Reply to Referee 2

We are grateful to the referee for the encouraging comments and careful reviews which helped to improve the quality of our paper. In the followings we quoted each review question in the square brackets and presented our response after each paragraph.

[Review Comment: Anthropogenic pollutant emissions and unfavorable meteorological conditions are commonly regarded as two key factors for haze pollution. This study investigated whether the structure of atmospheric thermodynamics in the troposphere and its intensity variation could act as a 'strong forewarning signal' for surface $PM_{2.5}$ concentration variations. It is a very interesting topic and significant for air pollution control. However, I think the current analysis is not sufficient to support the conclusion. Thus, some quantitative estimation and mechanisms illustration is suggested before publication. The detailed reason and suggestions are listed below.]

Reply: Thank you for the encouraging comments.

[1. Fig 1 and Fig 2 demonstrate the key role of "warm cover" in the haze process. However, the illustration of the connection of "warm cover" with the Tibetan Plateau has lacked. The "warm cover" shown in Figure S1 is below 900 hPa, which is similar to the height of the PBL top. It results in a very stable ABL and further improves the surface $PM_{2.5}$ concentration. However, the "warm cover" induced by Tibetan Plateau is about 600 hPa, which is 4 km. The mechanisms of the impact of "warm cover" in such altitude on PBL is needed to be illustrated in the manuscript.]

Reply: Many thanks for the referee's discussion. We agree with the suggestion. Following this comment, the content of Section 3.3 have adjusted (lines 188-193 and Figure 5) with following

sentences:

"The concept of interdecadal variations of the tropospheric 'warm cover' has been proposed in this work. Under the background of climate change, it is worth considering whether the variational tendency of the structure of the plateau's heat source induces variations of the tropospheric thermal structure in downstream areas of the Plateau, leading to the interdecadal variations of the frequency of haze events seen in Eastern China since the 21th century. Thermal anomalies of the TP also play an important role in the variations of the frequency of haze events in EC apart from the anthropogenic pollutant emission related to the rapid industrialization of China. The observational and modeling studies have demonstrated that the interannual variations in the thermal forcing of TP are positively correlated with the incidences of wintertime haze over EC (Xu et al., 2016). The TP induced changes in atmospheric circulation, increasing atmospheric stability and driving frequent haze events in EC (Xu et al., 2016). In this study, the data analysis concerning the interannual variations of the TP's apparent heat source and air temperature in wintertime at the TP with the altitudes above 3000 meters showed that since the 1960s the heat source in areas vulnerable to TP climate change strengthen continuously as the surface temperature increased (Fig. 5a). Furthermore, the TP's apparent heat and air temperature of the middle troposphere over EC presented the significant positive, which is similar to 'warm cover' structure characteristic (Fig. 5b). Therefore, we considered that the 'warm cover' change in the middle troposphere over EC was closely related to TP's apparent heat and the surface temperature. The TP induced changes in thermodynamic structure of atmospheric provided favorable climatic backgrounds driving air pollution events in EC."

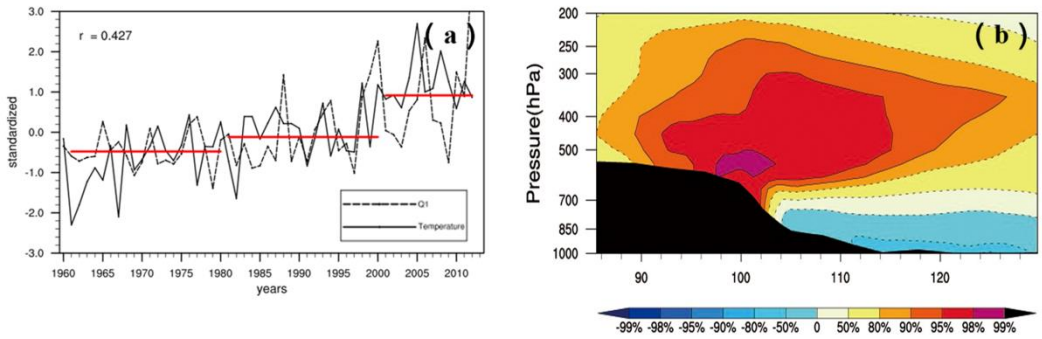

Figure 5. (a) TP's apparent heat source (Q1) and air temperature variations with interanual variations of TP's apparent heat source (Q_1) and air temperature of meteorological stations in the TP with the altitudes above 3000 meters in the winters during 1960-2014; (b) Vertical cross sections of the correlations between TP's apparent heat (Q_1) and air temperature latitude-averaged along 30-35 ℃N in the winters during 1960-2014.

We have accordingly cited the following article in the revised manuscript:

Xu, X. D., Zhao, T. L., Liu, F., Gong, S. L., Kristovich, D., Lu, C., Guo, Y., Cheng, X. H, Wang, Y. J., and Ding, G.: Climate modulation of the Tibetan Plateau on haze in China, Atmos. Chem. Phys., 16, 1365–1375, https://doi.org/10.5194/acp-16-1365-2016, 2016.

[2. Fig 3 shows that the "upper warming and bottom cooling" vertical structure in Autumn and Winter favors haze formation. It is interesting. However, the analysis is on the seasonal scale and did not directly support the haze formation on the daily scale.]

Reply: Based on the study of the Great Smog of London in 1952 and the heavy pollution of Beijing in February 2014, it is found that the abnormal 'warm cover' in the middle troposphere connected to both severe air pollution events (Sect. 3.1 and in Sect. 3.2). This study attempts to explore that whether such the similar structural characteristic of thermodynamic structure, i.e. the abnormal 'warm cover' in the middle troposphere, also exist from the perspective of different time scales, we have further analyzed the $PM_{2.5}$ concentrations and the number of haze days with

seasonal and interdecadal variations of the thermodynamic structures in the atmosphere. We found that the thermal vertical structure of atmospheric showed a ‘upper warming and bottom cooling’ vertical structure under heavy pollution conditions. The concept of the tropospheric ‘warm cover’ has been confirmed on the seasonal and climatic scale.

Following this comment, we have added these in the revised Abstract (line 32) as follows:

"The anomalous structure of the troposphere’s “warm cover” not only exist in heavy haze pollution on the daily scale, but also provide seasonal and interdecadal ‘strong signals’ for frequently occurring regional haze pollution."

[3. Fig 4 compares the interdecadal change of thermal structure in EC and eastern TP with haze days. However, the anthropogenic emissions in EC have increased several times from 1961 to 2018. It is hard to attribute the increase of haze days to the change of TP thermal structure.]

Reply: The pollutant emission with high intensity was the internal cause of frequent air pollution in EC, and the adverse weather conditions were often the key ‘inducement’ for the accumulation of air pollutants in the atmosphere. Although the variation trends of air pollution in EC depend on the air pollutant emissions,, the air pollution, including its intensity and duration, are closely related to meteorological conditions. Thus, we analyzed the anomalous thermodynamic structure (air temperature anomalies) from the perspective of meteorological conditions, in order to reveal the influence difference of the background field of meteorological conditions on regional atmospheric dispersion conditions. Furthermore, we found that the TP induced changes in thermodynamic structure of atmospheric provided favorable climatic backgrounds driving air pollution events in EC.

[4. I guess the impact of TP thermal structure on air pollution may cover a large part of EC. Maybe large-scale haze processes could be tried.]

Reply: Yes, the observational and modeling studies have demonstrated that the interannual variations in the thermal forcing of TP are positively correlated with the incidences of wintertime haze over EC (Xu et al., 2016). The TP induced changes in atmospheric circulation, increasing atmospheric stability and driving large-scale haze events in EC (Xu et al., 2016).

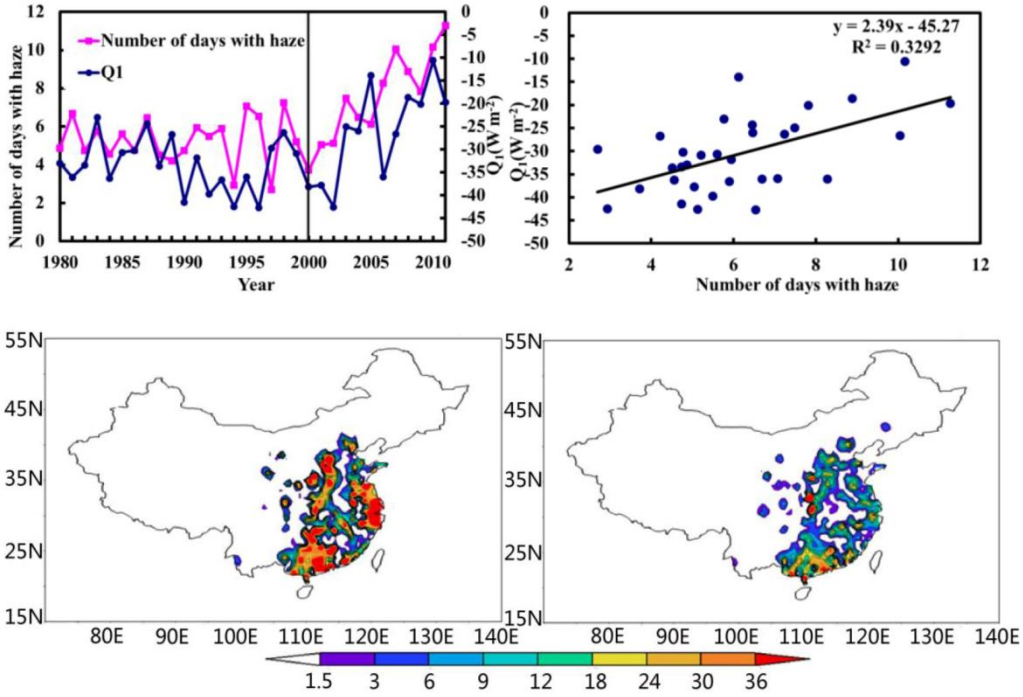

Figure 4. Interannual variability in the apparent heat source Q1 (the negative values denote cooling) integrated vertically over the TP and haze event frequency averaged in the CEC in winter (December, January and February) over 1980–2012 and their correlation (upper panel). The haze frequencies (days) averaged in five winters with most positive (lower left panel) and most negative Q1 anomalies (lower right panel) on the TP relative to the mean haze frequency from 1980 to 2012 (Xu et al., 2016).

References:

Xu, X. D., Zhao, T. L., Liu, F., Gong, S. L., Kristovich, D., Lu, C., Guo, Y., Cheng, X. H, Wang, Y. J., and Ding, G.: Climate modulation of the Tibetan Plateau on haze in China, Atmos. Chem. Phys., 16, 1365–1375, https://doi.org/10.5194/acp-16-1365-2016, 2016.