Interactive comment on "Dominant role of emission reduction in $PM_{2.5}$ air quality improvement in Beijing during 2013–2017: a model-based decomposition analysis" by Jing Cheng et al.

Anonymous Referee #2
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This paper systematically quantifies the relative importance of local control measures, surrounding emission reductions and meteorological changes in PM2.5 air quality improvement in Beijing during 2013-2017. A number of sensitivity simulations are performed, which are huge load of work. The paper is generally well written and the conclusions have strong policy implications. I would suggest publishing it after addressing the following issues.

Response:

We thank the reviewer #2 for the constructive comments and address them as below.

1 The authors provide comprehensive validation of meteorological variables and concentrations of criteria pollutants. It would be nice to include also validation of $PM_{2.5}$ compositions and draw conclusions on which species are more important for the declines in $PM_{2.5}$.

Response: to better analysis the validation of $PM_{2.5}$ compositions, we firstly add the validation of $PM_{2.5}$ compositions simulations in Sect.2.4.2; the detailed comparison of the simulation and observations of $PM_{2.5}$ compositions are listed in SI, Table S4; the data source of observational $PM_{2.5}$ compositions is introduced in Sect.2.1. Then the analysis about the aerosol chemical composition changes is added in Sect.3.4.1 as follows, and the variation trends of simulated $PM_{2.5}$ compositions can be found in SI, Figure S6.

Although there was a steady decline in $PM_{2.5}$ concentrations of Beijing during 2013-2017, the trends of $PM_{2.5}$ compositions varied differently. The simulation results of base cases (which adopted the real meteorology and emissions of each year) showed that the sulfate (SO_4^{2-}) and organic matter (OM) were dominate species for the decline in $PM_{2.5}$ concentrations during 2013-2017, with the decrement of 7.5 μg m^{-3} (56.6%) and 9.6 μg m^{-3} (40.5%) respectively. The contribution of SO_4^{2-} to the total $PM_{2.5}$ also decreased obviously, from 15.3% in 2013 to 10.7% in 2017; and OM proportion decreased from 27.5% in 2013 to 26.5% in 2017. The rapid decrement of SO_4^{2-} was consistent with the remarkable SO_2 emission reductions in Beijing during 2013-2017. Along with the effective SO_2 emission control measures, the SO_4^{2-} was basically no longer the key contributor leading to heavy pollution in Beijing while the nitrate-driven haze pollution has become more dominate in Beijing in recent years, especially in the summertime (Li et al., 2018). The decrement of OM was mainly caused by the prominent emission reductions of primary organic carbon (mainly come from the residential burning and other coal combustion sources). VOCs emission reductions also contributed to the OM decreasing, however, due to the insufficient simulation of secondary organic aerosols (SOA) formulations in CMAQ model, the contributions of VOCs emission control might be underestimated. In contrast, nitrate (NO_3^-) increased in 2014-2016, and kept basically the same concentration level in 2017 (10.4 μg m^{-3}) as 2013 (10.9 μg m^{-3}). However, the contribution of NO_3^- to the total $PM_{2.5}$ increased a lot, from 12.7% in 2013 to 19.4% in 2017. The specific concentration and proportion trends of $PM_{2.5}$ concentrations can be found in SI, Table S6.

2 The description of scenario design and decomposition analysis is very confusing. In equations (2) and (3), i=1...9, but in Table 2, i=1…7. I understand the other two cases are impact of meteorology and emission reduction of surroundings, but it would be better to improve the descriptions here. Additionally, the response of $PM_{2.5}$ is not linear to emission changes in the inventory, so it might be questionable to sum them up directly in equations (2) and (3).

Response: 1) we rewrite the Sect.2.5 (Scenario design and decomposition analysis) as follows:

All scenario cases were labelled as $E_{LiSj}M_k$. $M_k(k)$ represents the metalogical period the case adopted and $E_{LiSj}(i, j)$ represents the emission period. Total emission inventories of China consisted of two parts, that the BJ-EI from BMEMC and the regional (all parts of China except for Beijing) emission inventories from MEIC model. The adopted emission period of these two parts were labelled as $Li(i)$ and $Sj(j)$ respectively.

$E_{L13S13}M_{13}$, $E_{L16S16}M_{16}$, and $E_{L17S17}M_{17}$ were three base cases and driven by the actual emission inventories and meteorology of 2013, 2016 and 2017, respectively, to reproduce the air quality of the corresponding year. $E_{L17S17}M_{13}$ and $E_{L17S17}M_{16}$ were designed to investigate the impact of meteorology. These two cases were driven by varying meteorological conditions (meteorology of 2013 and 2016, respectively) and the same emission inventory (for the year 2017). $E_{L17S13}M_{17}$ and $E_{L17S16}M_{17}$ were designed to quantify the impact of surrounding emission reduction during 2013-2017 and 2016-2017. In these two cases, the emission inventory of Beijing was set to the 2017 level, while the regional emission inventory was set to the 2013 and 2016 levels, respectively.

Another fourteen simulations were designed to quantify the air quality improvements contributed by seven types of local control policies during two periods. Cases for 2013-2017 and 2016-2017 were labelled as $E_{L_{pI}S17}M_{17}$ and $E_{L_{qI}S17}M_{17}$ respectively, where i represents the number of each policy (described and listed in Table 1). The meteorological conditions and regional emission inventories of these fourteen cases were set to 2017. For each simulation, emission reduction introduced by the corresponding policy type and adopting period was added to the 2017 baseline, equivalent of "turning off" this type of policy during this period. And then the derived emission inventory was applied to drive the corresponding air quality modelling.

A linear additive relationship was assumed among all contributors to perform a decomposition analysis, and the simulated contributions of all sensitivity cases were then normalized by the difference in observed $PM_{2.5}$ concentrations from 2013-2017 and 2016-2017. The normalization process of 2013-2017 period were calculated by the following equations, while the simulated results for period of 2016-2017 can be normalized with the similar process.

$$\mathrm{SCon(M)} = \mathrm{SPM}_{2.5}(\mathrm{E}_{L17S17}\mathrm{M}_{13}) - \mathrm{SPM}_{2.5}(\mathrm{E}_{L17S17}\mathrm{M}_{17}) \quad (1)$$

$$\mathrm{SCon(S)} = \mathrm{SPM}_{2.5}(\mathrm{E}_{L17S13}\mathrm{M}_{17}) - \mathrm{SPM}_{2.5}(\mathrm{E}_{L17S17}\mathrm{M}_{17}) \quad (2)$$

$$\mathrm{SCon(pi)} = \mathrm{SPM}_{2.5}(\mathrm{E}_{L_{pi}S17}\mathrm{M}_{17}) - \mathrm{SPM}_{2.5}(\mathrm{E}_{L17S17}\mathrm{M}_{17}) \quad (3)$$

$$\mathrm{NCon(M)} = (\mathrm{PM}_{2.5OBS2013} - \mathrm{PM}_{2.5OBS2017}) \times \frac{\mathrm{SCon(M)}}{\mathrm{SCon(M)} + \mathrm{SCon(S)} + \sum_{i=1}^{7}\mathrm{SCon(pi)}} \quad (4)$$

$$\mathrm{NCon(S)} = (\mathrm{PM}_{2.5OBS2013} - \mathrm{PM}_{2.5OBS2017}) \times \frac{\mathrm{SCon(S)}}{\mathrm{SCon(M)} + \mathrm{SCon(S)} + \sum_{i=1}^{7}\mathrm{SCon(pi)}} \quad (5)$$

$$\mathrm{NCon(pi)} = (\mathrm{PM}_{2.5OBS2013} - \mathrm{PM}_{2.5OBS2017}) \times \frac{\mathrm{SCon(pi)}}{\mathrm{SCon(M)} + \mathrm{SCon(S)} + \sum_{i=1}^{7}\mathrm{SCon(pi)}} \quad (6)$$

where $SCon(M)$ represents the simulated contribution of meteorology change during 2013-2017, which equals the balance of simulated $PM_{2.5}$ (μg m^{-3}) from case $E_{L17S17}M_{13}$ and case $E_{L17S17}M_{17}$. Similarly, $SCon(M)$ and $SCon(pi)$ represent the simulated contribution of regional emission reductions and each local control policy type. $NCon(M)$ represents the normalized contribution of meteorology change during 2013-2017, which equals the product of the observational $PM_{2.5}$ balance (from 2013-2017) and the proportion of simulated meteorology contribution (in the simulated contributions of all factors). Similarly, $NCon(M)$ and $NCon(pi)$ represent the normalized contribution of regional emission reductions and each local control policy type.

2) we add a discussion part in Sect.3.5.1 to quantify the extra non-linearity effects of the zero-out approach in our study; meanwhile, we also explained the reason why we used zero-out approach in Sect.3.5.1 (as follows).

Although various methods have been developed to quantify the source of $PM_{2.5}$ and evaluate their contributions, such as receptor-based methods (like CMB and PMF), trajectory-based methods (like PSCF and EEI)), source-oriented methods (like CAMx-PSAT and CMAQ-ISAM)) (Li et al, 2015), they can hardly consider the meteorology and emission changes simultaneously. Therefore, the zero-out approach might be a better choice to attribute the contribution of local and regional emission control as well as meteorology changes under one complete decomposition framework. The zero-out method is also widely used in estimating the contribution of air pollution sources (Lelieveld et al., 2015; Han et al., 2016; Baker et al., 2016; Zhang et al., 2017; Zhang et al., 2017; Ni et al., 2018).

However, the response of $PM_{2.5}$ formulation is not linear to the meteorology and emission changes; thus, the zero-out approach would introduce extra bias in research. The non-linear effects of the analyse period of 2013-2017 could be evaluated by the following equation (Zhang et al., 2017).

$$\mathrm{Bias} = (\mathrm{SCon(M)} + \mathrm{SCon(S)} + \sum_{i=1}^{7}\mathrm{SCon(pi)}) - (\mathrm{SPM_{2.5}}(\mathrm{E}_{L13S13}\mathrm{M_{13}}) - \mathrm{SPM_{2.5}}(\mathrm{E}_{L17S17}\mathrm{M_{17}})) \qquad (7)$$

Where $SPM_{2.5}(E_{L13S13}M_{13})$ and $SPM_{2.5}(E_{L17S17}M_{17})$ represent the direct simulated $PM_{2.5}$ concentration of base case in 2013 and 2017. The balance of their values is the actual $PM_{2.5}$ decrement during 2013-2017 under the mixed impacts of meteorology change, regional and local emission reductions. The sum of $SCon(M)$, $SCon(S)$ and $\sum_{i=1}^{7} SCon(pi)$ represents a linear result of all contributors during this period. The extra bias can be estimated as the difference between the linear addition and the actual decrement. According to equation (7), we estimated biases in the analyse of 2013-2017 were 1.4 μg m^{-3}, accounting for 4.3%. Similarly, the absolute and relative biases in the analysis of 2016-2017 were estimated as -0.6 μg m^{-3} and -3.6%. Both indicated the non-linear effects are relatively small and acceptable.

Minor comments: Page 7 line 11: SIME17S13M17 and SIME17S13M17 typo?

Response: SIME17S13M17 **represents the simulation that adopted the meteorology of 2017, Beijing local emission of 2017, Beijing surrounding emission of 2013. In the previous version manuscript, "Page 7 line 11:** SIME17S13M17 **and** SIME17S13M17**", the second** SIME17S13M17 **was wrong and should be** SIME17S13M17, **which represents the simulation that adopted the meteorology of 2017, Beijing local emission of 2017, Beijing surrounding emission of 2016. This section is rewritten now, and please refer to the response of comment 1.**

Page 7 line 12: change "In both of these cases" to "in both cases"

Thanks for the kind remind; and the error is corrected in the new version.