## Reply to Reviewer #1:

General comments: This paper presents results from a study on the impact of climate variability on the rapid increase of winter haze pollution in northern China around 2011-2015. It is a well written paper on an important subject. The authors have posed a pivotal scientific question about the haze pollution in northern China, which can have a critical implication on the long-term trends of haze. In addition, the authors have addressed the scientific question effectively by using a nested-grid global photochemical model. **I believe that the paper deserves publication in ACP** provided that the following two specific comments are addressed.

**1. (1) The main argument of the paper depends fundamentally on the validity of model simulations described in the "section 2.2 Geos-Chem description and experimental design". It is essential that the performance of the model used to simulate haze pollution in North China is validated or at least evaluated against observations. Figure 1 of the paper could be used to some extent for evaluating the model performance, but additional simulations with historical emissions are needed.**

**(2) Judging from the trends of anthropogenic emissions, this reviewer is afraid that results from simulations with historical emissions might turn out to be significantly different from observed haze days. In any case, uncertainty in the model needs to be included in the discussions of sections 3-5.**

***Reply:***

(1) We selected the year of 2015, which has just begun to strengthen emission reduction, and 2017, which has launched the air pollution prevention and management plan for "2+26" cities (Yin and Zhang, 2020), as two representative years to **simulate the actual $PM_{2.5}$ concentration**, so as to evaluate the performance of the GEOS-Chem model. The emission factors and meteorological conditions of 2015 and 2017 were be used respectively to simulate the $PM_{2.5}$ concentrations in early winters of 2015 and 2017. The simulation results are very **close to the observed data** in the two years (Figure S3) with high correlation coefficients reaching **0.88 and 0.85**, indicating that **the simulated data could basically reflect the change of actual $PM_{2.5}$ concentrations.** We have added this part about the model evaluation in the Section 2.2, and added a new Figure S3.

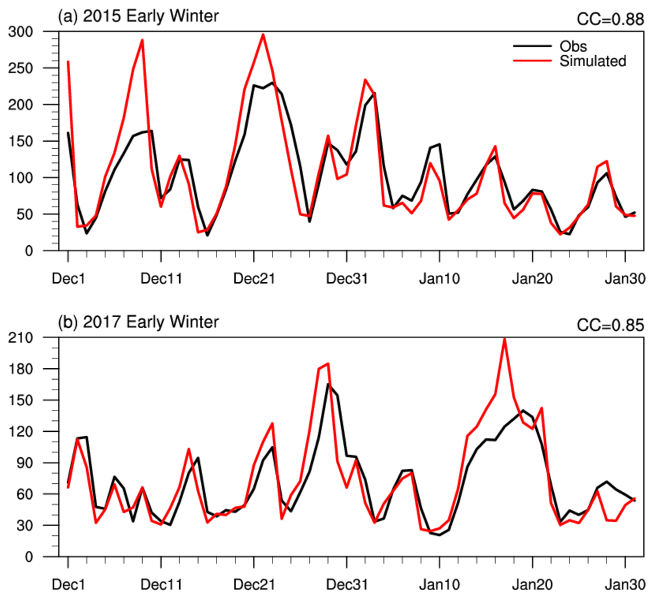



**Figure S3.** Temporal evolutions of observed (black) and simulated (red) PM2.5 concentrations (unit: μg $m^{-3}$; blue) in 2015 (a) and 2017 (b) early winter in North China.

In fact, the GEOS-Chem model has a **wide application**, and we have introduced **a few applications of others studies** in Section 2.2 to demonstrate the performance of the model laterally.

(2) Our simulations were designed to **emphasize the effects of climate**, so we used fixed emissions. In addition to the experiments with fixed emission in 2010, **a new set of experiments** was carried out by GEOS-Chem with **fixed emissions in 1985**, representing a low emission level. This simulation of the frequency of haze days (>50 μg $m^{-3}$) also **reproduced the trend reversal of haze pollution very well (Figure R1), similarly with the observed haze days.**

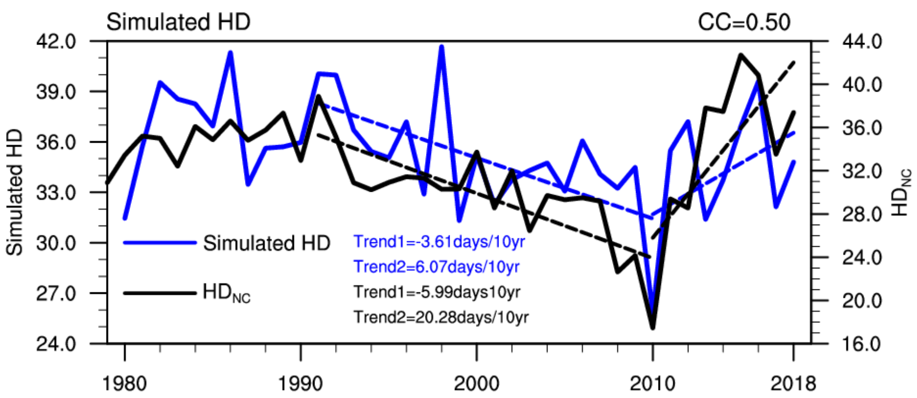
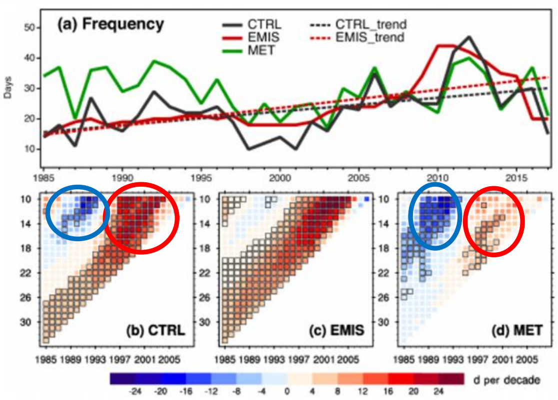



**Figure R1.** Temporal evolutions of $HD_{NC}$ (in black), simulated haze days under 1985 (unit: days; blue) emission scenarios in NC. The dashed lines denote linear regressions for 1991–2010 (P1) and

2010–2018 (P2). The black and blue Trend 1 and Trend 2 represent the linear trends of the observed and simulated haze days 1985 emission scenarios in P1 and P2, respectively.

Considering the change of anthropogenic emission, in Dang and Liao's finding (2019), the CRTL experiment (black line in Figure R2a) also **showed a decreased trend during 1985 to 2002** (blue grids in Figure R2b) and **an increased trend after 2010** (red grids in Figure R2b). Although this trend is weaker than the MET experiment, which only considered the effects of meteorological conditions (green line R2a), the overall change of trend in the CTRL experiment is **consistent with observations**. And Mao L. et al. (2019, National Science Review) also raised the **contradiction between the change of anthropogenic emissions and haze days** based on an observation approach, which was manifested as the number of winter haze days with no significant trend in most provinces and districts in eastern China from 1973 to 2012, contrary to the 2.5-fold increase in the emissions of particulate matter and its precursors (PM emissions) in the same period of time. And we have **added the discussion of the uncertainties** in section 5.




1. CTRL is the control simulation with variations in meteorological parameters, anthropogenic emissions, and biomass burning emissions from 1985 to 2017.
2. EMIS is the simulation with changes in anthropogenic and biomass burning emissions over 1985–2017, while the meteorological fields were fixed at the 1985 levels. The aim of this simulation is to quantify the impacts of changes in emissions on SWHDs during 1985–2017.
3. MET is the simulation with changes in meteorological fields over 1985–2017, while anthropogenic and biomass burning emissions were fixed at the 2015 levels. This simulation is set to examine the impacts of changes in meteorological parameters on SWHDs during 1985–2017.

**Figure 10. (a)** Time series of frequencies (days) of regional SWHD in BTH from three simulations (CTRL, EMIS, MET) for 1985 to 2017. **(b–e)** Time series of linear trends calculated over different periods for simulated frequencies of the **(b)** CTRL, **(c)** EMIS, and **(d)** MET simulations. The *x* axis indicates the start year, and the *y* axis indicates the number of years since the start year during which period the trend is calculated. The filled color in each square shows the calculated trend value, and those values marked with black borders are significant above the 95 % confidence level.

**Figure R2**. A key figure and design of three numerical experiments in ***Dang and Liao (2019) published in Atmos. Chem. Phys.***

***Related references:***


Yin, Z., and Zhang, Y.: Climate anomalies contributed to the rebound of PM2.5 in winter 2018 under intensified regional air pollution preventions, Sci. Total Environ., 726, 138514, 2020.

Dang, R. and Liao, H.: Severe winter haze days in the Beijing–Tianjin–Hebei region from 1985 to 2017 and the roles of anthropogenic emissions and meteorology, Atmos. Chem. Phys., 19, 10801–10816, https://doi.org/10.5194/acp-19-10801-2019, 2019.

Mao, L., Liu, R., Liao, W., Wang, X., Shao, M., Liu, S. and Zhang, Y.: An observation-based perspective of winter haze days in four major polluted regions of China. National Science Review, **6**, 515–523, doi: 10.1093/nsr/nwy118, 2019.

***Revisions:***

**Lines 79-85:** At present, GEOS-Chem model has been widely used, Dang et al. (2019) showed that the simulated spatial patterns and daily variations of winter $PM_{2.5}$ based on this model agree well with the observations from 2013 to 2017, available years with measured $PM_{2.5}$. We selected the year of 2015, which has just begun to strengthen emission reduction, and 2017, which has launched the air pollution prevention and management plan for "2+26" cities (Yin and Zhang, 2020), as two representative years to simulate the actual $PM_{2.5}$ concentrations, so as to evaluate the performance of the GEOS-Chem model. The simulation results are very close to the observed data (Fig. S3) with high correlation coefficients reaching 0.88 and 0.85 in 2015 and 2017, indicating this model could basically reflect the change of actual $PM_{2.5}$ concentrations.

**Lines 278-282:** Note that a number of factors contribute to the uncertainties in our results. Although a high emission scenario was used to simulate the number of haze days and emphasized the influence of meteorology, no complete and varied emission inventories were used to drive the GEOS-Chem model to make a comparison, which caused certain uncertainty. Furthermore, when assessing the contribution percentages of the external forcing factors, the coupling effect between climate variability and anthropogenic emissions was not considered, therefore the contribution rate of climate conditions might be overestimated.

**2. "The autumn SST in the Pacific and Atlantic, Eurasian snow cover and central Siberian soil moisture, which exhibited completely opposite trends before and after 2010, were proven to stimulate identical trends of meteorological conditions related to haze pollution in North China." in the abstract and conclusion section**

**maybe an overstatement, at least in terms of the relatively large uncertainty of the model. A more fundamental concern is that the method used in evaluating contributions of the four climate drivers does not imply any causal relationship.**

***Reply:***

We have adopted **a more rigorous statement** to explain the effect of the four external forcing factors on haze events in abstract and conclusion section.

***Revisions:***

**Lines 14-16:** The autumn SST in the Pacific and Atlantic, Eurasian snow cover and central Siberian soil moisture, which exhibited completely opposite trends before and after 2010, might had close relationships with the identical trends of meteorological conditions related to haze pollution in North China …….

**Lines 267-269:** In this study, the external forcing factors that closely related to the significant growth of $HD_{NC}$ after 2010 and the associated physical mechanisms were investigated. These factors might strongly linked to the anomalous anticyclone over NC via exciting the EA/WR teleconnection pattern……