Reply letter to the anonymous Referee #1

Received and published: 14 September 2016

The paper aimed at the severe haze events during the winter of 2014 happened in North-Central North China Plain, in which the authors attributed the main cause of haze in 2014 winter to the positive phases of the three teleconnection patterns: the East Atlantic/West Russia (EA/WR), the Western Pacific (WP), and the Eurasia (EU). The authors supplied some correlation analysis to explain the influences of three patterns to haze days over the North-Central North China Plain (WHD_{NCP}), and they put the results of SVD to illustrate the causes of three patterns in 2014. The severe haze events in China has become a hotspot in the research of atmospheric environment, thus the issue of this paper is interesting, as documented by some other papers in recent years. **This paper pointed out the three patterns of teleconnection exerted important effects to haze days in China in 2014, and there are some other papers raised similar view of atmospheric circulation, therefore, there is no enough novelty in this paper.**

***Reply*:**

Since several years ago, we have been working on the impact of climate change on the haze pollution in China (associated publications were listed below) and keeping tracking the related researches. We confirmed that this study had some new and key progress, such as:

(1) We investigated the joint effects of the EA/WR, EU and WP teleconnection patterns for the first time and pointed out the pivotal role of the anomalous high over North China.

(2) The latest extremes of haze days in 2010, 2013 and 2014 were analyzed. Not from a specific perspective, but the comprehensive climate conditions (i.e., the related anomalous circulations and external forcings) were researched.

(3) By comparing 2010 and 2014, we confirmed both local climate conditions and climate teleconnections influenced haze weather very much.

(4) Furthermore, the reconstructed haze dataset based on meteorological observations

agree well with the atmospheric composition measurements (particularly the GAWS), thus providing a basis for long-term variability study on the haze pollution.

Associated publications

1. Chen H. P., and **H. J. Wang**, 2015: Haze days in North China and the associated atmospheric circulations based on daily visibility data from 1960 to 2012. J. Geophys. Res. Atmos., 120, 5895-5909, doi:10.1002/2015JD023225.
2. **Wang H. J.**, H. P. Chen, and J. Liu, 2015: Arctic sea ice decline intensified haze pollution in eastern China. Atmos. Oceanic Sci. Lett., 8, 1-9.
3. **Wang H. J.**, H. P. Chen. 2016: Understanding the recent trend of haze pollution in eastern China: roles of cliamte change. Atmos. Chem. Phys., 16, 4205—4211
4. **Yin Z. C., H. J. Wang**, 2015: The relationship between the subtropical Western Pacific SST and haze over North-Central North China Plain. Int. J. Climatol., doi:10.1002/joc.4570.
5. **Yin Z. C., H. J. Wang,** W. L. Guo, 2015: Climatic change features of fog and haze in winter over North China and Huang-Huai Area. SCIENCE CHINA EarthSciences, 58(8): 1370-1376.
6. **Yin Z. C., H. J. Wang,** D. M. Yuan, 2015: Interdecadal increase of haze in winterover North China and the Huang-huai Area and the weakening of the East Asia Winter Monsoon，Chin Sci Bull, 2015, 60: 1395–1400 (in Chinese).
7. **Yin, Z. and Wang, H.**: Seasonal Prediction of Winter Haze Days in the North-Central North China Plain, Atmos. Chem. Phys., doi:10.5194/acp-2016-691, accetped, 2016.

1, The WHD_{NCP} shown in Fig. 4 includes significantly spatial changes in the research domain, and the domain is very small with respect to the spatial scales of three patterns. How can the authors explain the difference of WHD_{NCP} in such a little region using so large three patterns?

***Reply*:**

Due to the influence of human activities, the distribution of WHD shows significantly spatial changes among the rural area, small cities and metropolises. In the paper, we supplemented some analysis about the rural stations in Figure 1. From the Figure 1 and 2a, we can see that the areas with less WHD were near the rural stations. Actually, the 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.**

We found that l**arge scale patterns could impact the haze events in the relatively small region by altering the local meteorological conditions via teleconnection** (i.e., EA/WR teleconnection pattern, WP teleconnection pattern and EU teleconnection pattern). For example, when the WP pattern showed stronger positive phase, there were stronger positive anomalies of geopotential height on surface, 850 hPa and 500 hPa over North China and northwest Pacific. The anomalous anti-cyclone was enhanced, thus, the vertical motion or convection on the NCP was confined and the southerly anomalies on the left side of the anti-cyclone were induced to weaken the cold air and wind speed. This is the way that the WP teleconnection pattern altered the local meteorological conditions. Under such meteorological conditions, the vertical and horizontal diffusions of atmospheric particulates were both restricted, and then the pollutant gathered in a narrow space that resulted in the occurrence of haze. **The main process could be summarized as "climate teleconnection → local climate conditions → weaker diffusion conditions → pollutant gathered in a narrow space".** The physical process related with EA/WR and EU were similar to that was described above. The Figures 4—5 was revised and the order was exchanged to match the improvement of the physical analysis. The revised text and Figures was showed in the replies to "Specific comment 2".

Additionally, the impact of ENSO (Gao et al. 2015) and Tibetan Plateau (Xu et al. 2016) on the haze frequency in eastern China was also obvious, whose scales were even larger. What's more, the North China severe summer drought in 2014 also been explained by the large scale teleconnections (Wang et al. 2015).

Associated references

Wang H J, He S P. 2015. The North China/Northeastern Asia Severe Summer Drought in 2014. Journal of Climate. 28(17), 6667–668

Gao H, Li X. 2015. Influences of El Nino Southern Oscillation events on haze frequency in eastern China during boreal winters. International Journal of Climatology. 35

Xu X et al. 2016. Climate modulation of the Tibetan Plateau on haze in China. Atmospheric Chemistry and Physics, 16(3): 1365-1375

Revision:

……Due to the quality and temporal range of the data, only four rural stations were qualified and selected (white circles in Figure 1)…….

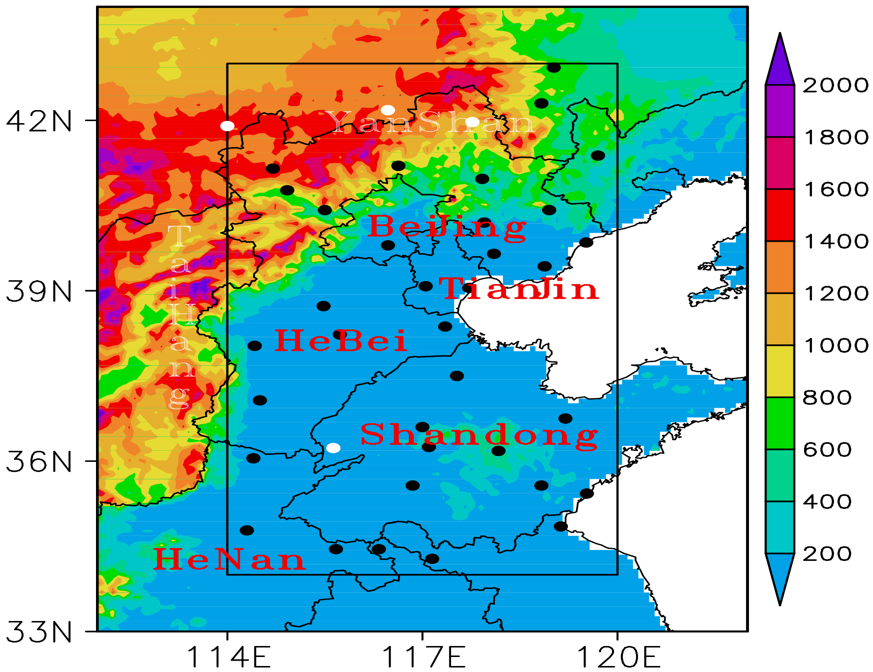

Figure 1. Topographic map (shading; unit: m) of North China and the locations of 39 NCP observation sites (Urban: black circle, Rural: white circle). The NCP area is represented by a black rectangle, and the names of provinces and mountains are written in red and white, respectively.

…… 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, Correlation coefficients have been supplied by in the paper to reveal the potential effects of three patterns to WHD_{NCP}, but necessary physical analysis of such influence has been nearly ignored by the authors.

***Reply*:**

Some necessary physical analysis has been added in section 3. The main physical mechanism was that **"climate teleconnection → local climate conditions → weaker diffusion conditions → pollutant gathered in a narrow space"**. The Figures was revised and **the order was exchanged to match the description of the physical analysis (from teleconnection to local conditions)**. The detailed analysis and revision was listed below.

Revision in section 3:

……These teleconnection patterns might contribute to WHD_{NCP} by impacting the pivotal and local anti-cyclone anomalies (i.e., the local climate conditions) over NCP (Figure 4a—b). The deep and broad positive anomalies resulted in a thinner boundary layer by suppressing vertical movement and progressed easterly to weaken the East Asia Jet Stream (EAJS) indicating weaker meridional cold air. Near the surface, the negative SLP anomalies in the Siberia region and the Chinese Mainland and the positive SLP anomalies over the West Pacific led to a reduced pressure gradient and weakened EAWM (Figure 5a). The weaker EAWM induced the southeasterly anomalies and reduced the surface wind speed (Figure 5b), indicating weaker cold air and warmer land surface over NCP (Figure 5a). Influenced by the circulations with weaker cold air, horizontal diffusion of the atmospheric particulates was impeded. Near NCP, the anomalous anti-cyclone also existed that illustrated weaker vertical motion. The main physical process was that the climate teleconnection patterns altered the local climate conditions, and then influenced the diffusivity of the local atmosphere. That is, when the positive pattern of EA/WR, WP and EU occurred together or partly, the anomalous anti-cyclone over NCP and Japan Sea was enhanced from surface to the middle troposphere, thus, the convection or vertical motion was confined. The southerly anomalies on the left side of this anti-cyclone weakened the cold air and wind speed. Under such local climate conditions, the vertical and horizontal diffusion of atmospheric particulates were both restricted and then the pollutant gathered in a narrow space that resulted in the occurrence of haze.

In winter 2014, many extreme climatic events occurred, such as severe drought and high temperatures in NCP (Wang et al. 2015). Corresponding external forcings should be observed as the background of these extreme synoptic and climatic events, which might persistently impacted the atmospheric circulations and led to an irregular distribution of teleconnection patterns in winter. It should be noted that EA/WR pattern in winter 2014 was distributed slightly westwards and broadly. Nevertheless, the three eastern centers of EA/WR, WP and EU patterns could be recognized (Figure 4c). The linkage system 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. Large scale circulations, such as the negative phase of EA/WR and WP, were quite clear in 2010 (Figure 5d). 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. This observation further supports the speculation that the anomalous EA/WR and WP patterns contributed to significant changes in WHD_{NCP} by altering the local climate conditions. The anomalies of the EU pattern in winter 2010 were not as significant as those in 2014. As shown by Table 1, the relationship between WHD_{NCP} and the EU index weakened after detrending, illustrating that the correlation was much weaker than the other two patterns……

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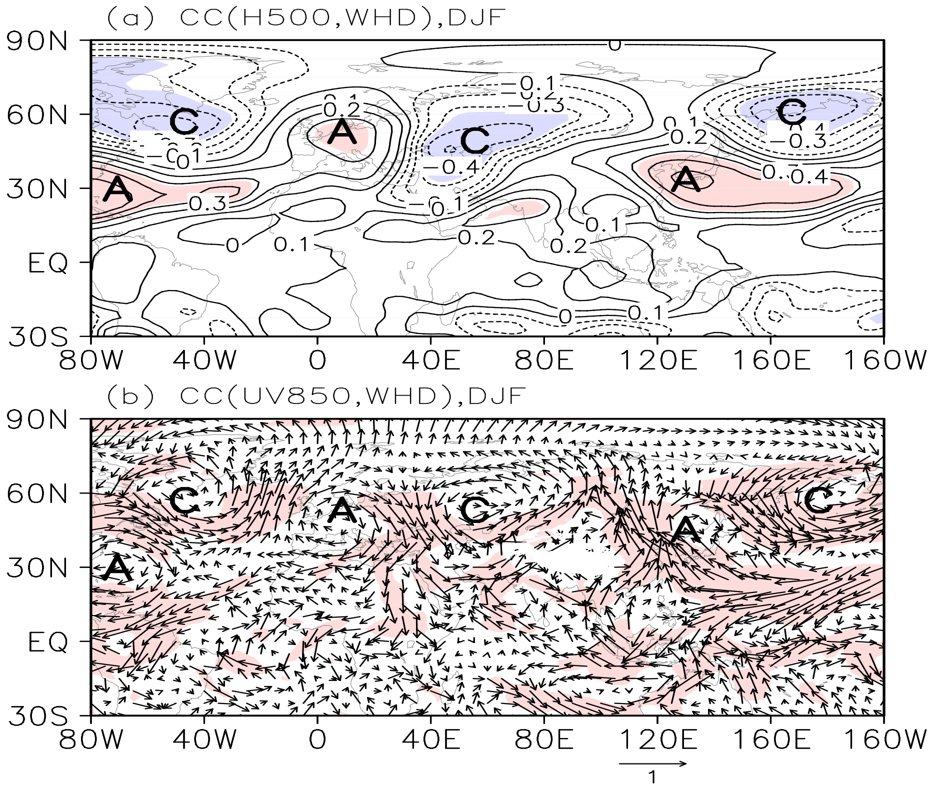


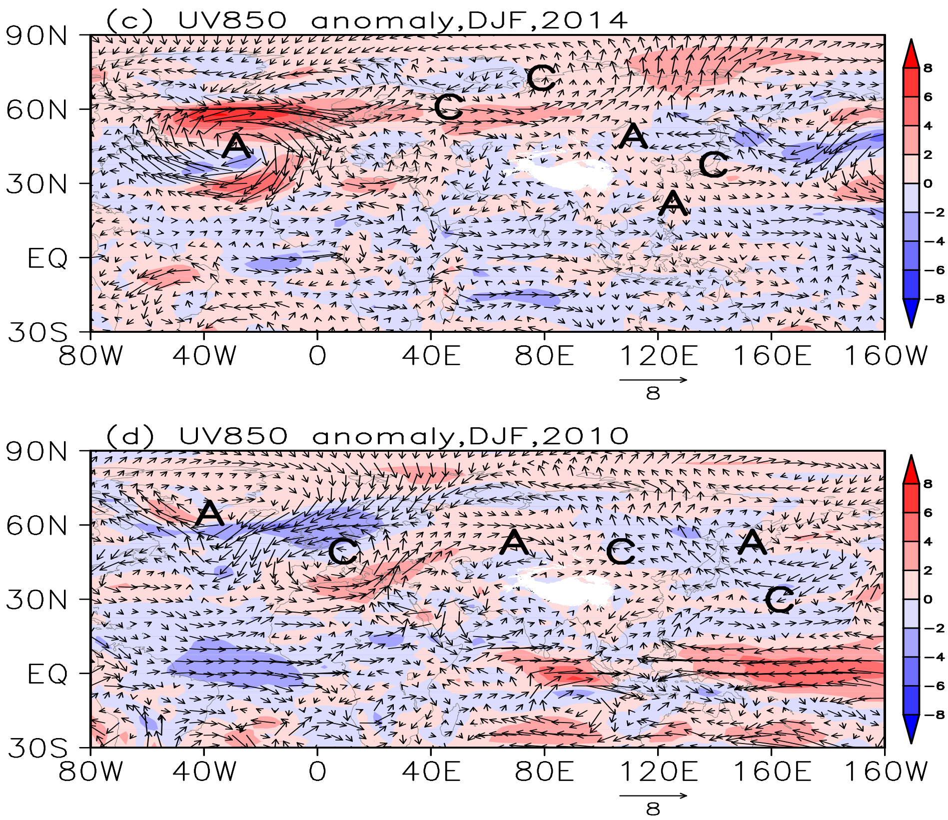
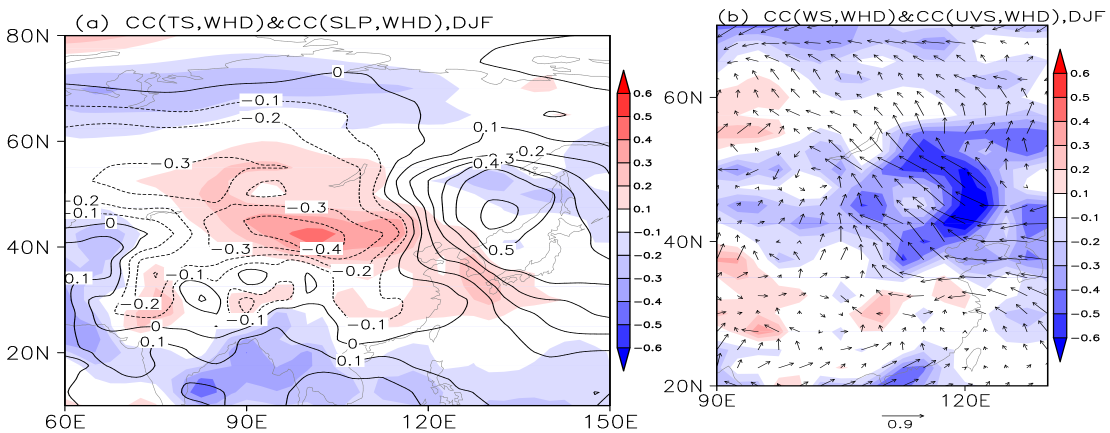


Figure 4. Correlation coefficients between WHD_{NCP} and winter H500 (a) / UV850 (b) from 1979 to 2012. The linear trend was removed, and shade indicates that CC exceeds the 95% confidence level. UV850 (arrow) and speed (shade) anomalies in winter 2014 (c) and 2010 (d). A and C represent anti-cyclone and cyclone, respectively.



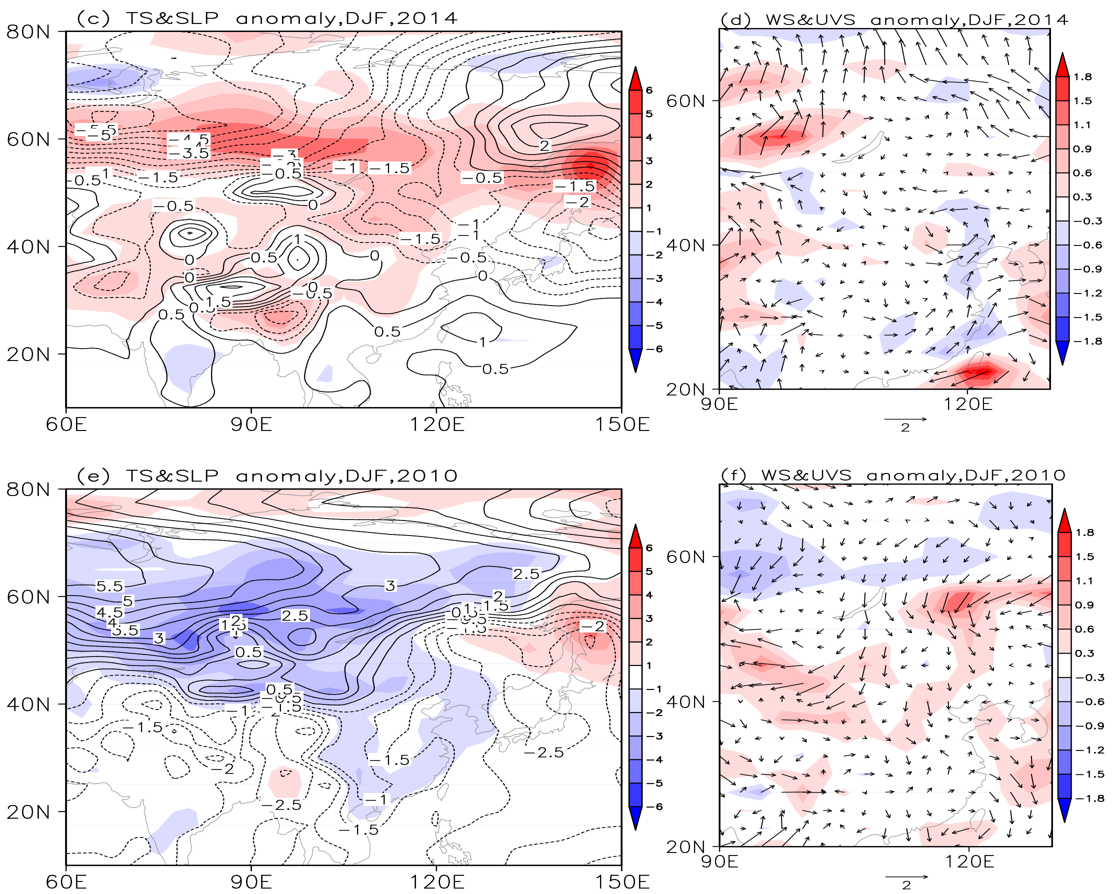


Figure 5. Correlation coefficients between WHD_{NCP} and winter circulations from 1979 to 2012 with linear trend was removed (a, b), and circulation anomalies in 2014 (c, d) and 2010 (e, f). The circulations in (a, c, e) are TS (shade) and SLP (contour) and those in (c, d, f) are surface wind speed (shade)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

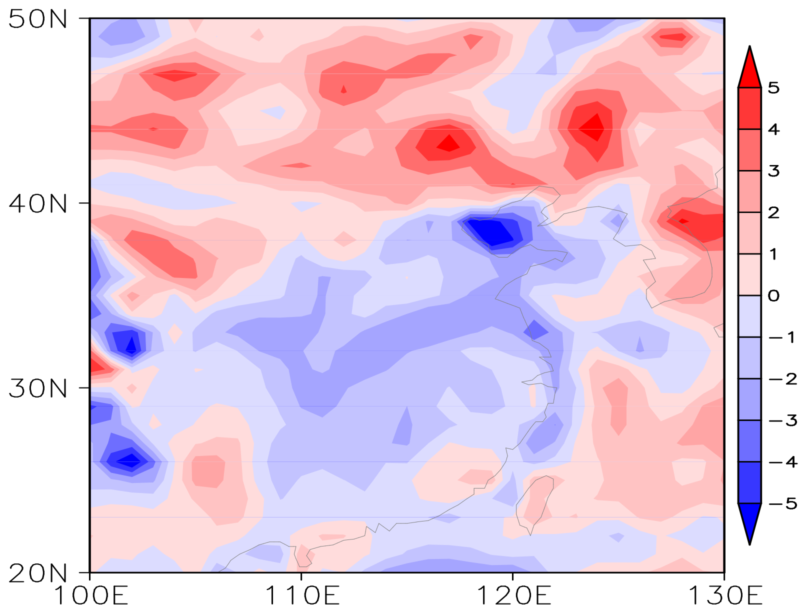


Figure 6. The difference of winter PBLH between 2014 and 2010

3, Concentration of PM2.5 reached its maximum in 2013, therefore the annual changes of emission should play an very important role in the haze days in recent years, but the author failed to arrange enough discussion and analysis about the emission change.

***Reply*:**

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 conditions. **The impact of emissions was written in the "Introduction" and "Discussion".**

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.** Furthermore, the $PM_{2.5}$ concentration of a global atmospheric watch station (Shangdianzi) and an urban station (Baolian) were **almost equal** 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**.

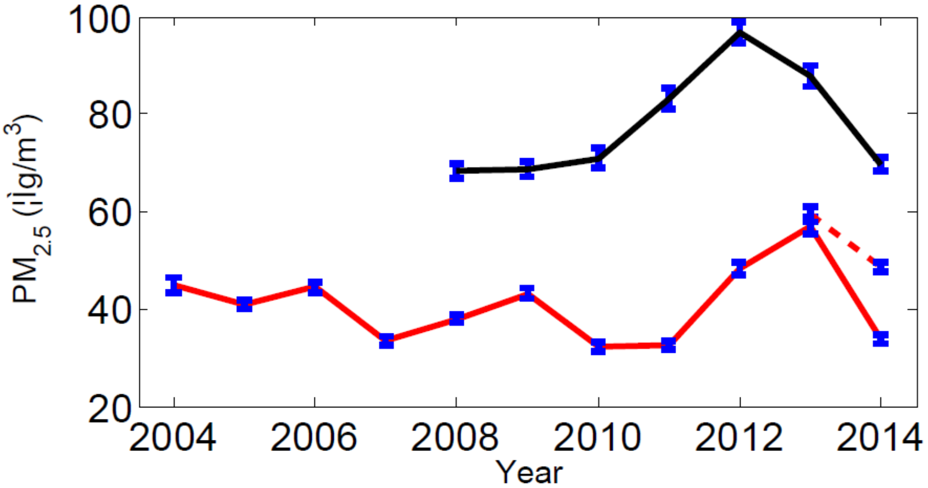


Figure 11. Mean mass concentration of $PM_{2.5}$ in winter at Shangdianzi (red; measured by the TOEM (solid) and β-ray (red dash) method) and Baolian (black) Station. The error bar represents one standard error among the different measured hours.

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.

The case studies of 2013 enhanced that the pollutant emission is the fundamental factor and highlighted the roles of anthropogenic influence. **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.** A brief summary of the impacts of these factors on WHD_{NCP} is offered in Table 2.

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	++		++
SON Atlantic SSTA		++	

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 the characteristics of that case. A brief summary of the impacts of these factors on WHD_{NCP} is offered in Table 2.……

4, Line 20: EA/WA should be EA/WR

***Reply*:**

The error has been corrected.

Revision:

……in 2010 further supports the mechanism of how EA/WR and WP patterns and associated external factors impact……

5, Line 36: What's the specific criterion of "static stability"?

***Reply*:**

The "static stability" was the ability of a fluid at rest to become turbulent or laminar due to the effects of buoyancy. The static stability of the atmosphere could indicate the vertical motion potential (or the intensity of convection) that was important for weather and pollution forecast.

Throughout the paper, the term "static stability" was only used once and in the introduction. Thus, we decided to correct it to a clearer and simpler expression "stable atmosphere".

Revision:

SWP-SST weakened EAWM circulation, leading to a favorable environment for haze with stable atmosphere and potential for hygroscopic growth (Yin et al. 2016).

6, Line 69-83: What's the role of Fig. 2 in such an analysis of large scale analysis for WHD_{NCP} in 2014 ?

***Reply*:**

As we know, haze is a multidisciplinary phenomenon that can be represented by visibility and humidity in meteorology, and by the concentration of the atmospheric composition in environmental science. The older Figure 2 was plotted to demonstrate the representation of haze data reconstructed primarily by visibility. After comparison, we confirmed that **the derived haze datasets not only agreed with the meteorological standard but also satisfactorily represented the concentration of the atmospheric composition.**

Following the reviewers advice, we putted this Figure into the supplementary material (i.e., Figure S1).

Revision:

Figure S1. Visibility of Beijing (green) and atmospheric………

7, Line 109: two “that”.

***Reply*:**

The error has been corrected.

Revision:

It is notable that WHDs in these two regions show significant increases, filling up the climatic WHD valley as shown in Figure 3a.