Response to Referee #1

We thank the Referee for the careful reading of the manuscript and helpful comments. According to the suggestions of the referee, the comments have been carefully addressed, and the paper is carefully revised. We believe that the revised paper has been significantly improved after addressing the comments of the referee. We respond to each specific comment below. The original comments by the Referee are shown in bold italics. Our reply is shown in blue.

General comments:

1. ***The paper by Long X. et al. assesses the impact of crop field burning (CFB) and topography on air quality in North China Plain. The contribution of crop field burning is quantified. This analysis would have a substantial impact on policy.***

   We thank the referee for the careful reading and the valuable comments that helped improving our paper.

2. ***However, I think the impact of CFB and mountainous topography are two distinct impact sources. Please justify the reason to address these two distinct impacts in this single study.***

   We thank the referee for the thoughtful comment. We added these two impacts together because these two effects are related to each other by the following reasons.

   a. One goal of the study is to analyze the effect of CFB on aerosol pollution in the northern NCP (NNCP), where the capital city of China (Beijing) locates. Whereas the major CFB occurred in the southern NCP (SNCP). As shown in the analysis, with the prevailing southerly winds, the regional transport plays important roles to transport CFB pollutants from SNCP to NNCP.

   b. As shown by the measurements, the mountains play important roles for the northward transport, and cause the accumulation of the aerosol pollutants at the foothill of the mountains. By considering the above reasons, it is important to add these two important effects together in the analysis. We added some statements in the revised paper.

      Line 99-104, "Thereafter we analyzed the regional transport of CFB emissions from SNCP to NNCP driven by prevailing southerly winds. Under the continuously southerly wind condition, the mountains play important roles for the northward transport, and cause the accumulation of the aerosol pollutants at the foothill of the mountains. We also analyzed the impact of mountains (especially the Taihang Mountains and the Yanshan Mountains) on the air pollution transport."

Line 147-149, "Considering the continuously southerly winds and the topographic conditions, we studied the impact of the mountains on the air pollution transport."

Line 351-355, "Indeed, the CFB pollution plume go through a long-range transport to NNCP can cause an obvious increase to $PM_{2.5}$ concentration, with the maximum daily average contribution of 32% (**Table 5**). Such a high transported contribution indicates that the CFB is not only one of the significant local pollution sources, but also a considerable regional pollution source."

Detailed Comments

1. Introduction. Page 3 Line 17, ". . .it is lack of study for the quantitative effect . . ." I do not think it is appropriate to claim this without justification. A number of source apportionment studies have quantified the contribution of biomass burning in Beijing with modeling approach[1,2,3]. A more comprehensive review of previous studies should be summarized in this part.

To response the Referee's comments, we modified and added a summary of previous studies.

Line 59-67, "Numerous studies have quantified the contribution of biomass burning and CFB to PM pollution in China. According to Yao et al. (2016), Cheng et al. (2013), Wang et al. (2009; 2007) and Song et al. (2007), biomass burning has important impacts on the ambient $PM_{2.5}$ concentrations (15-24% in Beijing and 4-19% in Guangzhou). Yan et al. (2010) captured a heavy pollution with PM_{10} concentrations higher than 350 $\mu g\ m^{-3}$ in some CFB locations. It is reported that CFB may contribute more than 30% of the PM_{10} increase during CFB incidents (Zhu et al., 2012; Zha et al. 2013;Su et al., 2012). Cheng et al. (2014) report a summer case that CFB contributed 37% of $PM_{2.5}$ concentrations in the Yangtze River delta."

Line 67-75, "The impact of CFB to air quality is continental and regional. Air quality in China is influenced by the CFB occurred in Southeast Asia and on the Indian Peninsula (Qin et al., 2006). Mukai et al. (2014) have reported that CFB emissions in Southeast Asia contribute the carbonaceous aerosols in Beijing. Within China, the inter-province transported air pollutants emitted from CFB significantly affect regional PM levels and air quality (Cheng et al., 2014;Zhu et al., 2012). For Beijing, the smoke particles from CFB are expected to be one of the major components (Wang et al., 2014;Cheng et al., 2013), though the percentage of transported sources are seldom specified (Zhang et al., 2016).”

2. It should be also noted in the manuscript on what the novelty of this study is.

Thanks. The novelty of this study is to use multiply methods to quantify the impacts of a serious CFB incident on the aerosol pollution in regional scale. The main methods and conclusions include (1) using satellite data to generate the CFB emission inventory with higher temporal and spatial resolution, (2) using WRF-CHEM model to study the regional transport from the burning region (SNCP) to the NNCP (where the capital city of Beijing locates), and (3) quantifying the effect of the mountains on the accumulation of pollutants at the foothill of the mountains. The combination of the multiply methods provides a better understanding of the effect of CFB on the regional air pollution. We modified and added explicit statements in the revised paper.

Line 32-34, “This study suggests that the prohibition of CFB should be strict not just in or around Beijing, but also on the ulterior crop growth areas of SNCP.”

Line 449-456, “In recent years, the NCP region, including the capital city of Beijing, has been suffering serious haze pollution problem, especially in winter and summer. Most studies concerned about the intense secondary formation, huge regional transport of pollutants, stationary meteorological conditions and large local emission. In autumn, CFB and movement of wind based on large scale topography are important in NCP, whereas the percentage of transported CFB emission sources are seldom specified. This is probably resulted from the contingency of CFB activities during harvest period and the limitation of temporal resolution of CFB emission inventories.”

Line 464-467, “A more detailed CFB emission inventory was generated in NCP. The daily CFB emissions were estimated depending on CFB activities captured by MODIS. Plenty of pollutants emitted from SNCP on Oct. 6^{th} and 7^{th}, producing plenty of $PM_{2.5}$ pollution, but few in NNCP during the entire haze period.”

Line 486-496, “Another major finding is that the mountains, surrounding the NCP in the north and west, play significant roles in enhancing the $PM_{2.5}$ pollution in NNCP through the blocking effect. The mountains block and redirect the airflows, causing the pollution accumulation along the foothill of mountains. The Taihang Mountains had greater impacts on $PM_{2.5}$ concentration than the Yanshan Mountains.

On account of various factors, such as pollutant long-range transport and pollutant accumulation caused by mountain effects, the prohibition of CFB should be strict not just in or around Beijing, but also on the ulterior crop growth areas of SNCP. Other $PM_{2.5}$ emissions in the SNCP should be significantly limited in order to reduce the occurrences of heavy haze events in NNCP region, including the Beijing City.”

3. ***Also, Summary of references on biomass burning emissions and the influence of mountains in NCP on air pollution is needed in introduction part as well.***

a. A comprehensive summary of biomass burning emission has been added in the revised paper.

Line 39-48, “Crop residue resources in China rank the first in the world, accounting for 17.3% of the global production (Bi et al., 2010), and increasing with the average annual proportion of 4% (Hong et al., 2015;Zhao et al., 2010). Compared with other approaches, crop field burning (CFB) is the most effective and less expensive to remove residues. The national annual average proportion of CFB to total residues is about 11-25%(Cao et al., 2008;Hao and Liu, 1994;Streets et al., 2003;Wang and Zhang, 2008;Zhao et al., 2010). Large numbers of annual CFB occur in China (Zhang et al., 2015; Yan et al., 2006), especially during the post-harvest seasons (Zhang et al., 2016;Shi et al., 2014;Cao et al., 2008).”

Line 52-66, “However, CFB have adverse impacts on traffic conditions and ecology environments (Shi et al., 2014;Zhang, 2009), and release plenty of pollutants, such as CO, SO_2, VOC, NOx and $PM_{2.5}$ (Koppmann et al., 2005;Li et al., 2008). According to Guan et al. (2014) and Lu et al. (2011), annual CFB contribute about 13% of the total particulate matter (PM) emissions in China (Zhang et al., 2016). And it is more prominent during the harvest periods due to its strong seasonal dependence. Numerous studies have quantified the contribution of biomass burning and CFB to PM pollution in China. According to Yao et al. (2016), Cheng et al. (2013), Wang et al. (2009; 2007) and Song et al. (2007), biomass burning has important impacts on the ambient $PM_{2.5}$ concentrations (15-24% in Beijing and 4-19% in Guangzhou). Yan et al. (2010) captured a heavy pollution with

PM_{10} concentrations higher than 350 μg m^{-3} in some CFB locations. It is reported that CFB may contribute more than 30% of the PM_{10} increase during CFB incidents (Zhu et al., 2012; Zha et al. 2013;Su et al., 2012). Cheng et al. (2014) report a summer case that CFB contributed 37% of $PM_{2.5}$ concentrations in the Yangtze River delta."

b. We modified and added explicit statements of provincial CFB emission inventory processing in Line 192-197 and Line 210-221. And we updated the provincial statistical data and related results. The detailed results and related references were added in supplementary data of Table S1, Table S2 and Table S3.

Line 192-197, **"**This situation may be resulted from the limitation of local enforcement of regulation despite CFB have already been banned (Zhang and Cao, 2015;Shi et al., 2014). The CFB have a seasonal pattern due to the post-harvest activities with two distinct peaks in summer and autumn, especially in June (33-59%) and October (6-19%) (**Fig. 2b**). The strong seasonal dependence character suggests that the CFB emissions during October are much larger than annual averages.**"**

Line 210-221, **"**where i stands for each province and k for different crop species of rice, corn and wheat. $E_{i,co}$ stands for CO emission from CFB of *i-th* province in gigagrams [Gg]. $P_{i,k}$ is the yield of crop in Gg. F_i is the proportion of residues burned in the field. D_k is the dry fraction of crop residue (dry matter). R_k is the residue-to-crop ratio (dry matter). CE_k is the combustion efficiency and EF_{co} is the emission factors of CFB. The $P_{i,k}$ values were taken from an official statistical yearbook (NBS, 2015) (**Table S1**), and the F_i on a provincial basis were taken from Wang and Zhang (2008) and Zhang Yisheng (Unpublished doctor thesis-in Chinese) (**Table S1**). The parameters of D_k, R_k, and CE_k are listed in **Table S2**. The EF_{co} from CFB was summarized range from 52 to 141 g kg^{-1} in China (**Table S3**). In this study, we used 111 g kg^{-1} as the average EF_{co} of crop residue, which was used to estimate the emissions from global open burning (Wiedinmyer et al., 2011).**"**

c. The influence of mountains in NCP on air pollution is added in ***Introduction.***

Line 80-91, "Yanshan and Taihang Mountains surround the NCP in the north and west (**Fig. 1c**). Such topography affects air pollution though PBL in complex ways (Miao et al., 2015b;Sun et al., 2013;Liu et al., 2009). Hu et al. (2014) have reported that the Loess Plateau and NCP result in a mountain-plains solenoid circulation, exacerbating air pollution over NCP. Chen et al. (2009) have founded that a mountain chimney effect is dominated by mountain-valley breeze, enhancing the surface air pollution in Beijing. The mountain-plain breeze develops frequently in Beijing and may play important roles in modulating the local air quality (Miao et al., 2015b;Hu et al., 2014;Chen et al., 2009). Miao et al. (2015a) founded that the mountains played a significant role in the sea-land aerosol circulation and the pollutants could be transported and accumulated in the NCP areas along the mountains, which is treated as the blocking effect (Zhao et al., 2015).**"**

4. ***Further work on modeling evaluation and validation of model are needed. Page 5 Line 20 states that the aerosol module from CMAQv4.6, released in 2006 is used in this study. Could the authors explain why to choose version 4.6 instead the latest version of CMAQ? It has been accounted by Baek, et al. 4 that the simulated OM tends to be underestimated due to the uncertainty in secondary organic aerosols mechanism. However, Figure 4 shows that simulated and observed PM2.5 mass concentration matches well. So is it possible to evaluate the model with PM2.5 species mass concentration and their precursor mass concentrations?***

In order to response the referee's comments, we added several revisions. We believe that these revisions help to better evaluate the model result.

a. A more detailed model description was added in **Section 3.1 Model description**:

Line 153-160, "The specific version of WRF-CHEM model is developed by Li et al. (2010; 2011; 2012), with a new flexible gas phase chemical module and the CMAQ (version 4.6) aerosol module developed by US EPA (Binkowski and Roselle, 2003). The wet deposition follows the CMAQ method and the dry deposition is parameterized following Wesely (1989). The photolysis rates are calculated using the FTUV (Li et al., 2005;Tie et al., 2003), in which the impacts of aerosols and clouds on the photochemistry are considered (Li et al., 2011)."

Line 162-166, **"**Meanwhile, the ISORROPIA Version 1.7 (http://nenes.eas.gatech.edu/ISORROPIA/) is utilized to simulate the inorganic aerosols, which is primarily used to predict the thermodynamic equilibrium between the ammonia-sulfate-nitrate-chloride-water aerosols and their gas phase precursors of H_2SO_4-HNO_3-NH_3-HCl-water vapor.**"**

Line 184-185, **"**The biogenic emissions are calculated on-line with the WRF-CHEM model using the MEGAN model (Guenther, 2006).**"**

b. The explanation of the statistical characteristics of the evaluation is added.

Line 272-280, **"**The simulations are overall lower than the observations with NMB of -12% in NNCP and -7% in SNCP. Considering the high average $PM_{2.5}$ concentration with 200.0 μg m^{-3} in NNCP and 184.1 μg m^{-3} in SNCP, obvious underestimates exist with the overall concentrations of 24.0 μg m^{-3} in NNCP and 12.9 μg m^{-3} in SNPC. This may be related to the CMAQ (version 4.6) aerosol module, which is likely to underestimated OM due to the uncertainty in secondary organic aerosols mechanism (Baek et al., 2011). Meanwhile, the underestimates are also related to the negative bias in S3, which may be related to cloud contamination (**Fig. S1**).**"**

c. More evaluations of model calculation, such as NO_2 and O_3, were added **in the Section 4.2 Statistical characteristics of the evaluation**. A new figure of the comparison between the calculated and measured NO_2 and O_3 is also added in the section (Fig. 4b and 4c), and related descriptions were modified.

Line 258-260, **"**In order to evaluate the model performance, the model simulations were compared with the measured results in both species concentrations ($PM_{2.5}$, O_3 and NO_2) and meteorological parameters (wind speed, wind direction and PBLH).**"**

Line 268-272, **"Figure 4** shows the measured and calculated temporal variations of regional average species concentrations, including $PM_{2.5}$, O_3 and NO_2. The WRF-CHEM model reproduced the pollution episode well, with a good agreement with observations. The correlation coefficients (R) of simulated and measured $PM_{2.5}$ concentrations are 0.88 in both NNCP and SNCP (**Fig. 4a**)."

Line 281-283, **"**The simulations of O_3 and NO_2 are also agree well with observations, with R greater than 0.77 and absolute NMB lower than 17% **(Fig. 4b and 4c)"**

d. Pattern comparisons of simulated vs. observed near-surface $PM_{2.5}$ concentrations were added in Fig. 9 and Fig.10.

Line 370-372, **“**The pattern comparisons between simulated and observed near-surface $PM_{2.5}$ concentrations ($TPM_{2.5}$) perform well (**Fig. 9 Left Panels**).**”**

Line 767-770, **“Figure 9 …** Left panels also show the pattern comparisons of simulated vs. observed near-surface $PM_{2.5}$ concentrations ($TPM_{2.5}$), with $PM_{2.5}$ observations of colored circles. Black arrows denote simulated surface winds.**”**

Line 414-415, **“**exhibiting a good performance of the pattern comparisons between simulated and observed near-surface $PM_{2.5}$ concentrations.**”**

Line 771-775, **“Figure 10** The elevation contours and the pattern comparisons of simulated vs. observed near-surface $PM_{2.5}$ concentrations from 12:00 7^{th} to 00:00 10^{th}. Colored circles: $PM_{2.5}$ observations of foothill sites; Colored squares: $PM_{2.5}$ observations of non-foothill sites; Black arrows: simulated surface winds. The 200-meter contour was highlighted with bold black line.**”**

5. ***Page 9 Line 10 states that “strong southerly wind, with mean wind speed of 2.5 (2.7) m s-1 in NNCP and 3.0 (3.6) m s-1 in SNCP” to illustrate that “The pollution is continuously transported from SNCP to NNCP”. It’s not strong enough to get such conclusion. Trajectory analysis and wind speed profile analysis should be included.***

According to the referee’s suggestions, we added a backward trajectory analysis and wind speed profile analysis **in the Section 4.3 Characteristics of the heavy pollution events.** A new figure of the backward trajectory analysis during S1 was added in the revised paper. As shown in Fig. 6, the prevailing wind during the analysis period (S1) is continuously from south to north.

Line 296-301, **“**The backward trajectories, with the HYSPLIT model online version, of BJ, TJ and BD during S1 reflected how the CFB influenced the NNCP region (**Fig. 6**). The air mass mainly came from the south, originating from the SNCP region. The pollutants are continuously transported from SNCP to NNCP, leading to pollutants accumulation in NNCP…”

6. ***In Section 4.5, it is written "The differences between the simulations with or without mountains showed the net effect of the topography on PM2.5 concentration". I wonder if it is appropriate to make this assumption for several reasons. First, the impact of topography is complicated. I am not sure if it is good to represent it just as "reduced to the averaged altitude". Second, the NCEP FNL Operational Global Analysis data is employed as the initial meteorological condition. It means the initial condition is "real" (with mountains) in all scenarios.***

   a. Thanks for the suggestion. As an online model, the reduction of the topography in WRF-CHEM can lead to dynamical changes, such as the wind speeds at the foothill of the mountains. We agree with the referee that there are some shortcomings of the method, and we modified the text to point out these shortcomings **in the Section. 4.5 Impact of mountains**.

      Line 396-405, **"**In this study, we utilized the differences between the simulations with or without mountains to represent the effect of the topography on $PM_{2.5}$ concentration, which were calculated based on Eq. (9). As an on-line dynamical model, the topography changes in WRF-CHEM can lead to dynamical changes, such as the wind speeds at the foothill of the mountains. This is a useful and traditional sensitivity analysis method for numerical model to quantify the mountains effects, but with some shortcomings, which are to bring uncertainties to the sensitivity experiment. Firstly, the impact of topography is complicated to be completely quantified only by the altitude remove behavior. Secondly, the initial NCEP FNL data with mountains is treated as "real" in scenarios without mountains.**"**

   b. The guiding effect is treated as part of the mountain blocking effect. We modified and added the description in the revised paper.

      Line 31-34, "…through the blocking effect. The mountains block and redirect the airflows, causing the pollutant accumulations along the foothill of mountains. This study suggests that the prohibition of CFB should be strict not just in or around Beijing, but also on the ulterior crop growth areas of SNCP."

      Line 418-423, "Here, it is attributed to the mountain blocking effect, which has two categories of influences. Firstly, the mountains block the airflows, causing pollutant accumulation and resulting in high $PM_{2.5}$ loading at the foothill of mountains (Influence-1, block). Secondly, the mountains redirect the airflows, causing the pollutants move toward the downwind foothill areas (Influence-2, redirect).”

Line 486-491, “Another major finding is that the mountains, surrounding the NCP in the north and west, play significant roles in enhancing the $PM_{2.5}$ pollution in NNCP through the blocking effect. Mountains block and redirect the airflows, causing the pollution accumulation along the foothill of mountains. The Taihang Mountains had greater impacts on $PM_{2.5}$ concentration than the Yanshan Mountains.”

Supplementary data of Fig. S3, “**Fig. S3** The schematic pictures of mountains effect along with the topography of the NCP region. (a) Mountains block the airflows and cause pollutants accumulated at the foothill of mountains. (b) Mountains redirect the airflows, and cause pollutants move toward the downwind foothill areas (Influence-2, redirect).”

7. ***The spin-up time is only 12 hours. I think the spin- up time is not long enough to get balanced. Also I wonder if any nudging method is used in this study (it should be explained in method part). If so, the contribution might be changed due to the nudging. Third, the domain is not large enough to ignore the impacts of “real” boundary condition. The mountainous topography may change the large-scale circulation.***

We rerun the model to extend the spin-up time to 3 days (Line 178), and updated related results (Line 442-444, Fig. 11…). As a regional model, the boundary effect cannot be avoided in the WRF-CHEM. We agree with the referee that change model domain and use nudging method can change the model results. But we also need to consider the balance between large domain and cost of computation time. As a result, we have tested for different sizes for the model domains (900km x 900km). We think that the current domain 1200km x 1800km is reasonable and large enough for considering the lateral boundary effects. The important mountains (Taihang and Yanshan) have included in this domain.