. This paper highlights the links between external forcings, teleconnection patterns and WHDs, but more discussions in detail were still needed in this paper:

1. 39 NCP stations were used to reconstruct the climatic WHDs, significant spatial variation of WHDs could be observed in Figure 4(a). Only four rural stations were selected to represent urban haze. The authors didn't introduce the locations of the four stations.

***Reply*:**

Our motivation is to address the haze pollution in large area, including both the urban and rural regions. The reason for that only 4 rural sites were selected was the limited quality and temporal range of the rural measurements. However, reminded by the reviewer, **the Figure 1 was revised to introduce the location of the rural sites and some new features were revealed.** From the Figure 1 and 2a, we can see that the areas with less WHD were near the rural stations. Actually, the fast increase of WHD in rural area was an obvious reflection of the severe haze disaster in recent years. In other words, the coverage of haze invaded into the rural region in 2014.

Revision:

……Due to the quality and temporal range of the data, only four rural stations were qualified and selected (white circles in Figure 1). ~~and the datasets tended to represent the characteristics of urban haze~~ ……

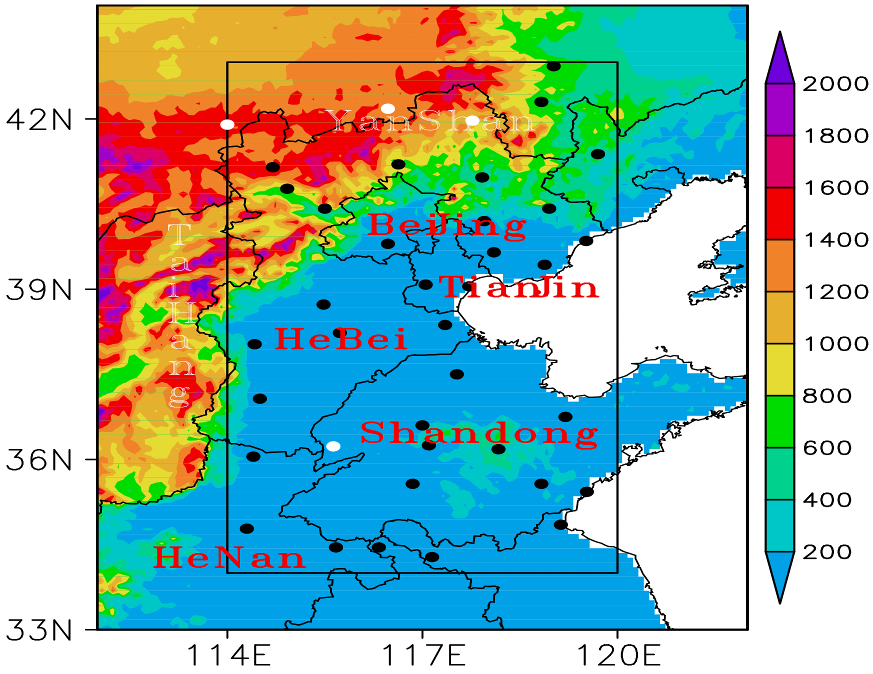

Figure 1. Topographic map (shading; unit: m) of North China and the locations of 39 NCP observation sites (Urban: black circle, Rural: white circle). The NCP area is represented by a black rectangle, and the names of provinces and mountains are written in red and white, respectively.

……As shown in Figure 1, there were four rural stations, three of which were located near the Yan Mountains and were corresponding to less WHD. Another rural site was near the boundaries of Shandong and Henan (BSH) and also resulted in less WHD. Figure 3b shows the WHD anomalies in 2014 with respect to 1979–2012. In addition to a few sites, a larger number of WHD occurred, especially on the BSH (rural area) and the northeast of Hebei. It is notable that WHDs in these two regions show significant increases, filling up the climatic WHD valley as shown in Figure 3a. As a result, the haze-prone area joined together, indicating that the haze pollution was more serious in this region. Actually, the fast increase of WHD in rural area was an obvious reflection of the severe haze disaster in recent years.…….

2. During the period from 1979 to 2012, the negative SLP anomaly in the Siberia region and the positive SLP anomaly over West Pacific led to weakened EAWM inducing the southeasterly anomaly (Figure 5 (a) and (c)), which was favorable for haze events. But in 2014, anomalies of meteorological fields (Figure 5 (b) and (d)) for WHDs in the NCP region were different from those in 1979-2012.

Although the surface temperature was higher than average over the Asian continent, the surface wind fields over NCP region didn't show favorable conditions for WHDs. As anthropogenic emissions could also influence air quality, meteorological conditions might not be the main cause of WHDs in 2014.

***Reply*:**

(1) So far, **there is no evidence that the emissions were more in 2014 than 2010**. Furthermore, the $PM_{2.5}$ concentration of a global atmospheric watch station (Shangdianzi) and an urban station (Baolian) were **almost the same** in winter 2010 and 2014. By our current and some previous analysis, we found that **the climate factor played key roles in the formation of the heavy pollution case like 2014**.

The anthropogenic emissions were the fundamental driver and mostly impacted the long-term trend of the haze pollution. To some extent, the energy consumption varied continuously and linearly in eastern China and **the socio-economic components of WHD_{NCP} could be removed primitively by detrending**, and then the interannual variability of haze pollution should be mainly the result of climatic anomalies.

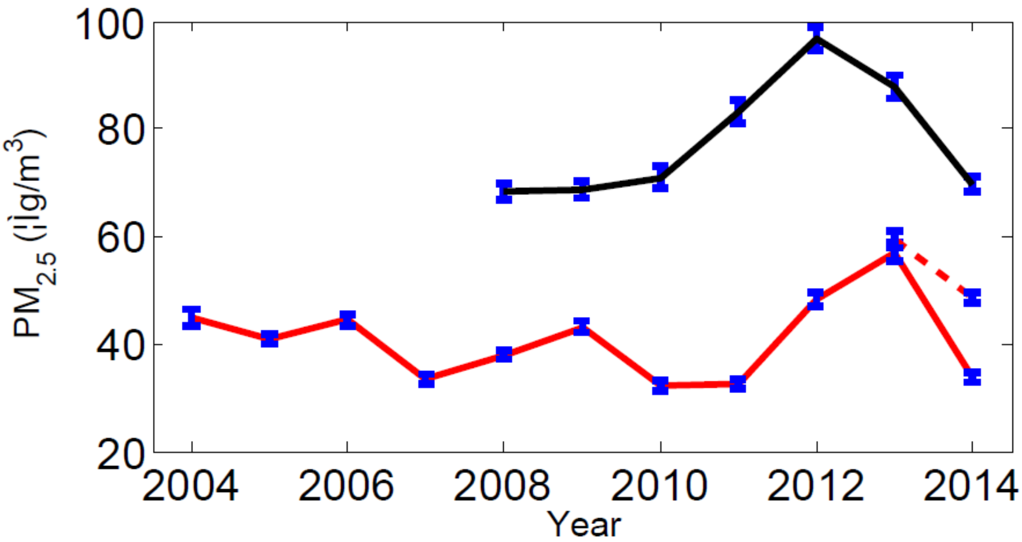

Figure 11. Mean mass concentration of $PM_{2.5}$ in winter at Shangdianzi (red; measured by the TOEM (solid) and β-ray (red dash) method) and Baolian (black) Station. The error bar represents one standard error among the different measured hours.

To enhance our perspective, the title has been changed to "Understanding Severe Winter Haze Events in the North China Plain in 2014: Roles of Climate Anomalies". The main purpose of this study was to discuss the roles of climate anomalies and the impact of emissions is discussed in the "Introduction" and "Discussion".

(2) In the discussion section, we pointed out "the associated circulations and external forcings in 2010 were still slightly different from those in 2014. It is possible that **not all of the above factors might be found in a specific case study**, i.e., **a few of these factors played the essential roles and led to the characteristics of that case**. A brief summary of the impacts of these factors on WHD_{NCP} is offered in Table 2". The Table 2 was improved to include all of the possible factors. In summary, the local climate conditions, (i.e., weaker surface wind speed and lower PBLH), the teleconnection patterns and the external forcings were benefit for the occurrence of the haze extreme in 2014.

Table 2. Summary of the various influnce factors for WHD_{NCP}. The "+++" indicates "more important"; "++" indicates "important", "+" indicates "less important" , and blank indicates "not important".

Factors	*2010*	*2013*	*2014*
$PM_{2.5}$ concentration	++	+++	++
Local surface wind speed	++	++	++
Local PBLH	++	++	++
EA/WR	++	++	++
WP	++		++
EU			++
Pre-autumn ASI	++		++
Winter TS	++		++
ON Pacific SSTA	+	++	++
Pre-autumn TS	++		++

To enhance our analysis of 2014 case, the anomalies of meteorological fields were re-plotted and the composite of PBLH was supplemented. ① For the horizontal diffusion: The main argument was that the weaker EAWM pattern could intensify the haze pollution in the NCP. Except the SLP anomalies over Northeast

China and Japan Sea, the pressure field was also similar with the climatic correlation. Furthermore, the surface wind anomalies at the high latitude blocked the cold air from their source and there were southerly to the south of 40^{o}N that occupied most of our research area. Unfortunately, the isolated northerly could be found to the north of 40^{o}N. That is, the large scale EAWM pattern and most of the synoptic scale circulations were benefit for the large number of WHD_{NCP} in winter 2014. ② **For the vertical diffusion**: The composite of PBLH was supplemented as Figure 6. The PBLH was a good indicator for air pollution, especially for the vertical diffusivity. The winter PBLH in 2014 was much lower than that in 2010, so the vertical diffusivity was worse in 2014 resulting in more haze days.

Revisions to the impact of human activities were showed in the replies to Q4:

Revision to the meteorological conditions in 2014:

……Nevertheless, the three eastern centers of EA/WR, WP and EU patterns could be recognized (Figure 4c). The linkage anti-cyclone of these three teleconnection patterns was enhanced and modulated the local climate conditions. The NCP area was influenced by the anomalous high resulting in lower PBLH (Figure 6). The southerly at the high latitudes deadened the cold air from its main source, so the atmospheric matters gathered easily. Near the surface, the negative SLP anomalies occupied the whole Asian continent and Japan Sea that weakened the continental cold high and stimulated significant southerly anomalies to the north of 50^{o}N with the weaker Aleutian low. The weaker EAWM circulations near the surface blocked the cold air from high latitudes and resulted in warmer surface (Wang et al. 2015). There were positive SLP anomalies over South China Sea and East China Sea that induced southerly and smaller surface wind speed over the coastal area in the east of China (Figure 5c—d). The diffusivity of atmosphere over the NCP was limited, so the high pollutant emissions were concentrated in a narrow space and severe haze events occurred easily..……

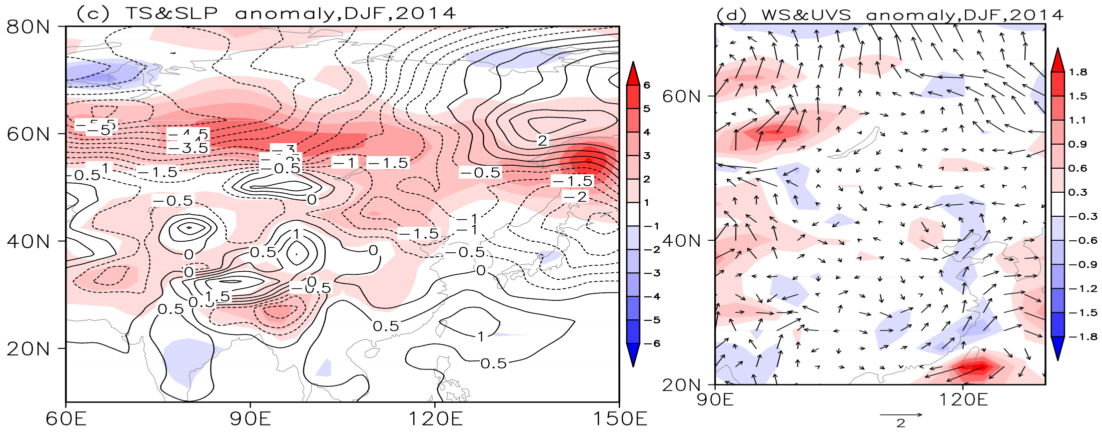

Figure 5. Correlation coefficients between WHD_{NCP} and winter circulations from 1979 to 2012 with linear trend was removed (a, b), and circulation anomalies in 2014 (c, d) and 2010 (e, f). The circulations in (a, c, e) are TS (shade) and SLP (contour) and those in (c, d, f) are surface wind speed (shade) and wind vector (arrow).

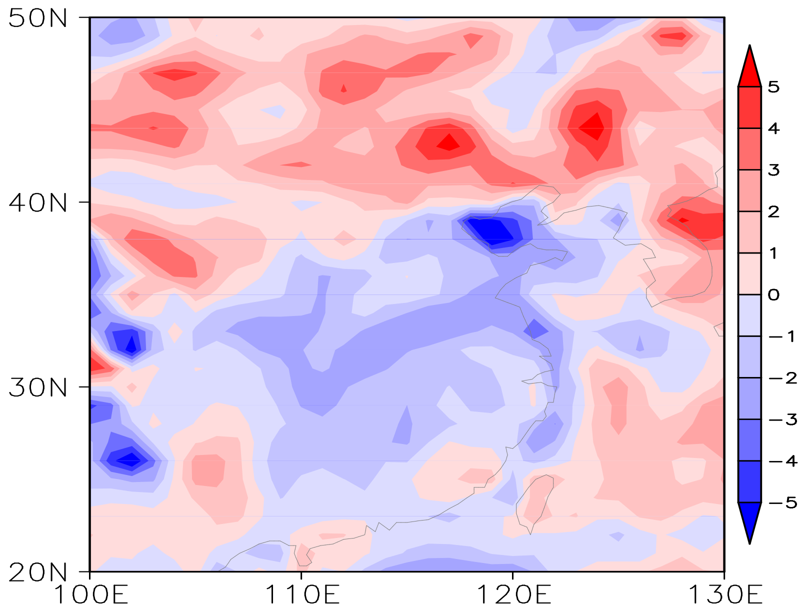

Figure 6. The difference of winter PBLH between 2014 and 2010

3. Two extreme haze phenomenon were discussed in this work. Teleconnection patterns in 2010 and 2014 were different, but over the NCP region, anomalous circulations of wind fields in 2010 were similar with those in 2014. And the authors didn't discuss the regional meteorological conditions over NCP region in detail in 2010. Thus, in order to prove the importance of meteorological conditions on these two haze events the authors need to provide more evidences to support their arguments.

***Reply*:**

The regional meteorological conditions in 2010 were supplemented as Figure 5e—f and 6 that showed similar but opposite features. As reply to Q2, we discussed that it is possible that not all of the above factors might be found in a specific case study, i.e., only a few of these effective factors **played the essential roles and** led to the characteristics of that case. A brief summary of the impacts of these factors on WHD_{NCP} is offered in Table 2". ① **For 2010**, the local climate conditions (i.e., weaker surface wind speed and lower PBLH), most of the teleconnections (except the EU) and the external forcings played positive roles to less haze days. ② **For 2014**, In the local climate conditions, (i.e., weaker surface wind speed and lower PBLH), the teleconnection patterns and the external forcings were benefit for the occurrence of the haze extreme in 2014.

Table 2. Summary of the various influnce factors for WHD_{NCP}. The "+++" indicates "more important"; "++" indicates "important", "+" indicates "less important" , and blank indicates "not important".

Factors	*2010*	*2013*	*2014*
$PM_{2.5}$ concentration	++	+++	++
Local surface wind speed	++	++	++
Local PBLH	++	++	++
EA/WR	++	++	++
WP	++		++
EU			++
Pre-autumn ASI	++		++
Winter TS	++		++
ON Pacific SSTA	+	++	++
Pre-autumn TS	++		++

Revision:

……Large scale circulations, such as the negative phase of EA/WR and WP, were quite clear in 2010 (Figure 4d). Near the surface, the anomalous circulations were distributed similarly but almost opposite, i.e., the stronger continental cold high and oceanic low (Figure 5e), the northerly and stronger surface wind over NCP

(Figure 5f), and the higher PBLH (Figure 6). The atmospheric diffusivity was heightened by the stronger cold air and vertical movement.…….

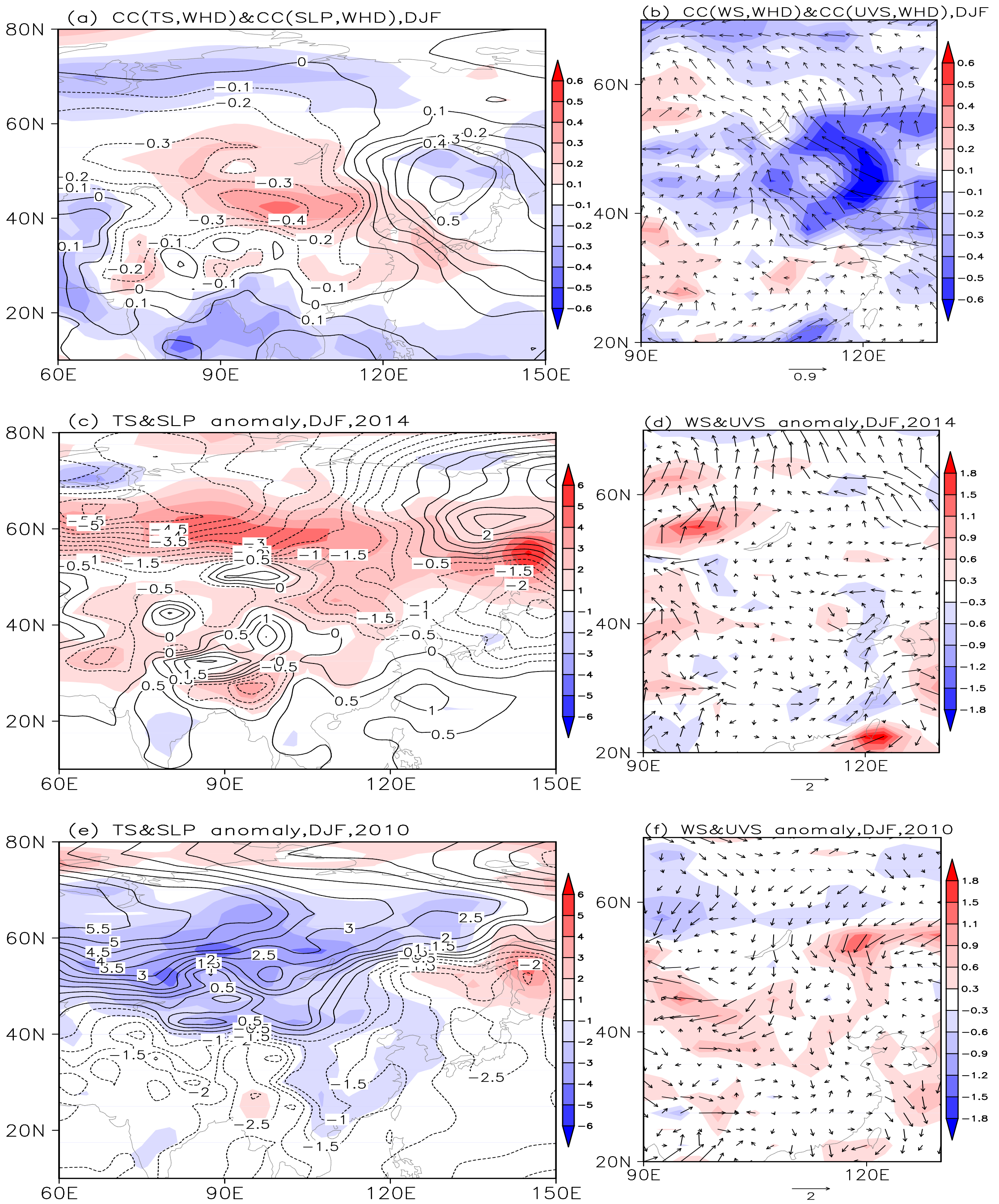

Figure 5. Correlation coefficients between WHD_{NCP} and winter circulations from 1979 to 2012 with linear trend was removed (a, b), and circulation anomalies in 2014 (c, d) and 2010 (e, f). The circulations in (a, c, e) are TS (shade) and SLP (contour) and those in (c, d, f) are surface wind speed (shade) and wind vector (arrow).

4. The authors concluded that anomalous circulations in winter 2013 were not as

favorable for haze conditions as those in 2014. But the number of WHDs in 2013 was as large as that in 2014. Does it mean that the influence of anthropogenic influence was more significant in 2013 than in 2014? How could the authors eliminate the influence of anthropogenic influence?

***Reply*:**

(1) No doubt that the long-term increase of pollutant emission is the fundamental factor for the haze pollution enhancement in recent years. **However, so far, there is no evidence that the emissions were more in 2014 than in 2010.** By our current and some previous analysis, we found that the climate factor played key roles in the formation of the heavy pollution case like 2014. After removal of the linear trend, the interannual variability of haze pollution should be mainly the result of climatic anomalies. **Thus, we removed the socio-economic components of WHD_{NCP} primitively by detrending.** To enhance our perspective, the title has been changed to "Understanding Severe Winter Haze Events in the North China Plain in 2014: Roles of Climate Anomalies".

(2) The impact of emissions was discussed in the "Introduction" and "Discussion". **We also talked about the anthropogenic influence to the 2013 case. The concentration in winter 2013 increased abruptly up to nearly twice that in 2010 and 2014 and was the highest in the observation history that broke down our assumption.** Even the anomalous circulations were not benefit enough for haze occurrence, the joint effect of highest pollution emissions and climate conditions could result in the serious haze event.

In the former version, we concluded that the anomalous in 2013 was not favorable as 2014 curtly. Now, we decided to cancel this conclusion and discuss the comparison more objectively in the last section to show the difference between 2013 and 2014.

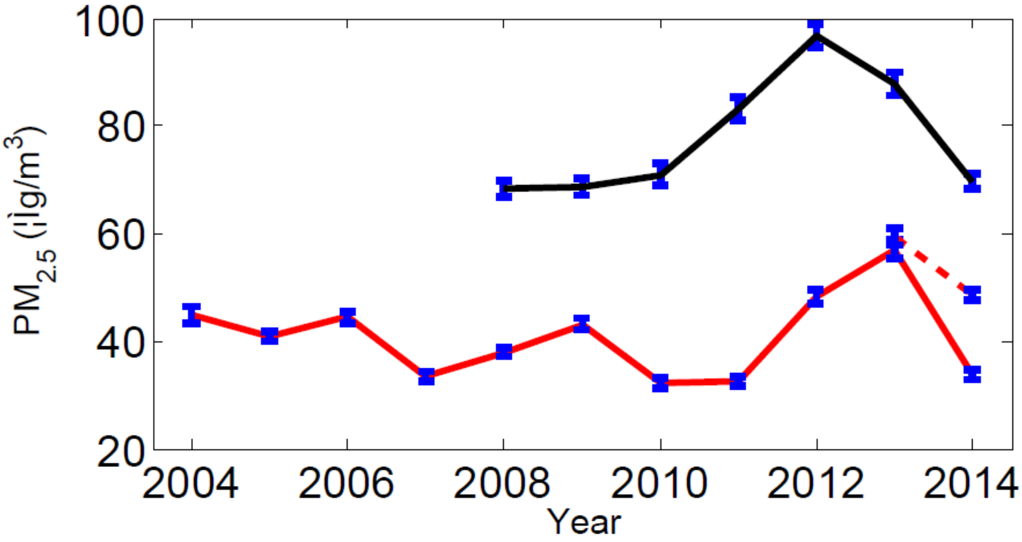

Figure 11. Mean mass concentration of $PM_{2.5}$ in winter at Shangdianzi (red; measured by the TOEM (solid) and β-ray (red dash) method) and Baolian (black) Station. The error bar represents one standard error among the different measured hours.

Revision:

In the Introduction section:

There is no doubt that the anthropogenic emissions were the fundamental cause for the long-term variation of haze days in eastern China (Wang et al. 2013). The enormous energy consumption supplied enough particulates, so the atmosphere tended to reach saturation. Thus, the impact of meteorological conditions is highlighted and the climate conditions are also vital contributors to the interannual variation of haze (Liao et al. 2014). For example, the joint effect of fast increase of total energy consumption, rapid decline of Arctic sea ice extent and reduced precipitation and surface winds intensified the haze pollution in central North China after 2000 (Wang et al. 2016)…….

In the discussion section:

……Except for a few sites, haze pollution over NCP in winter 2014 was the severest in the past 30 years. On the BSH area and the northeast of Hebei, WHD increased significantly and invaded into the rural area, illustrating a joint and broad severe haze-prone region. **The $PM_{2.5}$ concentration at a GAWS and an urban site were almost equal in winter 2010 and 2014, so there was no evidence that the**

emissions were more in 2014 than 2010. The climate conditions played key roles in the formation of heavy haze pollution case in 2014. On the lower and middle troposphere, the positive phases of EA/WR, WP and EU patterns modulated the local anti-cyclone anomalies over North China. The anti-cyclone anomalies over East Asia not only resulted in stable atmospheric stratification and a thinner boundary layer but also led to a southeasterly anomaly that weakened the cold air but enhanced the moisture transport. The atmospheric matters would accumulate easily both on the vertical and horizontal direction. In winter 2014, the teleconnection patterns, such as EA/WR, EU and WP, combined to alter the local climate conditions to contribute to the extreme haze case. SVD analyses indicated that the pre-autumn ASI anomalies of the Eastern Hemisphere and the warmer winter surface of Eurasia could have induced or intensified the responses in the atmosphere, resembling a positive EA/WR pattern. These two external forcings, together with the SSTA in Pacific (i.e., cooler in the northwest Pacific and warmer in the central-east Pacific and Alaska Gulf) might stimulate or enhance positive EU-like patterns. In autumn 2014, the "southwest to northeast" anomalous TS belts were other factors that efficiently intensified the haze pollutions, which resulted in a positive phase of the WP pattern. The case of 2010, with the least WHD_{NCP}, was diagnosed as an opposite case, which further supports the speculation that the anomalous EA/WR and WR patterns and associated external forcings have a significant impact on WHD_{NCP}. Additionally, as pointed out by Wang et al. (2015), the Asian high temperature and drought from summer in 2014 was an extreme climate event. Our studies proved that this previous extreme climate event possibly contributed to the serious haze event in the following winter.

The rapid increase of WHD_{NCP} began in January 2013, and in winter 2013 and 2014, WHD_{NCP} was significantly greater than before. The WHD_{NCP} in 2013 and 2014 was greater than 50 days and almost equal to each other (Figure 2). Therefore, the causes of serious haze in 2013 should also be discussed. The anomalous circulations in winter 2013 were not as favorable for haze as those in 2014. The EA/WR pattern was well organized and showed a positive phase that was distributed slightly eastwards (Figure S6). Influenced by the upper EA/WR pattern, the surface wind speed was slower and the PBLH was lower, illustrating the horizontal and vertical diffusivity of the atmosphere was weaker (Figure S7). The EU and WP patterns were unclear. The source region of EU even showed characteristics of a negative phase. According to the 2010 and 2014 case studies, the proceeding and simultaneous external forcings could have impacted the WHD_{NCP}. In contrast, the pre-autumn ASI and TS and winter TS in 2013 did not show features similar to those in 2014 (Figure S8). The pre-autumn Pacific SSTA, which was slightly negative in the northwest Pacific and positive in the Alaska Gulf and central-east Pacific, could have stimulated positive anomalies over NCP and weakened the East Asia trough. Thus, it can be observed that, among many external reasons for the extreme haze in 2014, only the pre-autumn Pacific SSTA was distributed similarly in 2013. The EA/WR Rossby wave train was the prominent circulation contributing to WHD_{NCP} in 2013, with a source located over the central-north Atlantic. We speculate that the air-sea interaction over north Atlantic excited the EA/WR pattern in the atmosphere and influenced WHD_{NCP} remotely. The correlation coefficients between the EA/WR index and the pre-autumn SST in Atlantic were calculated and were significantly positive to the south of Greenland (Figure S9b). When the SSTA to the south of Greenland was positive, the responses similar to EA/WR occurred in the atmosphere. The pre-autumn SSTA in the Atlantic in 2013 was similar to that shown in Figure S9b and might have remotely impacted WHD_{NCP} via the EA/WR pattern. It should be noted that the SSTA of the key region in the Atlantic was negative and had an adverse effect on WHD_{NCP} in 2014.

From the point of facilitating a larger amount of WHD_{NCP}, the associated circulations and external forcings in 2013 were different from that in 2014, but the serious situations of haze were almost the same. **In our study, we assumed that the energy consumption linearly increased in the recent years. On such hypothesis, the human activities mainly impacted the long-term trend of WHD_{NCP}. After removal of the linear trend, the interannual variability of haze pollution should**

be mainly the result of climatic anomalies. The Shangdianzi site is the only GAWS in North China and was chosen to reflect the natural or background situation of the atmosphere. The mean mass concentrations of $PM_{2.5}$ in winter from 2004 to 2014 are plotted in Figure 11. **The concentration in winter 2013 increased abruptly up to nearly twice that in 2010 and 2014 and was the highest in the observation history that broke down our assumption.** Furthermore, the $PM_{2.5}$ concentration of an urban site, Blaolian station, was also much higher than 2010 and 2014. **Even the anomalous circulations were not benefit enough for haze occurrence, the joint effect of highest pollution emissions and climate conditions could result in the serious haze event.** Documented by these three case studies, the influences of the highest concentrations of $PM_{2.5}$ were the fundamental cause, and the associated with atmospheric anomalies and external forcings played key roles in the severe haze pollution. In this study, we focused on the roles of climate conditions and did not discuss the impact of human activities deeply that should be researched in the future work. To separate the contributions quantitatively by numerical models or advanced statistical approaches would be a meaningful task that was helpful to the interpretation of mechanism and the seasonal prediction (Yin et al. 2016b). In the case studies, 2010 and 2014 exhibited approximately equal $PM_{2.5}$ concentrations of the background atmosphere, but the associated circulations and external forcings in 2010 were still slightly different from those in 2014. It is possible that not all of the above factors might be found in a specific case study, i.e., a few of these effective factors played the essential roles and led to lead to the characteristics of that case. A brief summary of the impacts of these factors on WHD_{NCP} is offered in Table 2……

5. In Line 10: inappropriate adjective "highest".

***Reply*:**

The error has been corrected.

Revision:

……The winter (December–February) haze days over the North China Plain (WHD_{NCP}) in 2014 were the most in the past 30 years……